Ingeniería y Competitividad
Vol 26 (3) 2024; doi: 10.25100/iyc.v26i3.14049

Vol 26 (3)

ISSN
0123-3033
e- 2027-8284

Original Article

A methodology for hydrologic design of porous-concrete pavements

Una metodología para el diseño hidrológico de pavimentos de hormigón poroso

Juan F. Weber[1]

[1]Research and Development Group in Water Resources and Sanitation. Cordoba Regional Faculty, National Technological University – Córdoba, Argentina.

How to cite?

Weber, J.F. A methodology for hydrologic design of porous-concrete pavements Ingeniería y Competitividad, 2024, 26(3)e-21214049

https://doi.org/10.25100/iyc.v26i3.14049

Recibido: 9-05-24
Evaluado: 06-06-24
Aceptado: 01-11-24
Online: 6-11-24

Correspondence
jweber@frc.utn.edu.ar

Abstract

Introduction
Porous concrete pavements represent an effective solution for reducing surface runoff in urban environments, contributing to the sustainable development of cities. These pavements allow water infiltration, which is crucial to mitigate the effects of urbanization, such as flooding. However, the infiltration capacity of the pavement depends not only on the porous concrete wearing course but also on the characteristics of the granular base and the natural soil subgrade, requiring an integrated analysis of the layered system.
Objectives
The main objective of this study is to present a simplified methodology based on the Horton model to define the hydrologically necessary thickness of the granular base and simulate the movement of water in the porous pavement system. This methodology aims to facilitate the design and analysis of permeable pavements in urban settings.
Methodology
The methodology is based on the Horton model, which is used to simulate water infiltration into soils. The necessary thickness of the granular base is defined through a simplified approach that takes into account both the characteristics of the pavement and the underlying layers. Subsequently, a simulation of water movement within the system is performed to evaluate the effectiveness of the proposed design. To illustrate its application, a typical hydrological design case is presented.
Results
The application of the proposed methodology to a typical design case allows for the determination of the appropriate thickness of the granular base required to ensure efficient water infiltration. The results show that the model can be used as an effective tool to calculate and simulate water behavior in porous concrete pavement systems.
Conclusions
The simplified method presented is useful for engineers involved in the hydrological design of permeable pavements, as it provides a quick and effective way to calculate the thickness of the granular base and simulate water movement. Additionally, this methodology can be of great value in academic training in urban drainage, both at the undergraduate and graduate levels.

Keywords: urban Hydrology, Sustainable Urban Drainage Systems, Infiltration, Porous Pavements

Resumen

Introducción

Los pavimentos de hormigón poroso se presentan como una solución efectiva para reducir el escurrimiento superficial en entornos urbanos, lo que contribuye al desarrollo sustentable de las ciudades. Estos pavimentos permiten la infiltración del agua, lo cual es fundamental para mitigar los efectos de la urbanización, como las inundaciones. Sin embargo, la capacidad de infiltración del pavimento no depende únicamente de la capa de rodamiento de hormigón, sino también de las características de la base granular y la subrasante del suelo natural, lo que requiere un análisis integral del sistema de capas.

Objetivos

El objetivo principal de este estudio es presentar una metodología simplificada basada en el modelo de Horton para definir el espesor hidrológicamente necesario de la base granular y simular el movimiento del agua en el sistema de pavimento poroso. Esta metodología busca facilitar el diseño y análisis de pavimentos permeables en contextos urbanos.

Metodología

La metodología se basa en el modelo de Horton, que se utiliza para simular la infiltración del agua en suelos. Se define el espesor necesario de la base granular mediante un enfoque simplificado que considera tanto las características del pavimento como las de las capas subyacentes. Posteriormente, se realiza una simulación del movimiento del agua en el sistema para evaluar la eficiencia del diseño propuesto. Para ilustrar su aplicación, se presenta un ejemplo práctico de diseño hidrológico típico.

Resultados

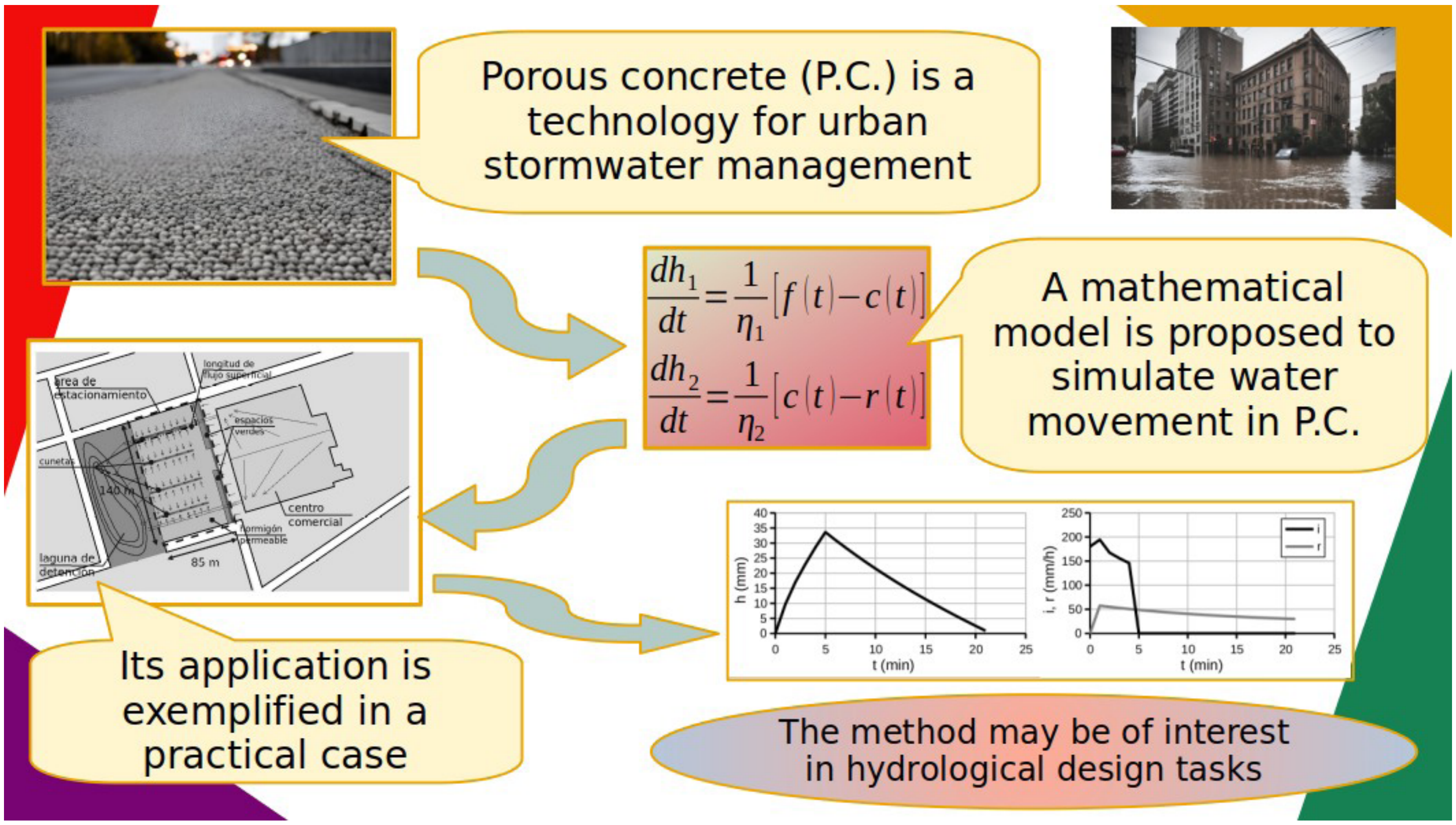
La aplicación de la metodología propuesta en un caso de diseño típico permite determinar el espesor adecuado de la base granular necesario para asegurar la infiltración eficiente del agua. Los resultados muestran que el modelo puede ser utilizado como una herramienta efectiva para calcular y simular el comportamiento del agua en sistemas de pavimentos de hormigón poroso.

Conclusiones

El método simplificado presentado es útil para los ingenieros que trabajan en el diseño hidrológico de pavimentos permeables, ya que proporciona una manera rápida y eficaz de calcular el espesor de la base granular y simular el movimiento del agua. Además, esta metodología puede ser de gran valor en la formación académica en áreas de drenaje urbano, tanto a nivel de grado como de posgrado.

Palabras clave: hidrología Urbana, Sistemas de Drenaje Urbano Sustentables, Infiltración, Pavimentos Porosos

doi: 10.25100/iyc.v26i3.14049



Introduction

Urban development and the construction of conventional pavements transform the natural, permeable soil into an impermeable surface. The creation of these impermeable pavement systems has led to two significant changes in the local environment: (a) alterations in hydrological aspects and (b) variations in the surrounding thermal environment. The impermeable nature of conventional pavement systems has resulted in an increase in the volume of stormwater runoff, contributing to a large quantity of water carrying unacceptable levels of pollutants and causing unjustified flash floods. Moreover, managing this flow requires large retention basins before releasing it into natural water bodies. (1).

On the other hand, porous pavements have the ability to reduce runoff volume and improve the quality of the water being discharged. In fact, they can store stormwater until it infiltrates into the ground or is transported downstream through the stormwater management system via a drainage network. For this reason, many communities are exploring their use as an alternative low-impact development design for stormwater control measures. These permeable pavement systems can help solve drainage problems and reduce the risk of flash floods resulting from continued urban development (2).

Porous Concrete Pavements

A porous concrete system is composed not only of the pavement itself (the top layer) made of this material but also of a granular base and the natural soil subgrade (which typically includes a geotextile layer for protection). For both hydrological and hydraulic analysis and design, the entire system must be considered because its storage and infiltration capacities are determined by the characteristics of all its components.

doi: 10.25100/iyc.v26i3.14049

The entire surface of porous concrete is permeable, unlike composite surfaces such as open-jointed blocks and grid pavers (3). As a result, the infiltration capacity of porous concrete pavements is usually several orders of magnitude higher than that of the subgrade, which is typically less permeable than natural soil due to the compaction process. For this reason (and structural considerations), it is common to place a coarse granular subbase between the porous concrete pavement and the subgrade. This subbase serves the hydrological function of acting as a temporary reservoir for infiltrated water while it percolates into the underlying soil. The typical profile is completed by a layer of geotextile between the granular subbase and the subgrade, which serves as a filter (Fig. 1).

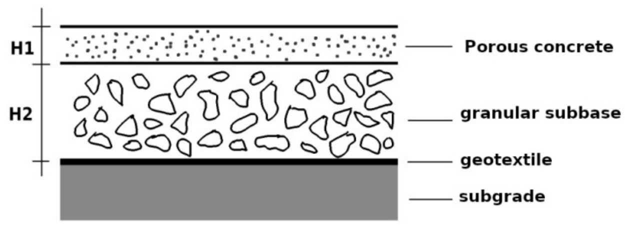


Figure 1. Typical profile of a porous concrete pavement (own elaboration)

In the case of subgrades with very low or no infiltration capacity, it is advisable to laterally drain the granular subbase to remove excess stored water. In this case, the primary function of the base-drain system is to act as an attenuation reservoir, thereby reducing runoff flow rates. Depending on the design grade, these drains can be constructed with granular material or perforated pipes (Fig. 2).

Figure 2. Schematic profiles of undrained (left) and drained (right) porous pavements. Components: porous concrete pavement (HP); granular subbase (BG); subgrade (SR); perforated pipe (CP). Dominant hydrological processes: infiltration (F), percolation (C), recharge (R), surface runoff (Q), evaporation (E), lateral drainage (D) (own elaboration).

The thickness H_1 of the porous concrete layer is primarily determined by structural considerations, typically ranging between 10 and 20 cm (4), with typical porosities around 15%. The thickness H_2 of the granular subbase is usually defined by hydrological considerations, as described later, and is then structurally verified for the entire pavement package. Its porosity is generally higher than that of the porous concrete layer (around 30%), meaning that its infiltration capacity is even greater (4).

In undrained permeable pavements (Fig. 2, left), all the water that infiltrates the porous concrete (F) and percolates into the granular subbase (C) must then infiltrate into the subgrade (R). Therefore, any excess percolation that exceeds the subgrade's infiltration capacity must be temporarily stored in the granular subbase. This hydrologically determines the thickness of the subbase layer. Thus, the thickness of the granular subbase depends, among other variables, on the infiltration capacity of the subgrade, which must be adequately characterized through in-situ measurements.

Background

Tennis et al. (5) present some hydrological design considerations for permeable pavements, including: permeability, storage capacity, and characteristics of the underlying soil: the methodology (applied in an example), of an empirical nature, can serve as a starting point for a

doi: 10.25100/iyc.v26i3.14049

preliminary design. Ferguson (3) conceptually describes the functioning of the porous pavement, including the granular subbase and the natural soil subgrade. It also presents a compilation of experimental or field parameters for porous pavements, including: infiltration rates, runoff coefficients, and surface runoff velocity.

Wanielista et al. (6) present a mass balance model applicable to a porous concrete pavement. The model discriminates between an event simulation and a continuous one. They applied this model to represent the behavior of various porous pavements located in Florida, Georgia, and South Carolina (USA). Rodden et al. (7) present a simplified hydrological design methodology for porous concrete pavements, based on a volumetric balance, which allows obtaining the required area of porous pavement and the thickness of the storage layer, as well as the detention time of the runoff. This methodology is implemented in the PerviousPave software of the American Concrete Pavement Association (8). The required thickness for the granular subbase is given by:

$$h_s = \frac{E \cdot t_d - h_{curb} - r_c \cdot h_c}{r_s} \tag{1}$$

where

E is the infiltration rate of the soil, t_d is the maximum detention time of water in the permeable section (typically 24 hours or less), h_{curb} is the height of the curb or the height available for surface flooding, r_c is the void ratio of the porous concrete, h_c is the thickness of the porous concrete, and r_s is the void ratio of the granular subbase. It should be clarified that this methodology assumes that the precipitation intensity is constant over time.

Eisenberg et al. (4) present a compilation of hydraulic and hydrologic design methods for permeable pavements. Among others, they present estimates of the Curve Number (CN) for the SCS loss method, runoff coefficients for the Rational Method, and the concept of routing in the granular base reservoir, but in generic terms, without specifying an implementation methodology.

The widely used SWMM software (9) includes, in its version 5.1, a module for modeling the so-called Low Impact Developments (LID). LIDs are represented by a combination of vertical layers whose properties are defined per unit area. This allows easy placement of LIDs with the same design but different area coverage within different sub-basins of a study area. During a simulation, SWMM performs a moisture balance that tracks how much water moves and is stored within each LID layer. The SWMM5-LID model has been successfully employed and calibrated in some permeable areas (10). However, this representation implies the inclusion of the LID within a larger SWMM project, which can be a limitation in preliminary analysis or hydrological pre-sizing tasks. Additionally, there are certain drainage system configurations that cannot be adequately represented by SWMM-LID (11).

Methodology

Water balance

In any hydrologic system, the application of the Reynolds transport theorem to the mass of water (as an extensive property) leads to Eq. (2), known as the hydrologic continuity equation (12):

$$\frac{dS}{dt} = I(t) - Q(t) \tag{2}$$

where S is the system storage (volume of stored water) (m³), I is the inflow rate (m³/s) and Q is the outflow rate (m³/s). Figure 3 (left) presents the visual relationship between these variables.

doi: 10.25100/iyc.v26i3.14049

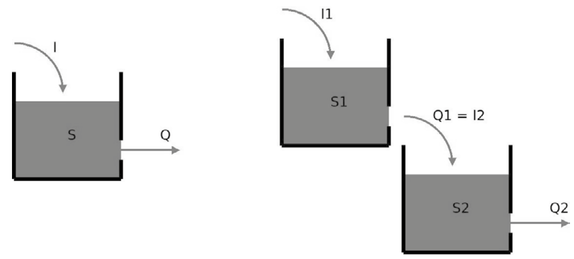


Figure 3. on the left: variables in the hydraulic continuity equation. On the right: a hydrological system formed by two parts (own preparation)

The Eq. (1) is an ordinary differential equation, which is usually solved numerically due to the discrete and/or empirical nature of the inputs and outputs. To do this, a initial condition must be set: the initial state of the system must be known, i.e., the storage S for t = 0, S(0).

When the hydrological system is composed (or conceptualized) by discrete parts interrelated, it is possible to propose a system of equations that describes the whole set, with as many equations and initial conditions as constituent parts. For example, take the system shown in Fig. 3 (right).

Taking into account that the output of part 1 is the input of part 2, it is possible to propose the following system of differential equations, whose solution describes the simultaneous variation of storage in both reservoirs:

$$\begin{aligned} \frac{dS_1}{dt} &= I_1(t) - Q_1(t) \\ \frac{dS_2}{dt} &= Q_1(t) - Q_2(t) \end{aligned} \tag{3}$$

To complete the definition of the problem, it is necessary to know the initial states S1(0) and S2(0). Likewise, as is usual in Hydrology, the volumes are expressed by surface area unit, that is, as depths (usually in mm) so that the flows are expressed as rates (usually in mm/h). Dividing both members of the previous expressions by the area gives:

$$\begin{aligned} \frac{dh_1}{dt} &= i_1(t) - q_1(t) \\ \frac{dh_2}{dt} &= q_1(t) - q_2(t) \end{aligned} \tag{4}$$

where h = S/A is the stored depth (mm), i = I/A is the intensity of precipitation (mm/h) and q = Q/A is the runoff per unit area (mm/h).

In any case, the quality of the solution obtained will depend on the adequate characterization of the incoming and outgoing flows in the system.

A Hortonian model for the porous concrete pavement

Considering the system indicated in Fig. 2 (left), it is possible to conceptualize the hydrological system under analysis as formed by the two upper layers: the porous concrete pavement 1 and the granular base 2. Under this assumption, the given system by the Eq. (4) is valid, taking into account that the incoming flow to layer 1 is the infiltration (fraction of precipitation that enters the porous concrete), the outgoing flow from layer 1 (and incoming to layer 2) is the percolation (disregarding

doi: 10.25100/iyc.v26i3.14049

evaporation), and the outgoing flow from layer 2 is the recharge:

$$\frac{dS_1}{dt} = F(t) - C(t)$$
$$\frac{dS_2}{dt} = C(t) - R(t) \tag{5}$$

As mentioned earlier, these equations can be converted into rates in mm/h by dividing them by the analysis area A. However, it is important to establish a relationship between the heights h and the porosities η of each layer, as some of the volume is occupied by the solid fraction. Therefore, the actual height of water in the porous medium can be determined by:

$$h = \frac{S}{\eta A} \tag{6}$$

Under these circumstances, the system described by Eq. (4) can be expressed as:

$$\frac{dh_1}{dt} = \frac{1}{\eta_1}[f(t) - c(t)]$$
$$\frac{dh_2}{dt} = \frac{1}{\eta_2}[c(t) - r(t)] \tag{7}$$

The previous equations must be complemented with expressions that characterize f(t), c(t), and r(t), with the initial conditions (usually $h_1(0) = h_2(0) = 0$ -empty state-) and, given that the storages of layers 1 and 2 are finite, the thicknesses H_1 and H_2 of those layers and their respective porosities η_1 and η_2. Specifically, it must be ensured for all time t in the solution, that:

$$h_1(t) \leq H_1 \cdot \eta_1$$
$$h_2(t) \leq H_2 \cdot \eta_2 \tag{8}$$

The function r(t) is potentially determined by the infiltration capacity of the subgrade soil. Various hydrological methods can be considered for its characterization. In real conditions, it may be limited by the percolation rate c(t): if this rate is lower than the potential recharge rate (or infiltration rate in the subgrade), then the actual recharge rate will be equal to the percolation rate. This implies that the porosity of the granular base is sufficiently large so that, on one hand, there is no significant redistribution of flow in that mantle, and on the other hand, the flow travel time in this granular base is small enough relative to the temporal integration step Δt to be used in the integration of the system given by Eq. (7).

If the Horton method (13) is used to characterize the infiltration capacity of the subgrade, then the function r(t) can be expressed as:

$$r(t) = \begin{cases} r_b + (r_0 - r_b)e^{(-kt)} & if\ h_2(t) > 0 \\ 0 & if\ h_2(t) = 0 \end{cases} \tag{9}$$

where r(t) is the potential infiltration rate in the subgrade soil (mm/h), r_b is the base infiltration rate in the subgrade soil (mm/h), r_0 is the initial infiltration rate in the subgrade soil (mm/h), and k is a shape factor of the Horton equation for the subgrade soil (h^{-1}).

In the case of the function c(t) (percolation from the porous concrete layer to the granular base), it is again possible to assume that the high porosity of this layer allows all the free water available in the porous concrete layer (from surface infiltration f(t)) to percolate freely, limited only by the availability of free space in the lower mantle, otherwise, it will be (simplified) limited by the hydraulic

doi: 10.25100/iyc.v26i3.14049

conductivity of the granular base. Expressed mathematically:

$$c(t) = \begin{cases} K_2 & if\ h_2(t) < H_2 \cdot \eta_2 \wedge f(t) > K_2 \\ f(t) & if\ h_2(t) < H_2 \cdot \eta_2 \wedge f(t) \leq K_2 \\ 0 & if h_2(t) = H_2 \cdot \eta_2 \end{cases} \tag{10}$$

where K_2 is the hydraulic conductivity of the granular base (mm/h) and H_2 is the height of the granular base (m).

The infiltration rate f(t) in the top layer of porous concrete can be expressed in general form (assuming the Horton equation is valid) as

$$f(t) = \begin{cases} f_p(t) = f_b + (f_0 - f_b)e^{(-kt)} & if\ h_1(t) < H_1 \cdot \eta_1 \wedge i(t) > f_p(t) \\ i(t) & if\ h_1(t) < H_1 \cdot \eta_1 \wedge i(t) \leq f_p(t) \\ 0 & if\ h_1(t) = H_1 \cdot \eta_1 \end{cases} \tag{11}$$

where $f_p(t)$ is the potential infiltration rate in porous concrete (mm/h), f_b is the base infiltration rate in porous concrete (mm/h), f_0 is the initial infiltration rate in porous concrete (mm/h), and k is the shape factor of the Horton equation for porous concrete (h^{-1}).

In the particular, but very common case, where the porosity of the porous concrete layer is high enough, the potential infiltration rate is independent of time and equal to a base infiltration rate f_b, which can be assumed to be equal to the permeability (saturated vertical hydraulic conductivity) of the medium. In this case, Eq. (11) can be simplified to:

$$f(t) = \begin{cases} K_1 & if\ h_1(t) < H_1 \cdot \eta_1 \wedge i(t) > K_1 \\ i(t) & if\ h_1(t) < H_1 \cdot \eta_1 \wedge i(t) \leq K_1 \\ 0 & if\ h_1(t) = H_1 \cdot \eta_1 \end{cases} \tag{12}$$

where K_1 is the hydraulic conductivity of porous concrete (mm/h).

If there is no experimental characterization of the permeability of the porous concrete to be used, it is possible to estimate it based on its porosity (14) through Eq. (13):

$$K = 18 \left[\frac{\eta_1^3}{(1-\eta_1)^2} \right] \tag{13}$$

where K is the permeability (cm/s) and η_1 is the porosity of the porous concrete (dimensionless).

Finally, if it happens that f(t) = 0 and i(t) > 0 (it rains when the saturation of the porous concrete layer is reached), the rate of surface runoff q(t) and the flow rate of surface runoff Q(t) will be given by:

$$\begin{gathered} q(t) = i(t) - f(t) \\ Q(t) = q(t) \cdot A \end{gathered} \tag{14}$$

The system given by Eq. (7) is usually solved numerically; the following expressions implement its solution through the Euler method:

doi: 10.25100/iyc.v26i3.14049

$$h_{1_{i+1}} = h_{1_i} + \frac{1}{\eta_1}[f_i - c_i]\Delta t$$
$$h_{2_{i+1}} = h_{2_i} + \frac{1}{\eta_2}[c_i - r_i]\Delta t \quad (15)$$

where $\Delta t = t_{i+1} - t_i$ is the calculation time interval.

Preliminary Sizing of the Granular Subbase

The thickness H_1 of the porous concrete pavement (Fig. 1) is generally defined by mechanical resistance considerations. The thickness H_2 of the granular subbase is determined by both mechanical and hydrological considerations. In general, it is preliminarily sized based on its hydrological functionality and then verified to ensure that this thickness meets structural requirements, with the greater of the two values being adopted.

In cases where all precipitation infiltrates and percolates into the granular subbase without horizontal flows, the thickness of this layer can be estimated in a simplified manner by assuming it must be able to temporarily store the entire infiltrated rainfall volume. This can be expressed as:

$$H_2 = \frac{P}{\eta_2} \quad (16)$$

where P is the rainfall (in mm) and η_2 is the porosity of the granular subbase (dimensionless). In this equation, it is assumed that the contribution of the subgrade through infiltration is negligible, which is appropriate if the rainfall P occurs over a brief period, meaning the intensity i is sufficiently high. However, for a given return period, the rainfall depth increases indefinitely with duration, as can be deduced from a standard intensity-duration-frequency (IDF) relationship (12):

$$i = \frac{aT^b}{(D+c)^d} \quad (17)$$

where i is the rainfall intensity (mm/h), T is the return period (years), D is the rainfall duration (minutes), and a, b, c, and d are the parameters of the IDF curve. The rainfall depth P is given by:

$$P(D) = \frac{aDT^b}{(D+c)^d} \quad (18)$$

As a result, it is not possible to determine in advance which duration will produce the highest excess depth P_e, considering the infiltration capacity of the subgrade. One way to solve this problem is to determine the duration D_m that produces the greatest accumulated excess depth P_e, which is the difference between the rainfall depth and the infiltrated amount. This situation is illustrated in Figure 4. It shows constant-intensity rainfall events of the same recurrence but varying durations, overlaid on the accumulated infiltration rate f(t). The shaded areas above this curve correspond to the accumulated excess depths P_e at the end of each rainfall event. While intensity i_1 is the highest (since it corresponds to the shortest duration), the excess depth P_{e1} may not represent the highest water accumulation in the granular subbase. At the other extreme, if the duration is long enough, as with D_5, the intensity i_5 may remain below the infiltration capacity of the subgrade, so no water would accumulate in the granular subbase.

doi: 10.25100/iyc.v26i3.14049

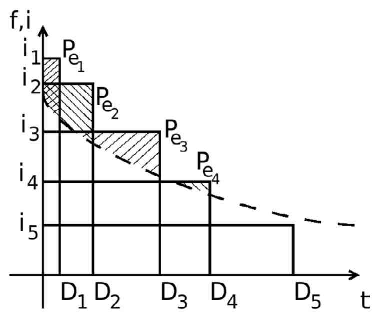


Figure 4. Rainfall events with the same recurrence, constant intensity, and varying durations, along with the potential infiltration rate. The shaded areas represent the accumulated excess depths (own elaboration)

Assuming the Horton infiltration model is valid, the infiltrated depth F(D) at the end of the rainfall event is given by:

$$F(D) = \frac{f_0 - f_b}{k}\left(1 - e^{-kD}\right) + f_b D \tag{19}$$

Therefore, if the rainfall intensity i(t) remains constant, the accumulated excess depth P_e is given by:

$$P_e(D) = \begin{cases} P(D) - F(D) & if\ P(D) > F(D) \\ 0 & if\ P(D) \leq F(D) \end{cases} \tag{20}$$

If the infiltration capacity of the porous concrete layer is lower than the rainfall intensity, then the value of P(D) in the above equation should be limited to that infiltration capacity.

The function given by the equation for Eq. (20) has a maximum value, which can be used in place of P in the equation (16) to estimate the maximum water height in the granular subbase. Figure 5 illustrates the conceptual model. For durations shorter than a characteristic duration D*, the accumulated rainfall exceeds the infiltrated amount, leading to water storage in the granular subbase. Dividing the accumulated excess depth P_e by the porosity η_2 gives the actual water height at the end of the rainfall event. For a duration D_m, this height reaches a maximum h_{2m}, which must be verified to ensure that it is less than or equal to the thickness H_2 of the layer.

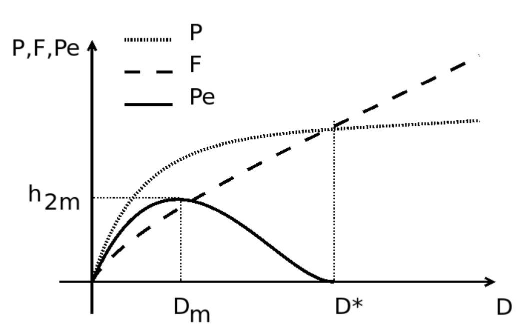


Figure 5. Conceptual model of the hydrological functioning of the granular subbase under constant-intensity rainfall events with the same recurrence (own elaboration)

doi: 10.25100/iyc.v26i3.14049

If a temporal distribution of rainfall P(t) is assumed (i.e. the rainfall is not constant over time), the conceptual model described can be applied by substituting P_e with:

$$P_e(D) = \begin{cases} \int_0^D \big(i(t) - f(t)\big)\, dt & if\ i(t) > f(t) \\ 0 & if\ i(t) \leq f(t) \end{cases} \qquad (21)$$

In practice, since the function i(t) is typically provided in discrete form as a hyetograph with a constant time step Δt, the integral in the above equation is solved numerically as:

$$\int_0^D \big(i(t) - f(t)\big)\, dt \approx \sum_{j=1}^{n} \big(i_j - f_{mj}\big)\, \Delta t \qquad (22)$$

where n is the number of time intervals of duration Δt in the hyetograph, and f_{mj} is the average infiltration rate during interval j.

Since the porosity η_2 is a scaling factor in the solution obtained, its proper characterization is essential. In the absence of experimental data, or for initial estimates, the following expression proposed by Wu and Yang (15) can be used to estimate it based on the average diameter d_m of the granular material:

$$\eta = 0.3 + 0.175 e^{-0.095\,(d_m - 1)} \qquad (23)$$

where d_m is the average diameter of the granular material (in mm). Likewise, if no experimental data are available, the hydraulic conductivity of the granular subbase can be related to the material diameter and porosity using the following equation (16):

$$K = 200 \cdot d_m^2 \left(\frac{\eta}{1-\eta}\right)^2 \qquad (24)$$

where K is the hydraulic conductivity of the granular subbase (in m/s) and d_m is the average diameter of the granular material (in mm).

In the case of permeable pavements with a constant-thickness granular subbase that is sloped (with a non-zero transverse gradient), the slope angle must be considered when calculating the storage capacity if the infiltration capacity of the subgrade is exceeded (5). This situation is unfavorable because the water level in the granular subbase will reach the maximum height H_2 more quickly than in a horizontal configuration (Fig. 6).

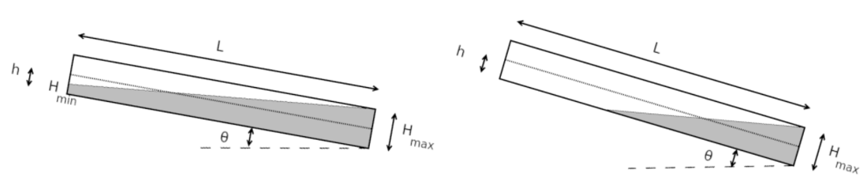


Figure 6. Effect of slope on the storage capacity of the granular subbase. Left: low slope; right: high slope (own elaboration)

In such cases, the porous area A should be explicitly considered to estimate the maximum water level in the granular subbase. For rectangular areas, this can be replaced by the length L of the inclined plane (Fig. 6). Assuming that the required depth h for the horizontal situation has already been corrected for the layer's porosity, the maximum water depth H_{max} (also corrected for porosity) is given by:

$$H_{max} = \begin{cases} h + \frac{L \cdot tan\theta}{2} & if h \geq \frac{L \cdot tan\theta}{2} \\ \sqrt{2Lh \cdot tan\theta} & if h < \frac{L \cdot tan\theta}{2} \end{cases} \qquad (25)$$

doi: 10.25100/iyc.v26i3.14049

where H_{max} is the maximum water height in the inclined layer (in meters), h is the equivalent water depth in the horizontal layer (in meters), and tan θ is the surface slope (dimensionless).

The first equation corresponds to the "low slope" situation (Fig. 6, left), while the second equation applies to the "high slope" situation (Fig. 6, right). These equations allow for a simplified consideration, based on geometric assumptions, of the pavement's slope when preliminarily sizing the thickness of the granular subbase.

Although this conceptual model does not predict the time-dependent variation of the water level in the granular subbase, it does establish the hydrologically required thickness of the layer. It can be used to define this dimension for further detailed analysis based on the water balance model described earlier.

Results and discussion

Example Application

The infrastructure management of a shopping center chain has decided to pave the parking areas at its branch in Río Cuarto (Córdoba province) using porous concrete pavement. Due to the characteristics of the natural soil, its infiltration capacity can be utilized, and thus a non-drained pavement design is adopted (Fig. 2, left). The parking area (11,900 m²) will be hydrologically isolated from its surroundings using perimeter channels (Fig. 7), so the only water input will be from precipitation. The paved surface will have an average surface slope of 1%. The parking design will also include green areas (550 m²) and, along the interior ditches, sections of traditional concrete pavement (240 m²). The maximum runoff length on the porous pavement perpendicular to the traditional concrete ditches is 28 meters. The entire system will drain into a detention pond, which also receives stormwater runoff from the main building through underground pipes.

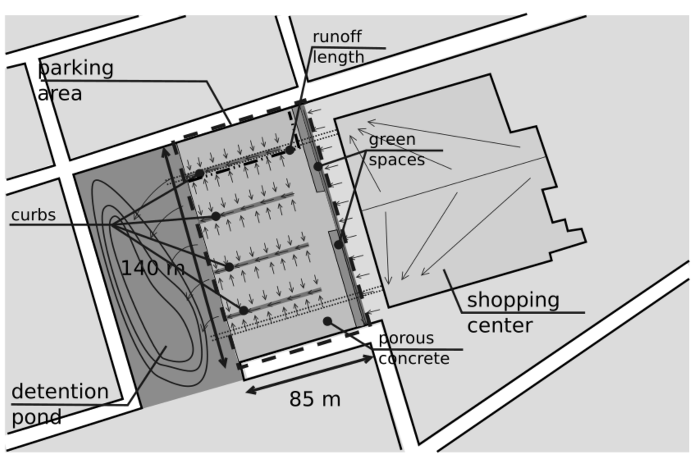


Figure 7. Shopping center and parking area (own elaboration)

For structural-mechanical reasons, the porous concrete layer will have a thickness of 15 cm, while the granular subbase must be at least 35 cm thick. The average diameters of the granular material for these layers are 15 mm and 30 mm, respectively. Based on laboratory tests, the porosity of the porous concrete to be manufactured is η_1 = 27%. The local soil (a sandy silt) was subjected to

doi: 10.25100/iyc.v26i3.14049

infiltration tests, determining the parameters for the Horton model: f_0 = 60 mm/h, f_b = 20 mm/h, k = 4 h^{-1}. A design return period of T = 25 years is assumed. The task is to preliminarily size the granular subbase and simulate the hydrological performance of the permeable pavement.

Data

Precipitation. According to Farías and Olmos (17), the intensity-duration-frequency relationship for the city of Río Cuarto is given by a standard expression (Eq. 17) of the form:

$$i = \frac{1840.57T^{0.21}}{(D+23)^{0.92}} \tag{26}$$

Porosity. In the absence of experimental data, the porosity η_2 of the granular subbase is estimated based on its granulometry using Eq. (23), resulting in η_2 = 0.311. The porosity η_1 of the porous concrete layer is defined as η_1 = 0.27.

Hydraulic Conductivity. In the absence of experimental data, the hydraulic conductivity k_1 of the porous concrete layer is estimated based on its previously determined porosity using Eq. (13), resulting in k_1 = 0.66 cm/s. The hydraulic conductivity k_2 of the granular subbase is estimated based on its previously determined porosity and granulometry using Eq. (24), resulting in k_2 = 3.67 cm/s.

Concentration Time. To determine the critical rainfall duration that maximizes surface runoff, the concentration time of the surface basin (constituted by the parking area) is estimated. For this, the Federal Aviation Agency equation (Eq. 27) is used (13):

$$t_c = 22.73(1.1 - C)L^{0.5}S^{-0.33} \tag{27}$$

where t_c is the concentration time (in minutes), C is the Rational Method runoff coefficient (dimensionless), L is the surface flow length (in kilometers), and S is the surface slope (in m/km).

For a surface flow length of 113 m (Fig. 8), a slope of 10 m/km (1%), and assuming a preliminary estimate of C = 0.033, an initial value of t_c = 3.81 min is calculated, and t_c = 5 min is assumed.

Design Hyetograph. To simulate the hydrological performance of the permeable pavement, a design hyetograph is created for a duration equal to the previously determined concentration time, using the Alternating Block Method (Eq. 26) for the same return period (25 years). With a time interval Δt = 1 min and placing the peak in the second quintile, the hyetograph in Fig. 8 is obtained.

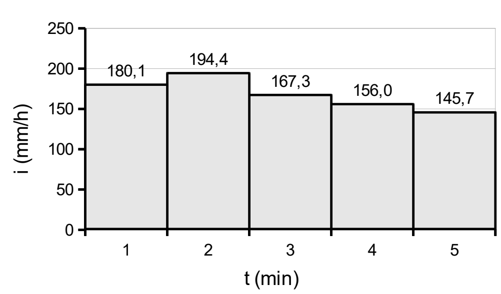


Figure 8. Design hyetograph (own elaboration)

Preliminary Sizing of the Granular Subbase

To preliminarily size the granular subbase, the methodology described is applied for durations D between 10 and 100 minutes. Table 1 summarizes the calculation procedure and the results for the initial time steps. In this table, column [2] is determined using Eq. (26); column [3] is obtained by

doi: 10.25100/iyc.v26i3.14049

multiplying column [1] by column [2] (Eq. 18); column [4] is determined using Eq. (19); column [5] is the difference between columns [3] and [4] (Eq. 20); and column [6] is obtained by dividing column [5] by η_2 (Eq. 16). As shown, the required thickness H_2 reaches its maximum value of 103.7 mm for a duration of D = 60 min. These results are plotted in Fig. 9.

Table 1. Pre-sizing of granular subbase

D (min)	**i (mm/h)**	**P (mm)**	**F (mm)**	**Pe (mm)**	**H_2 (mm)**
[1]	[2]	[3]	[4]	[5]	[6]
10	145.04	24.17	8.2	15.97	51.3
20	113.69	37.9	14.03	23.87	76.7
30	93.80	46.9	18.65	28.25	90.8
40	80.01	53.34	22.64	30.70	98.7
50	69.87	58.22	26.31	31.91	102.6
60	**62.08**	**62.08**	**29.82**	**32.27**	**103.7**
70	55.91	65.23	33.24	31.99	102.8
80	50.90	67.87	36.62	31.25	100.4
90	46.74	70.11	39.98	30.13	96.9
100	43.23	72.05	43.32	28.73	92.4

As the permeable pavement is sloped with tan θ = 0.01 (1%), it is necessary to correct the maximum value obtained earlier, according to Eq. (25). For a runoff length L = 28 m, the critical value L·tan θ/2 = 0.140 m is greater than h_{2m}, so the system is in a "high slope" condition. Consequently, the correction provided by the second equation in (Eq. 25) is valid, and the hydrologically required thickness of the granular subbase is calculated as H_2 = 24.1 cm. Since this thickness is less than that required for structural-mechanical considerations, the final thickness of the granular subbase will be H_2 = 35 cm.

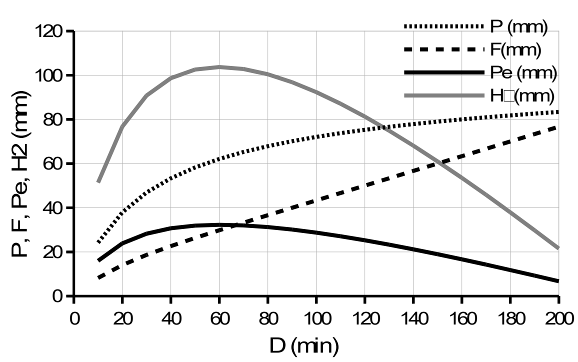


Figure 9. Preliminary sizing of the granular subbase (own elaboration)

For comparison purposes, the simplified methodology proposed by Rodden et al. (2011) was applied, considering the following parameters: E = f_b = 20 mm/h, t_d = 15 h, h_{curb} = 12 cm, r_c = 0.11, h_c= 15 cm, r_s = 0.45. The application of Eq. (1) yields a result of h_s=H_2=362 mm. However, it should be noted that the choice of detention time t_d is arbitrary and introduces additional uncertainty to the procedure.

doi: 10.25100/iyc.v26i3.14049

Simulation of the Hydrological Performance of the Permeable Pavement

To simulate the hydrological performance of the permeable pavement, the previously described methodology is applied. Given the estimated hydraulic conductivities K and the respective thicknesses H of the porous concrete layer and the granular subbase, the flow travel times within these layers can be estimated (as the ratio H/K) to be 22.6 seconds and 9.5 seconds, respectively. Therefore, a time interval $\Delta t = 1$ min is adopted, ensuring the validity of the assumption. Table 2 summarizes the calculations for the first few time intervals.

Table 2. Simulation of the hydrological performance of the permeable pavement

t (min)	t (h)	i (mm/h)	h_1 (mm)	h_2 (mm)	f_i (mm/h)	c_i (mm/h)	rp (mm/h)	r_i (mm/h)
[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]
0	0.00000	180.1	0	0	180.1	180.1	60.00	0.00
1	0.01667	194.4	0	9.6	194.4	194.4	57.42	57.42
2	0.03333	167.3	0	17.0	167.3	167.3	55.01	55.01
3	0.05000	156.0	0	23.0	156.0	156.0	52.75	52.75
4	0.06667	145.7	0	28.5	145.7	145.7	50.64	50.64
5	0.08333	0.0	0	33.6	0.0	0.0	48.66	48.66
6	0.10000	0.0	0	31.0	0.0	0.0	46.81	46.81
7	0.11667	0.0	0	28.5	0.0	0.0	45.08	45.08
8	0.13333	0.0	0	26.1	0.0	0.0	43.47	43.47
9	0.15000	0.0	0	23.8	0.0	0.0	41.95	41.95
10	0.16667	0.0	0	21.5	0.0	0.0	40.54	40.54

It should be noted that for the calculation of the unknown values h_1 and h_2 (for $t \geq 1$ min) in Eq. (15), the values on the right-hand side (those with subscript i) correspond to the row above in Table 2.

As can be observed, water does not accumulate in the porous concrete layer at any time ($h_1 = 0$ for all t), and the maximum water height accumulated in the granular subbase ($h_2 = 33.6$ mm at t = 5 min) is well below the thickness $H_2 = 350$ mm of that layer. Therefore, the assumptions regarding the calculation of f and c (columns [6] and [7], respectively) are valid, and no surface runoff is generated on the permeable pavement.

In Fig. 10, the results are presented: on the left, the variation in the water height within the granular subbase; on the right, the rainfall intensity (rainfall) and recharge rate (infiltration into the granular subbase).

It is important to note that the simplified model applied assumes that the layers are horizontal. However, by applying the geometric correction provided by Eq. (25) (and considering the previously discussed aspects in the preliminary sizing of the granular subbase), the maximum accumulated water height in the granular subbase increases to $\mathbf{H_{max} = 13.7\,cm}$, which is still below the thickness $\mathbf{H_2 = 35\,cm}$ of the layer.

doi: 10.25100/iyc.v26i3.14049

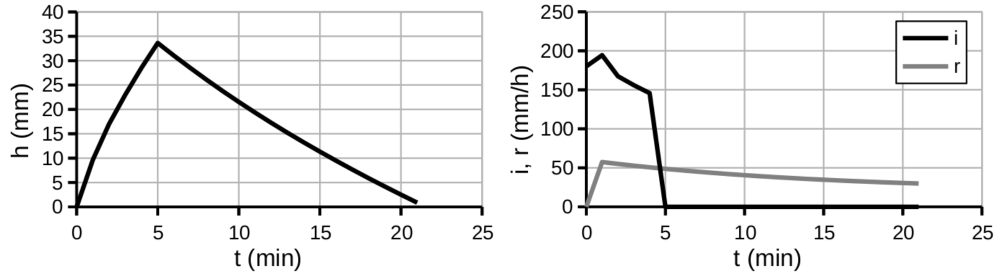


Figure 10. Simulation results of the hydrological performance of the permeable pavement: variation in the water height in the granular subbase (left); rainfall intensity and recharge rate (right) (own elaboration)

The simulation extends up to t = 21 min since, after that time, all the stored water in the granular subbase infiltrates into the subgrade (h_2 = 0), and thus, the event concludes.

Although the standard practice in hydrological design aims to maximize the surface runoff by assuming a storm duration equal to the concentration time (here t = 5 min), the previous procedure can be repeated for longer storms to verify the hydrological performance of the permeable pavement under other scenarios.

Conclusions

This work has developed and exemplified a simplified methodology (based on water balance concepts) to quickly analyze the hydrological performance of porous concrete pavements. The infiltration capacity (and, consequently, the generation of surface runoff) of these pavements does not depend solely on the properties of the porous concrete top layer but also on the corresponding granular subbase and the natural soil subgrade. Therefore, these components must be analyzed together.

The example developed through the simplified procedures described in the previous sections had two objectives: to provide a numerical example of the application of these methods to a typical urban hydrological design case and to highlight the significant hydrological advantages of using these sustainable urban drainage systems.

The results obtained from the described method, due to its important simplifications, may deviate from the actual behavior of the analyzed system. However, it provides an adequate preliminary hydrological sizing of the system, which can serve as a starting point for applying more rigorous methodologies. Nonetheless, when selecting the method in the context of engineering applications, it is essential to weigh other sources of uncertainty, particularly those related to the physical characterization of existing or available materials, as well as the hydrological data sources consulted.

The proposed methodology explicitly develops the necessary formulations for implementing methods generally described in the literature. The proposed methodology offers several advantages over previous calculation procedures: regarding the preliminary sizing of the granular subbase, it explicitly considers the design duration, unlike the method proposed by Rodden et al. (7), where the maximum detention time or a precipitated volume must be arbitrarily established. In terms of hydrological performance (Eq. 7), the proposed methodology allows for explicitly visualizing the evolution of the water level within the pavement. Among the previously described procedures, the only equivalent is the SWMM5-LID model (9). However, applying it involves integrating the porous pavement into a more complex computational model, which may be excessive for preliminary analysis.

The proposed methodology is considered useful for hydrological design tasks within the paradigm of Sustainable Urban Drainage Systems (SUDS) and for undergraduate and graduate education in urban drainage.

doi: 10.25100/iyc.v26i3.14049

CRediT authorship contribution statement

Juan F. Weber: Conceptualización – Ideas, Curación de datos, Análisis formal, Adquisición de financiación, Investigación, Metodología, Administración de proyectos, Recursos, Software, Supervisión, Validación, Visualización – Preparación, Redacción – borrador original – Preparación Escritura – revisión y edición – Preparación.

Conflict of interest

The authors no declare.

Ethical implications

The authors do not have any type of ethical involvement that should be declared in the writing and publication of this article.

Financing

No, the author declare that they did not receive resources for the writing or publication of this article.

References

1. Chandrappa, A, Biligiri, K. Pervious concrete as a sustainable pavement material–Research findings and future prospects: A state-of-the-art review. Construction and building materials. 2016. 111:262-274.
2. Sonebi M, Bassuoni M, Yahia A. Pervious concrete: mix design, properties and applications. RILEM Technical Letters. 2016; 1:109-115.
3. Ferguson B. Porous pavements. Boca Raton, FL: Taylor & Francis; 2005.
4. Eisenberg B, Lindow K, Smith, D. Permeable pavements. Reston, VA: American Society of Civil Engineers; 2015.
5. Tennis PD, Leming ML, Akers, DJ. Pervious concrete pavements (No. PCA Serial No. 2828). Skokie, IL: Portland Cement Association; 2004.
6. Wanielista M, Chopra M, Spence J, Ballock C. Hydraulic performance assessment of pervious concrete pavements for stormwater management credit. Orlando, FL.: Storm Water Management Academy, University of Central Florida; 2007.
7. Rodden, R, Voigt, G, Smith, T. Structural and hydrological design of sustainable pervious concrete pavements. 2011 Congress et Exhibition de l'Association des Transports du Canada. Les Succes en Transports: Une Tremplin vers l'Avenir Transportation Association of Canada (TAC); 2011.
8. American Concrete Pavement Association. PerviousPave: Background, Purpose, Assumptions and Equations. American Concrete Pavement Association; 2013.
9. Rossman, LA. Storm Water Management Model User's Manual, Version 5.1. Cincinnati, Ohio, USA: US EPA National Risk Management Research Laboratory; 2015. Report No.: EPA-600/R-14/413b.
10. Hohaia, N, Fassman, E, Hunt, WF, Collins, KA. Hydraulic and hydrologic modelling of permeable pavement. World Environmental and Water Resources Congress 2011: Bearing Knowledge for Sustainability; 2011. p. 587-597.

doi: 10.25100/iyc.v26i3.14049

11. Mogenfelt, P. Modeling LID-units in SWMM. Master of Science Thesis No. TVVR 17/5022. Division of Water Resources Engineering, Department of Building and Environmental Technology, Lund University; 2017. Disponible en: http://lup.lub.lu.se/student-papers/record/8928265

12. Chow VT, Maidment DR, Mays, LW Hidrología Aplicada. Santa Fe de Bogotá, Colombia: McGraw-Hill; 1994.

13. Tucci CEM. Hidrologia: Ciência e Aplicação, 3ª Ed. Porto Alegre, Brasil: Editora da Universidade. UFRGS/ABRH; 2004.

14. Montes F, Haselbach L. Measuring Hydraulic Conductivity in Pervious Concrete. Environmental Engineering Science. 2006; 23(6):960–969.

15. Wu W, Wang SSY. Formulas for Sediment Porosity and Settling Velocity. Journal of Hydraulic Engineering. 2006; 132(8): 858–862. https://doi.org/10.1061/(ASCE)0733-9429(2006)132:8(85

doi: 10.25100/iyc.v26i3.14049