Characterization of the Hydraulic Behavior of Porous Pavements

William D. Martin III[1], Nigel B. Kaye[2]

AUTHORS: [1]Lecturer, General Engineering Department, Clemson University, 104 Holtzendorff Hall, Clemson, SC 29634, USA. [2]Associate Professor, Glenn Department of Civil Engineering, Clemson University, 114 Lowry Hall, Clemson, SC 29634, USA.

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ABSTRACT. We present two models for the characterization of the hydraulic behavior of porous pavements. The first model is based on the widely used curve number parameterization for relating rainfall depth to runoff depth. For undrained pavements the pavement's effective curve number (ECN) is shown to be a function of the pavement storage capacity and infiltration capacity, and the local rainfall IDF curve and SCS rainfall type. For underdrained pavements the ECN is independent of the local rainfall IDF curve, though is dependent on the type and size of underdrain used. The ECN can be used in preliminary design calculations for estimating the reduction in runoff that results from using a porous as opposed to impermeable pavement. While the ECN provides a familiar, simple to use single number to characterize porous pavement performance, the actual behavior of porous pavements does not match the curve number behavior for undrained pavements, particularly for rainfall depths close to the pavement storage capacity. Improved characterization for these undrained pavements is achieved by using a broken-line model that characterizes the pavement in terms of an initial abstraction and a linear relationship between rainfall depth and runoff depth for rainfall depths greater than the initial abstraction. For this model, the initial abstraction and line slope are independent of the local IDF curve and, therefore, universal characterization curves can be calculated that are applicable for a given SCS rainfall distribution. Examples of the use of both characterization models will be presented.

INTRODUCTION

Porous pavements provide both stormwater quality and quantity benefits when used in new or existing developments. While a number of case studies have reported these benefits (Dietz 2007), none provide a model that can predict the runoff response for a pavement system.

This lack of predictive model also extends into design. One common design method is to design the effective storage volume of the pavement system to hold a certain design storm and then check the drawdown time, the time for the pavement system's storage to empty after the storm, to ensure it is acceptable (Tennis et al. 2004). While this is a very basic and easy to understand design process, it does not provide any understanding of the hydrologic behavior of the pavement system for storms larger than the design storm. Furthermore, if the drawdown time is unacceptable and an underdrain is installed to provide adequate drainage, the entire hydrologic behavior of the pavement system will change.

It is critical to stormwater designers, managers, and regulators to be able to accurately predict the runoff behavior of a porous pavement system before installation. Without this knowledge, the stormwater quantity benefits of the system will likely go underutilized and discourage the use of porous pavements on a broad scale. By developing a model that characterizes the hydraulic behavior of porous pavements, it ensures that users will have a better understanding of how the pavement will integrate with the overall stormwater system and increase a pavement's positive impact.

RELATED WORK

A number of researchers have focused on using a model analogous to the runoff curve number (RCN) model to provide a simple model of a porous pavement system's behavior. However, because a porous pavement has a marked difference in behavior depending on if it has an underdrain and because an undrained pavement behaves more as a retention pond than a typical subbasin, difficulties arise in trying to fit that model to porous pavement behavior. Leming et al. (2007) numerically calculated a RCN for an individual design event by routing a design storm through the pavement system utilizing stage-storage-discharge equations but this produces multiple RCNs for a single pavement based on the storm depth. Bean et al. (2007) used rainfall-runoff and storage data collected over a period of one to two years to find an equivalent curve number for a pavement system installation. This is in line with the how the Soil Conservation Service (SCS) RCN method was originally developed (Hawkins et al. 2009), however, this approach is difficult to implement for use in design as changing locations or altering the dimensions of the pavement system changes the curve number.

Schwartz (2010) proposed a method to calculate an effective curve number (ECN) that was not limited to a certain rainfall event depth. Schwartz models a number of single storm rainfall-runoff pairs over a range of rainfall depths and fits one ECN value to it. This ECN model was proposed for both undrained and drained porous pavement systems, neglecting the differences in the hydrologic behavior between the two. Martin and Kaye (submitted, 2014a; b) broke these cases apart and looked at the undrained and underdrained cases separately and developed figures that allow the look up of ECN values directly from pavement properties. These models provide a simple process for designers and regulators to effectively size and design porous pavement systems.

MODEL

ECN

The ECN models for both undrained and underdrained pavements use the RCN equations

$$S = \frac{1,000}{CN} - 10 \qquad (1)$$

$$Q_{CN}\left(P\right) = \frac{\left(P - I_a\right)^2}{\left(P - I_a + S\right)} \qquad (2)$$

with the standard Ia=0.2S assumption to calculate the ECN value for a pavement. The model used to calculate the rainfall-runoff data which the ECN is fit to is more complex than the standard user is most likely comfortable with, therefore Martin and Kaye (submitted, 2014a) characterized the results from a range of porous pavements and created figures based on two pavement parameters, the storage capacity and the 24-hour infiltration depth. The storage capacity is defined as

$$\text{Storage Capacity} = \Phi_P H_P + \Phi_S H_S \qquad (3)$$

which is the effective depth of water that can be held in the pavement system. The 24-hour infiltration depth is

$$\text{24-hour Infiltration Depth} = f_{soil} \Phi_S 24 \qquad (4)$$

which is the depth of water able to be infiltrated by the soil over one day (24 hours).

Undrained Pavements

Because the undrained pavement's theoretical hydrologic behavior is not well suited for the ECN model, as described above, the ECN values are not only dependent on the two pavement parameters, but also on the rainfall data used to produce them, namely the storm type and normal precipitation range. This precludes the production of a single design figure applicable anywhere, so a location specific figure must be created. Figure 1 is an example of ECN design figure for Columbia, SC created using an online tool created by the authors (http://people.clemson.edu/~nbkaye/ecn.html).

The contours in Figure 1 give the ECN values as a function of the storage capacity and 24-hour infiltration depth. Also shown are lines of constant drawdown time which are defined by

$$\begin{aligned} t_{drawdown} &= \frac{\Phi_P H_P + \Phi_S H_S}{24 f_{soil} \Phi_S} \\ &= \frac{\text{Storage Capacity}}{\text{24-hour Infiltration Depth}} \end{aligned} \qquad (5)$$

Underdrained Pavements

For underdrained pavements creating design figures comes with a different set of problems. Because an underdrained pavement's hydrology better matches that of the ECN model, there is not a need for location specific figures. However, because of the presence of an underdrain, there are more pavement parameters (drain size and type, drain height, and drainage area) which cannot be incorporated into one graph, therefore requiring multiple ECN figures.

To summarize these three new parameters, a set of drawings has to be created for each drain type (size and geometry). The set is made up of individual figures representing different drainage areas (area drained by a single underdrain). The height of the underdrain can be incorporated by interpolating between the figures (where the drain invert is at the bottom of the storage layer) and

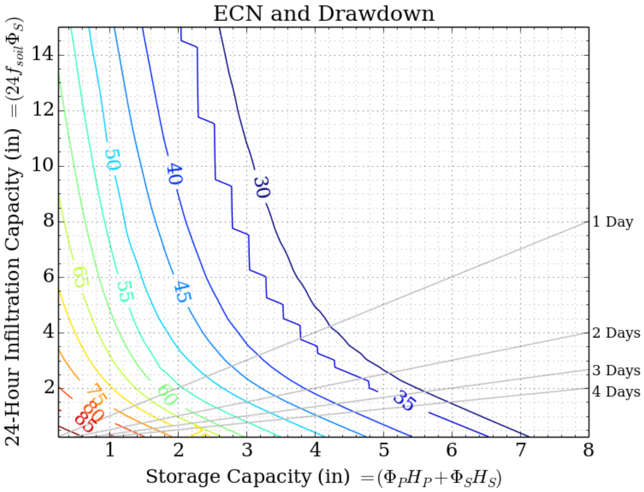


Figure 1: Undrained pavement ECN figure for Columbia, SC.

the undrained ECN figure for that location. Because the changes in ECN and drawdown are approximately linear with invert elevation (in terms of effective storage), they can easily be estimated. The ECN for an underdrain at any given height, *h*, is approximated by

$$ECN_h = ECN_D + \left(\frac{ECN_{UD} - ECN_D}{\eta_H} \right) \eta_h \qquad (6)$$

Where η_H is the total effective storage of the pavement system, η_h is the effective storage under the drain invert. *ECN* is the effective curve number with the sub-scripts representing the underdrained case with the invert on the soil, *D*, undrained case, *UD*, and underdrained at the effective height η_h, *h*.

The drawdown time has similar behavior, but to prevent the need for the creation of contour plots for all the different drains and drainage areas it was approximated by a simplified linear model

$$\begin{aligned} & Drawdown_h \\ & = t_{drained} + t_{undrained} = \left(1 - \frac{\eta_h}{\eta_H}\right) + \frac{\eta_h}{24 f_{soil} \Phi_S} \qquad (7) \\ & = 1 + \left(\frac{Drawdown_{UD} - 1}{\eta_H} \right) \eta_h \end{aligned}$$

where $t_{drained}$ is the time for the water level to drain to the underdrain invert and $t_{undrained}$ is the remaining time for the pavement storage to empty. The $Drawdown_{UD}$ is the drawdown time for the undrained pavement which can be calculated using equation (5).

Broken-Line Model for Undrained Pavement

To address the location specific restrictions and inherent error in the ECN model for undrained pavements discussed previously, the broken-line model was developed to actually match the theoretical fill and spill behavior of undrained porous pavement systems.

The basic concept of the model is that no runoff, *R*, occurs until some initial abstraction, *Ia*, is reached (synonomus to that of the RCN method but actually calculated) and then almost all additional rainfall, *P*, becomes runoff except what little is infiltrated which is represented by the slope, *m*, of the second line yielding the model

$$R = \begin{cases} 0 & P \le I_a \\ m \times (P - I_a) & P > I_a \end{cases} \qquad (8)$$

To calculate the slope and initial abstraction for a paired data set of total rainfall and runoff, a line is fitted to the data pairs for which the runoff is non-zero, that is, through the data points with total rainfall greater than the initial abstraction.

$$R = C_1 \times P + C_2 \qquad (9)$$

The slope and initial abstraction can then be calculated from the coefficients in equation (9) to give

$$m = C_1 \qquad (10)$$

and

$$I_a = -C_2 / C_1 \qquad (11)$$

The initial abstraction and slope can be presented for a range of pavements and infiltration capacities using the same storage capacity and 24-hour infiltration depth parameters used for the ECN presentation.

RESULTS

The ECN figures from Martin and Kaye (2014a; 2014b) allow for the direct lookup of any pavement's ECN value regardless of soil, aggregate, or pavement properties, as well as presence and location of underdrains. In addition to this, they can be used to preliminarily size or design a porous pavement installation.

For an undrained pavement this is very simple. If the soil infiltration capacity, aggregate porosity, and target ECN (such as the predevelopment RCN) are known, all a user must do is follow the 24-hour infiltration capacity across the chart until it intersects the target ECN, and then read the storage capacity from the x-axis. For example, if the soil infiltration capacity was 0.26 in/hr, the aggregate porosity was 40%, and the target ECN was 65, the 24-hour infiltration depth can be calculated using equation (4) to be 2.4 in/day. This infiltration depth intersects the 65 contour line at a storage depth of 1.2 inches which is the required depth of effective storage. From equation (5), the drawdown for this pavement is calculated to be 0.5 days.

For underdrained pavements the process is more complicated, but a similar process can be utilized to determine the elevation and spacing of underdrains. Using this method, a porous pavement system can be designed to have an acceptable drawdown time while minimizing the ECN to get the most hydrologic benefits from the system.

Similarly to the undrained ECN calculation, the design ECN needs to be established, and the soil infiltration capacity for the site must be known. Because this method only adjusts the elevation and spacing of the underdrains to achieve the design ECN, the pavement system dimensions (pavement thickness, subbase thickness, and aggregate porosities) must be designed based on either structural or general hydrologic guidelines. Additionally the choice of what drain type to use can be made at the onset of design because the spacing of the drains will account for the difference in drain capacities.

With these two inputs (design values and pavement system design), the location and spacing of the underdrain can be determined as follows:

1. *(1) Undrained drawdown time* – The undrained pavement system's drawdown time, in days, can be calculated using the pavement dimensions, using equation (5). If the drawdown time is acceptable, no underdrain is needed and the pavement can be designed as described above.
2. *(2) Underdrain height* – If the drawdown time for the undrained pavement system is unacceptable, the drawdown time as a function of drain height can be calculated using equation (7), and the maximum drain height can be found based on the drawdown requirements. Additionally, it is necessary to check that the drain is located fully within the subbase for construction purposes, that is H_s - $H_d > D_d$.
3. *(3) Fully underdrained ECN* – Using the ECN for the undrained pavement system (Figure 1), the design ECN, and the drain height, the fully underdrained ECN, ECN_D, can be calculated from equation (6).
4. *(4) Drainage area (underdrain spacing)* – Then, using the set of charts for the underdrain size and type to be used (Martin III and Kaye submitted), the drainage area required to match the ECN_D value can be found. This drainage area can be used to calculate the number of underdrains for a given pavement area.

Take for example a 12,000 m^2 pavement system that has 15.2 cm (6.0 in) of surface pavement with 20% porosity and 23.2 cm (9.1 in) of aggregate subbase with 30% porosity located on a soil with an infiltration rate of 0.25 cm/hr (0.10 in/hr). The pre-development curve number, which is also taken to be the design ECN, is 78, the maximum allowable drawdown is three days, and 10.4 cm diameter perforated underdrains will be used.

The storage capacity for the system is 10 cm, from equation (3), and the 24-hour infiltration depth is 1.8 cm, from equation (4). The drawdown time for the undrained system is 5.6 days, from equation (5), which means an underdrain is necessary. The drain height is then determined using equation (7)

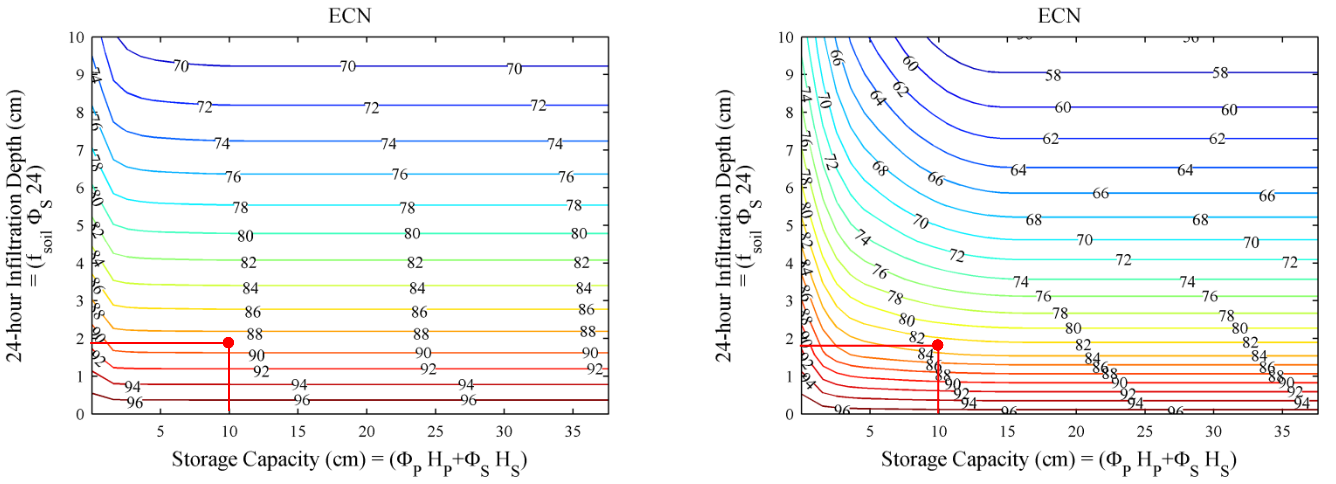
$$\eta_h = \left(3\text{ days}-1\right)\left(\frac{10\text{ cm}}{5.6\text{ days}-1}\right) = 2.2 \tag{12}$$

Since the effective height of the drain is 2.2 cm, the actual height in the 30% porosity aggregate would be 7.3 cm (= 2.2 cm/0.3). The crown of the 10.4 cm underdrain would therefore be located 17.7 cm above the soil which places the underdrain completely in the 23.2 cm deep aggregate subbase so no adjustments need to be made.

The ECN is then found for the completely drained case using equation (6). This equation requires the ECN for the undrained case which is found on Figure 1 to be 48 (using proper conversions).

$$ECN_D = \frac{\left(78-48\times\left({}^{2.2\text{ cm}}\!/_{10\text{ cm}}\right)\right)}{\left(1-\left({}^{2.2\text{ cm}}\!/_{10\text{ cm}}\right)\right)} = 86.5 \tag{13}$$

The number of pipes needed to achieve the design ECN can be calculated from Figure 2. Using the effective storage depth and 24-hour infiltration depth, the ECN can be read from subfigures (a), drainage area of 1000 m^2, and (b), drainage area of 5000 m^2, (89 and 83 respectively for this example). By interpolating between the two curve numbers and areas, the ECN_D value of 86.5 is achieved with a pavement area per drain of 2700 m^2. For the 12,000 m^2 pavement, this means that 4.4, 10.2 cm perforated drains are required. Because this design is not



(a) (b)

Figure 2: ECN figures for type II storm and a 10.2 cm (4 in) perforated underdrain with drainage area of (a) 1000 m^2 and (b) 5000 m^2 (Martin III and Kaye submitted).

based on the capacity of the drains, but rather on the volume of the discharge, by rounding down to using only four drains a slightly better ECN will be achieved. Therefore if four drains, placed with an invert elevation of 7.3 cm above the soil, were used the final ECN would be 77.6 and the drawdown time would still be acceptable.

DISCUSSION

Both of the models demonstrated have their strengths and weaknesses. For undrained pavements the broken-line model matches the theoretical behavior and predicts runoff totals more accurately than the ECN model does, and has the benefit of not being location dependent. However, since the ECN model is based on a very common and familiar runoff model it provides a simple preliminary design method to roughly size an undrained porous pavement's storage capacity based on a target RCN.

For underdrained pavements, the ECN method provides a good model of actual runoff behavior and a method to calculate the location and spacing of the underdrains such that the hydrologic benefit of the pavement is maximized.

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