Effective Curve Number and Hydrologic Design of Pervious Concrete Storm-Water Systems

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Abstract: The effective use of pervious concrete in environmental site design requires consistent design procedures integrating the structural and material properties of the pervious concrete pavement with hydrologic performance of the pervious concrete system. Design procedures to size pervious concrete storm-water systems are presented based on criteria for freeze-thaw protection and drawdown reliability. Hydrologic performance criteria are quantified by an effective curve number, estimated from simulated routing of design storm hydrographs using standard storm-water computations. Combining *operational* design criteria with the evaluation of hydrologic *performance* criteria, as an effective curve number, integrates pervious concrete systems with traditional storm-water management practice and emerging standards for environmental site design.

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Introduction

Profound hydrologic changes accompany urban land transformations, motivating the continuing development of environmentally sensitive approaches for on-site storm-water management. Sustainable approaches to storm-water management and design are actively evolving to manage the hydrologic response of the developed landscape through integrated site design embodying distributed systems of best management practices (BMP). Storm-water management to maintain hydrologic services spans low impact development hydrology (Davis 2005; Dietz 2007; Rushton 2001), water sensitive urban design (Walsh 2004), sustainable urban drainage systems (Charlesworth et al. 2003), and integrated site design (Berke et al. 2003; Pitt and Clark 2008; van Roon 2007; Walsh 2004; Walsh et al. 2005). In the state of Maryland, new storm-water criteria define environmental site design (ESD) as postdevelopment conditions that mimic the hydrologic response of woods in good condition to the maximum extent practicable [Maryland Department of the Environment (MDE) 2008].

ESD encourages the coordination of site planning, design, staging, and construction, to integrate the hydrologic performance of every element of the developed landscape. ESD represents another step in the evolution of storm-water management, from individual BMP-based criteria, to the design of sustainable landscapes that manage the full rainfall spectrum (BC 2002; Pitt 1999). In contrast to traditional BMP-based storm-water management, ESD embraces a total site design perspective, jointly synchronizing all the landscape drainage elements (road widths, curbing versus swales, etc.) to achieve the site performance goal of mimicking woods in good condition.

As science and policy supporting sustainable landscape design advance (Alberti 2007; BC 2002; Walsh et al. 2005) the effective use of pervious concrete and other pervious pavements, present especially rich opportunities to incorporate on-site storm-water infiltration within traditional development forms. The value of pervious pavements in sustainable landscape designs may be greatest in urban and suburban environments where the availability of land for conventional storm-water BMPs is a limiting constraint (Bean et al. 2007a; Booth and Leavitt 1999; Kwiatkowski et al. 2007). To advance the effective use of pervious pavement in sustainable urban design, the functional design and hydrologic performance of pervious pavement systems must be reconciled with conventional and emerging criteria for storm-water management.

This paper presents a procedure for the consistent design and hydrologic evaluation of pervious concrete storm-water management systems. Design parameters of subbase thickness and the size and elevation of drains are identified to satisfy basic *operational* criteria based on freeze-thaw risk and the timely drawdown of subbase storage. In contrast to current structural BMP design based on unified sizing criteria [Comstock and Wallis 2003; Maryland Department of the Environment (MDE) 2000b], the hydrologic performance of the pervious concrete system is characterized by an *effective curve number*, evaluated empirically from simulated routing of design storms. The procedure offers a consistent risk-based framework to size and quantify the hydrologic services of pervious concrete systems as an integral component of ESD.

Background

Pervious concrete has been used in the United States for over 30 years [American Concrete Institute (ACI) 2006], yet its widespread application has been limited by inconsistent information and the absence of uniform standards that address freeze-thaw

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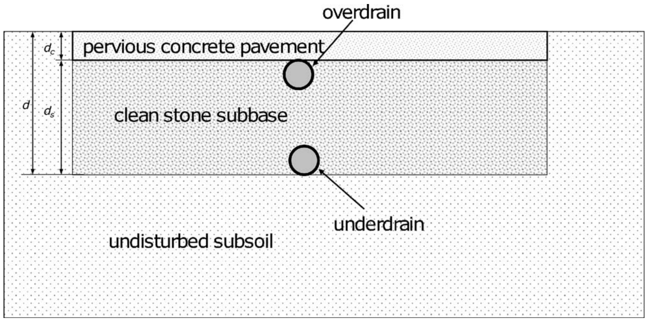

Fig. 1. Basic pervious concrete cross section

performance, clogging, strength and durability, and appropriate use and design. Regulatory differences in treating pervious concrete as either a structural BMP or an alternative surface contribute to uncertainty about successful design and regulatory approval in storm-water management plans. The contributing drainage area to a pervious concrete system may significantly exceed the area of the pervious pavement footprint or the area of the active subgrade soils that control infiltration, and must be considered explicitly in attributing hydrologic services or storm-water credits to pervious concrete.

Pervious Concrete

Like conventional concrete, pervious concrete is a mixture of cement, aggregate, admixtures, and water. Pervious concrete has developed as a "no-fines" concrete mixture, in which fine-grained materials are limited or excluded from the aggregate, resulting in a dense network of interconnected void spaces. Design decisions include mix design variables, of which the size distribution of the aggregate, cement content, water to cement ratio, and the compaction energy used during placement, all affect the inherent tradeoff between permeability and compressive strength of the finished concrete pavement (Delatte 2007; Schaefer et al. 2006). Pavement permeabilities on the order of 200–800 cm/h (78.8–315 in./h) are commonly realized, and permeability exceeding 2,000 cm/h (787.4 in./h) is readily achievable, albeit with lower compressive strength (Bean et al. 2007b; Schaefer et al. 2006).

Storm-water management services of pervious concrete are not determined by pavement properties alone. The rigid load-bearing pervious concrete pavement may best be viewed as the *inlet* to a storm-water management practice. The specification of pervious concrete for storm-water management therefore entails the design of a pervious concrete *system* consisting of a structural design for pavement services, and a hydrologic design for storm-water services. With reliable data on the strength and material properties of pervious concrete, conventional pavement design can be used to determine the required thickness of the pavement (Delatte 2007; Wanielista and Chopra 2007; Yang and Jiang 2003). Alternate mix designs and thicker pavements can extend the structural envelope of reliable paving applications that are primarily constrained by the properties of the pervious concrete pavement. In contrast, the design of a pervious concrete storm-water system is primarily constrained by site-specific infiltration properties of subgrade soils and the storage volume in the pavement subbase.

The conceptual design for a pervious concrete system shown in Fig. 1 consists of a section of pervious concrete pavement overlying a stone subbase of clean uniformly graded gravel. Storm-water infiltrates through the pervious concrete pavement and percolates through the subbase to the underlying subgrade soils. Inflow in excess of the underlying soil infiltration rate is temporarily stored in the subbase voids before draining to the subgrade soils (referred to as exfiltration) or discharging back to surface runoff through subbase drains.

Freeze-Thaw Performance

In cold-weather climates, one of the most common reservations about the use of pervious concrete is freeze-thaw durability. Pervious concrete's high permeability results in rapid failure in samples subjected to standard freeze-thaw testing under saturated conditions, such as ASTM C666A. Nevertheless, a growing body of experience research and testing has advanced the effective use of pervious concrete in cold-weather climates [Kevern et al. 2008; Miller 2007; National Ready Mixed Concrete Association (NRMCA) 2004; Roseen et al. 2009]. Systematic experiments with mix designs incorporating small proportions of sand and air entrainment of cement paste significantly increase concrete strength and improve freeze-thaw durability (Kevern et al. 2008; Schaefer et al. 2006). Beyond engineering improved mix designs to produce a more durable material, the risk of freeze-thaw failure can be reduced by designing pervious concrete systems to minimize the likelihood of fully saturating the pavement during freeze-thaw conditions. An experimental test plot on the campus of Cleveland State University designed specifically to demonstrate freeze-thaw performance, incorporated perforated PVC drains within the subbase to assure positive drainage by rapidly discharging infiltrated runoff to the existing storm sewer. The system has performed without any evidence of freeze-thaw damage since its installation in 2005 (Delatte et al. 2007).

Freeze-Thaw Design Criterion

Experience with freeze-thaw performance of pervious concrete systems [National Ready Mixed Concrete Association (NRMCA) 2004] motivates a basic design criterion, sizing the subbase with adequate storage to prevent any saturation of the pervious concrete pavement for a design storm event. Recognizing that such a design will have a nonzero probability of saturation over the full range of storm events, the choice of design storm quantifies this risk-based design criterion, providing minimum constraints on the storage and thickness of the subbase. The 10-year storm is commonly specified as the design storm for overbank flooding in conventional storm-water BMP design (Carr et al. 2001; Clar et al. 2004) and is used here to parameterize design as the default freeze-thaw design storm. Sizing pervious concrete systems to avoid saturation for the design storm creates a residual risk of partial saturation that increases with larger less frequent storm events. In climates and applications where this residual risk is judged to be unacceptable, additional drainage can be engineered in the subbase to further restrict the likelihood of pavement saturation.

Additional criteria such as vulnerability to frost heaving, and reduced permeability in frozen soils may require a deeper subbase than the minimum thickness determined by the hydrologic freeze-thaw criteria of avoiding pavement saturation for the design storm. The loss of infiltration in frozen soils increases the risk of freeze thaw failure and may require a deeper subbase to maintain reliable drainage (Leming et al. 2007). For regions subject to "hard wet freezes" the National Ready Mix Concrete Association recommends that combined pavement and subbase depths should equal or exceed 65% of the local frost depth [Portland Cement Association (PCA) 2006]. Yet, pervious pavements have shown greater resistance to freezing (Tyner et al. 2009) and frost penetration (Bäckström 2000; Houle 2006) than conventional pavements, attributed to the higher soil water content accompanying infiltration. The latent heat of infiltrating meltwater has also been credited with the more rapid thaw (accelerating cold-weather infiltration) observed in pervious pavement (Bäckström 2000; Houle 2006). Researchers at the University of New Hampshire, with frost depths exceeding 120 cm (48 in.), reported filter media within their pervious asphalt system maintained drainage year round, even under conditions favoring frost penetration [University of New Hampshire (UNH) 2007].

The choice of design storm for freeze-thaw performance establishes the design tradeoff between the frequency of saturated conditions (a surrogate for freeze-thaw failure risk) and costs (from thicker subbases, drains, and engineered channel protection requirements at the drain outlet). In practice, reliable freeze-thaw performance has been consistently reported from less conservative designs, although most of the experience in cold-weather climates in the United States is generally limited to pavements that have been installed relatively recently [Delatte et al. 2007; National Ready Mixed Concrete Association (NRMCA) 2004].

Drawdown Design Criterion

Like all storm-water retention, detention, or infiltration practices, the design of a pervious concrete storm-water system is also constrained to ensure a timely drawdown of runoff that is temporarily stored in subbase voids. Limiting the duration of subbase storage increases the probability that the full subbase storage volume will be available to capture runoff at the beginning of each storm. Drawdown criteria may be established based on the mean time between storms. For the mid-Atlantic states, the mean time between storms is approximately 3 days. In practice, recommended drawdown times for structural BMPs have typically ranged from 1 to 5 days [Leming et al. 2007; Maryland Department of the Environment (MDE) 2000b; Roesner et al. 2001]. The sizing procedure presented next uses an operational criterion of completely draining the 10-year 24-h design storm in no more than 72 h. The small likelihood of two 10-year storms occurring within 3 days contributes to the conservative nature of this design criterion. Like the choice of a 10-year design storm, the choice of a 72-h drawdown time is a reasonable conservative value used to parameterize the design procedure, and would be expected to vary with climate, and the risk preferences of the local permitting authority.

The following section develops the procedure to size and evaluate pervious concrete infiltration systems. In contrast to unified sizing criteria for storm-water BMPs (based on hydrologic performance criteria) the configuration of the pervious concrete systems is sized based on operational criteria for freeze-thaw durability and timely drawdown of stored inflow. The resulting site-specific hydrologic performance is evaluated (rather than prescribed in design) and quantified by an effective CN.

Sizing Pervious Concrete Storm-Water Systems

Computational tools using Natural Resources Conservation Service (NRCS) curve number hydrology and storage-indication routing are routinely used in the design and evaluation of storm-water management ponds. These standard computational methods are adapted to simulate the basic pervious concrete system as in Ladd (2004), enabling the procedure to be easily incorporated in current storm-water practice. More physically based simulation is feasible and increasingly common in the design and evaluation of bioretention structures (Dussaillant et al. 2004, 2005; Heasom et al. 2006) and pervious pavement infiltration systems (Kwiatkowski et al. 2007). Computational approximations and conservative design assumptions are described further in the Discussion section.

Hydrologic Design

As with conventional storm-water BMP design, the design storm is routed through the pervious concrete system using a stage-storage relationship that accounts for the porosity of the subbase. Here and throughout, porosity refers to the effective porosity, i.e., the connected freely draining pore volumes in the pavement and subbase. More compact mixtures of pervious concrete can isolate embedded pores, reducing the effective porosity or specific yield (Luck et al. 2006) of the pavement. All design storm routing computations assume a constant soil infiltration rate (i.e., do not explicitly account for the influence of storage depth on exfiltration). The constant infiltration rate is conceptualized as the steady-state infiltration rate of the subgrade soil, f (cm/h) (analogous to Horton's asymptotic infiltration rate f_c), and should be determined in the field through standard site-evaluation testing such as the Maryland Department of the Environment's (MDE) falling head drainage test for infiltration structures [Maryland Department of the Environment (MDE) 2000a].

For conservative design, routing calculations only consider vertical infiltration into subgrade soil as in Braga et al. (2007). Infiltration is further assumed to only occur over the effective area of the subgrade excavation that is exposed among the subbase voids. The simulated exfiltration rate, q_x (m^3/s) is therefore proportional to subbase porosity, $q_x \propto f\phi_s$, reducing the effective infiltration by a conservative estimate of the masking effect of the subbase stone on the subgrade soils (Radcliffe et al. 2005). The constant infiltration rate is a conservative design assumption in that it does not account for the recovery of infiltration capacity between storm events or the increase in infiltration with temperature observed by Braga et al. (2007) and Emerson and Traver (2008).

The basic design (Fig. 1) considers a rectangular subgrade excavation with depth d composed of the thicknesses of the concrete pavement d_c, and the stone subbase d_s, where $d = d_c + d_s$. The subbase voids of the pervious concrete system can store a maximum inflow depth of $d_s\phi_s$, where ϕ_s is the subbase porosity. Here and throughout it is useful to distinguish the pervious pavement area, A_P, that serves as the inlet area through which storm water infiltrates; the infiltration area, A_I, of subgrade soil over which infiltration may occur; and the contributing drainage area A_D generating inflow to the pervious concrete system. In the simplest basic design, $A_D = A_P = A_I$. The same procedures can be used to design and evaluate pervious concrete systems with runon, in which $A_D > A_P = A_I$. Innovative site designs that integrate pervious concrete inlets within a larger site area underlain by infiltration beds may yield designs in which $A_D > A_I > A_P$ (Kwiatkowski et al. 2007). For pervious concrete systems on sites with cut and fill grading, the Carroll County, Maryland Bureau of Resource Management has developed recommended design tables (Covington 2009) in which subgrade areas of compacted fill are assumed to be impermeable and $A_D = A_P > A_I$.

Hydrologic design variables include the depth and porosity of the subbase (defining storage), areas of contributing drainage and exfiltration, and the size and elevation of any drains. To establish consistent designs adapted to varying site conditions, the design

Table 1. Pervious Concrete Prototype Designs $A_D = A_P = A_I$

(1)	(2)		(3)		(4)		(5)		(6)	
Subsoil infiltration rate	0.13 cm/h (0.05 in./h)		0.38 cm/h (0.15 in./h)		0.76 cm/h (0.3 in./h)		1.27 cm/h (0.5 in./h)		2.54 cm/h (1.0 in./h)	
Subbase thickness										
Drained Undrained	29.9 cm (11.8 in.)	38.4 cm (15.1 in.)	31.1 cm (12.2 in.)	33.2 cm (13.1 in.)	na	27.1 cm (10.7 in.)	na	23.2 cm (9.1 in.)	na	18.3 cm (7.2 in.)
Drawdown time										
Drained Undrained	63 h[a]	305 h	71.5 h[b]	93 h	na	43 h	na	23.3 h	na	12 h
Drains	9–2.54 cm UD[c]		2–2.54 cm UD[c]		None		None		None	
ECN	87.3		60.6		40.5		36.7		28	
10-year storm, percent infiltrated	23.2		76.7		100		100		100	

Note: na=not applicable.
[a]Includes nine 2.54-cm underdrains.
[b]Includes two 2.54-cm underdrains.
[c]UD—underdrain.

procedure determines the size and configuration of the pervious concrete system to satisfy basic freeze-thaw and drawdown criteria.

Sizing for Freeze Thaw and Drawdown: $A_D = A_P = A_I$

Consider a 15.2 cm (6 in.) thick section of pervious concrete with porosity $\phi_c = 0.2$ over a stone subbase with $\phi_s = 0.3$ in which the only storm-water inflow originates from direct precipitation onto the pavement ($A_D = A_P$). The pavement area is equal to the infiltration area ($A_P = A_I$) which drains the subbase at the effective exfiltration rate, conservatively modeled as $f\phi_s$ (cm/h). For the mid-Atlantic region near Baltimore a 43.2 cm (17 in.) subbase would be required to fully store the 10-year storm depth of 13 cm (5.1 in.) without exfiltration. The minimum subbase thickness to satisfy the freeze-thaw criterion is estimated as the maximum water surface elevation reached within the subbase when the design storm is routed with exfiltration. The inflow hydrograph for the design storm is derived as runoff from a drainage area $A_D = A_P$ with a 5-min time of concentration and a curve number of 98. The time to fully drain the maximum water surface elevation from the design storm defines the drawdown time. As the site-specific exfiltration rate increases, the drawdown time and the subbase thickness required to satisfy the freeze-thaw criterion decrease. Table 1 summarizes the minimum subbase thickness, drawdown time, and number of drains (if any) needed to satisfy the freeze-thaw and drawdown criteria, determined by routing the 24-h design storm through pervious concrete systems with soil infiltration rates ranging from 0.13 to 2.54 cm/h. The pervious concrete computations in Table 1 are based on a drainage area of $9{,}290\ \mathrm{m}^2$ ($100{,}000\ \mathrm{ft}^2$).

For a subgrade soil infiltration rate of 1.27 cm/h (0.5 in./h) the operational freeze-thaw and drawdown criteria are satisfied with a minimum subbase thickness of 23.2 cm (9.1 in.). The 23.2-cm subbase without drains results in a 23.3-h drawdown time. Although this design satisfies the freeze-thaw criterion without any drains it still embodies a residual risk of pavement saturation for storms larger than the 10-year storm.

Soil infiltration rates of 0.76 cm/h (0.3 in./h), 0.38 cm/h (0.15 in./h), and 0.13 cm/h (0.05 in./h) in Table 1 correspond to minimum infiltration rates commonly ascribed to soils in NRCS hydrologic soil groups A, B, and C, respectively (ASCE 1996; Maidment 1993). For the lowest infiltration rates, the designs in Table 1 that satisfy the basic freeze-thaw criteria without drains do not satisfy the 72-h drawdown criteria. Pervious concrete systems in these soils therefore require additional drainage to meet the drawdown constraint. The addition of underdrains with the effective discharge area of a 2.54 cm (1 in.) circular orifice, reduces the drawdown time to 71.5 h for soil infiltration rates of $f = 0.4$ cm/h, and 63 h for $f = 0.1$ cm/h. The underdrain discharge also decreases the maximum elevation of stored runoff for the 10-year design storm, reducing the minimum subbase thickness required to satisfy the freeze-thaw criterion to about 31.1 cm (12.2 in.) for $f = 0.4$ cm/h and 29.9 cm (11.8 in.) for $f = 0.1$ cm/h. These basic configurations with underdrains satisfy the drawdown and freeze-thaw criteria by discharging subbase storage, decreasing the total exfiltration volume.

The basic designs in Table 1 conform to risk-based operational criteria for freeze-thaw and drawdown defined by the 10-year design storm. Operational criteria are used to size the pervious concrete system and establish a consistent level of freeze-thaw and drawdown reliability for storms up to the 10-year design storm. Rather than viewing hydrologic performance as a design criteria or an inherent property of a pervious concrete system, the consistent criteria for risk-based operational performance (freeze thaw and drawdown) determine the design of the system; the resulting site-specific hydrologic performance is a derived attribute rather than an explicit design criteria, and is characterized by an effective curve number.

Hydrologic Services-Effective Curve Number

NRCS curve number hydrology parameterizes the rainfall-runoff relationship of catchments and has been used to characterize the rainfall-runoff characteristics of pervious concrete systems by Leming et al. (2007) and Bean et al. (2007a). Leming et al. (2007) compute a storm event curve number for each simulated design event. Any pervious concrete configuration may thereby be characterized by a different curve number for each individual runoff-generating storm event. Estimating a single effective curve number over a broad set of storm events usefully characterizes the hydrologic services of a pervious concrete system design in a single consistent performance measure that is readily interpretable by storm-water managers. Bean et al. (2007a) estimated the equivalent curve number from monitored rainfall-runoff data for several instrumented pervious paving systems in North Carolina. Equivalent curve numbers were estimated from the system storage parameter S (cm) estimated using linear regression, and from event curve numbers for storms with more than 50 mm of precipitation. A single effective CN is similarly used here to characterize the hydrologic performance of each design.

The pervious concrete system is characterized by a single effective curve number estimated from simulated routing of a set of design storms with precipitation depths ranging from the 1-year storm to depths greater than the 100 year storm. Although the runoff produced by any storm event can be characterized by an event curve number, events that produce no runoff only provide an upper bound on the effective curve number. Estimating the effective curve number as the best fit over a wide range of storm depths unambiguously quantifies the system's hydrologic response, and is most consistent with the original derivation of curve number hydrology, which characterized catchment response over a suite of observed storms (Hawkins et al. 2009). The effective curve number also directly supports ESD criteria referenced to the hydrologic response of woods in good condition. The following section briefly summarizes the rainfall-runoff relationship characterized by the NRCS curve number, and uses standard curve number hydrology and nonlinear optimization to estimate the best fitting effective curve number for the pervious concrete systems configured in Table 1.

Curve Number Hydrology

NRCS curve number hydrology was developed as an empirical means to characterize the rainfall-runoff relationship of small watersheds for the design of water resource infrastructure. Originally derived using observed storm depth and storm runoff data from monitored watersheds, the curve number parameterizes the maximum potential storage (after initial abstractions) S (mm) in a catchment as

$$S = \frac{25{,}400}{\mathrm{CN}} - 254 \tag{1}$$

Curve number hydrology assumes no runoff is generated from precipitation depths less than a catchment-specific initial abstraction, I_a, parameterized by the curve number through (1) as $I_a = \lambda S$. Increasing precipitation losses affect the runoff volume for larger storm depths, with the change in expected runoff asymptotically approaching $dQ/dP=1$ as the storm depth increases (Hawkins 2001). The standard curve number assumptions (Hawkins et al. 2009) result in the familiar prediction of runoff depth as

$$Q_{\mathrm{CN}}(P) = \frac{(P-I_a)^2}{(P-I_a+S)} \tag{2}$$

where $Q_{\mathrm{CN}}(P)$=curve number runoff computed for a storm depth P. Historically, the empirical inspection of storm runoff data led to what is today the conventional implementation of curve number hydrology, which assumes $\lambda=0.2$ or

$$I_a = 0.2S \tag{3}$$

More recent reanalysis of this empirical relationship suggests the accuracy of runoff predictions may be improved by assuming $\lambda=0.05$ (Hawkins et al. 2002; Lim et al. 2006), especially in urban watersheds.

Using conventional curve number assumptions embodied in (2) and (3), the nonlinear relationship between simulated design-event precipitation and runoff can be characterized by the curve number that best fits the routed runoff. For a set of N paired rainfall-runoff values $\{p_i, Q(p_i),\ i=1,2,\ldots,N\}$ the best fitting curve number is estimated to minimize the sum of the squared differences between $Q(p_i)$ and $Q_{\mathrm{CN}}(p_i)$ as

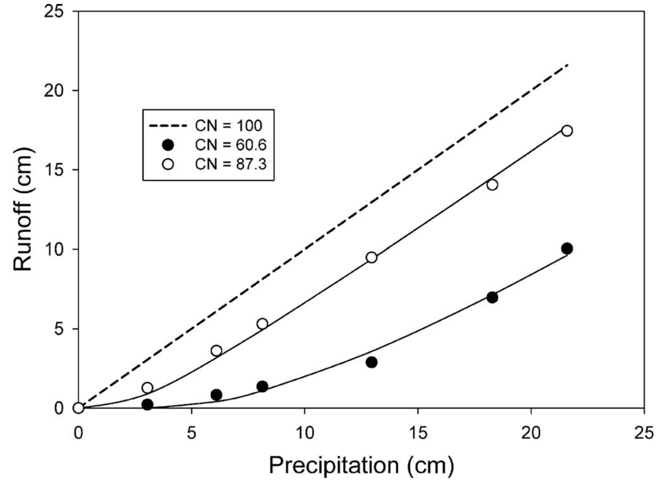

Fig. 2. Routed runoff (symbols) and effective curve number (lines) for pervious concrete systems with subsoil infiltration $f=0.38$ cm/h (CN=60.6) and $f=0.13$ cm/h (CN=87.3). Dashed line—1:1 (CN =100)

$$\min_{\mathrm{CN}} \sum_{i=1}^{N} [Q(p_i) - Q_{\mathrm{CN}}(p_i)]^2 \tag{4}$$

subject to

$$Q_{\mathrm{CN}}(p_i) = \begin{cases} \dfrac{(p_i-0.2S)^2}{(p_i+0.8S)} & p_i > I_a \quad i=1,2,\ldots,N \\ =0 & p_i \le I_a \end{cases} \tag{5}$$

For any pervious concrete system (characterized by the drainage and infiltration areas, thickness and porosity of pavement and subbase, exfiltration rate to the subgrade soil, and the specification of hydraulic parameters for any drains) standard storm-water computations can be used to compute the simulated discharge for a 24-h design storm of arbitrary depth. Repeating these computations over a range of storm depths provides a set of simulated rainfall-runoff values that can be characterized by an effective curve number, estimated as the solution to (4) and (5). Effective curve number values for each pervious concrete configuration are presented in Table 1, along with the fraction of the 10-year storm that is infiltrated by each design. Simulated and computed runoff depths used to estimate the best fitting curve numbers for the configurations with $f=0.13$ cm/h (0.05 in./h) and $f=0.38$ cm/h (0.15 in./h) are shown in Fig. 2.

Runon Designs: $A_D > A_P = A_I$

Pavement designs in Table 1 correspond to $A_D=A_P=A_I$. The design and evaluation procedure can be readily applied to systems with runon, where $A_D > A_I$. Given the site-specific infiltration rate, f, increasing the ratio of the drainage area to the infiltration area requires a thicker subbase or subbase drains to satisfy the freeze-thaw criterion. Increasing the drainage ratio (i.e., $A_D:A_I$) also results in greater discharge from larger storms, resulting in larger effective curve numbers. As subbase storage increases for freeze-

Table 2. Effective Curve Number and Designs for Runon $A_D > A_I$; $f = 1.27$ cm/h (0.5 in./h)

(1)	(2)	(3)	(4)	(5)
Drainage ratio $A_D:A_I$	1:1	2:1	3:1	3:1
Subbase thickness without drains	23.3 cm (9.1 in)	56.7 cm (22.3 in.)	95.7 cm (37.7 in.)	95.7 cm (37.7 in.)
Drawdown time without drains	23.2 h	49.4 h	76.4 h	76.4 h
Drawdown time with drains	NA	NA	61.4 h	70.6 h
Effective curve number	36.7	46.9	60[a]	56[b]

Note: NA=not applicable.

[a]Includes one 2.54 cm (1 in.) underdrain; subbase thickness is reduced to 90.2 cm (35.5 in.).

[b]Includes one 5.1 cm (2 in.) over drain with invert elevation at 68.6 cm (27 in.); subbase thickness is reduced to 88.7 cm (34.9 in.).

thaw performance, additional underdrains may also be required to satisfy the drawdown criteria. Table 2 summarizes representative designs and effective curve numbers for pervious concrete systems with drainage ratios up to 3:1. All designs assume the area and permeability of the pavement provide infiltration rates that far exceed the peak inflow rates, so the pavement area A_P, is never limiting and does not affect the design.

For subgrade soils with an infiltration rate of 1.27 cm/h (0.5 in./h), a 2:1 drainage ratio is readily accommodated in a 56.7 cm (22.3 in.) subbase without drains. Drawdown time for drainage ratios of 3:1 exceeds 72 h, requiring additional drains. The design in column (4) of Table 2 includes one 2.54 cm (1 in.) underdrain resulting in an effective curve number of 60. The 72-h drawdown constraint is not binding for this design, indicating that the design could be further optimized to incrementally extend the drawdown time, increasing infiltration and reducing the effective curve number. The design in column (5) achieves somewhat greater infiltration by placing a 5.1 cm (2 in.) drain 20.1 cm (7.9 in.) below the pavement. This configuration provides freeze-thaw pavement protection for the 10-year design storm, while leaving the lower 68.6 cm (27 in.) of the subbase drained only by exfiltration. Raising the drain invert reduces drainage and increases exfiltration, lowering the effective curve number from 60 to 56.

Discussion

The design procedure is developed with curve number hydrology, storage-indication routing, and standard computational methods routinely used by storm-water practitioners. The computations do not account for the effects of flow through the coarse porous media of the pavement and subbase, or transitions from unsaturated to saturated flow conditions. A number of conservative design assumptions are also incorporated in the design computations including:

1. Use of the 10-year storm as the design event for both freeze thaw and drawdown;
2. Reducing the effective soil infiltration rate by the porosity of the subbase to compute exfiltration;
3. Assuming constant subgrade infiltration, i.e., not accounting for the recovery of infiltration capacity between storms or the temperature dependence of infiltration; and
4. Only considering vertical exfiltration beneath the subbase.

Routing the design storms through subbase storage with storage-indication routing may introduce greater approximation error compared to its common use in computations for storm-water management ponds with a free water surface. A more physically based computational approach might include an explicit representation of flow through the porous subbase media (Radcliffe et al. 2005; Reinson et al. 2005) and dynamic process-based representations of soil infiltration processes (Braga et al. 2007; Dussaillant et al. 2004). The conservative assumptions yield inherently conservative designs, providing an added safety factor for regulatory approval and a conservative margin of error for approximation errors that may be introduced by the computational approach. The significance and sensitivity of design performance to these assumptions is the subject of ongoing research and field verification.

Maintenance and Construction

Like every storm-water management practice, reliable performance of pervious concrete system designs depend on proper care in site preparation and construction, and reliable inspection and maintenance.

Compaction, Sealing, and Site Preparation

Conventional excavation and grading practices can result in significant reductions in subgrade infiltration due to inadvertent compaction and surface sealing (Gregory et al. 2006; Pitt et al. 1999, 2008; Tyner et al. 2009). State storm-water manuals, specifications, and construction notes for infiltration practices (with or without pervious concrete) therefore routinely call for special care to minimize compaction during site preparation, including scarifying the final subgrade surface and restricting or excluding heavy earthmoving equipment from the subgrade excavation (VADCR 2009). Ferguson (2005) described a notable exception for pervious concrete constructed in Florida, where sandy soils are routinely compacted to 90–95% Proctor density. For storm-water management with infiltration, field verification of infiltration rates following compaction (with modification of pavement and subbase thickness as appropriate) is required. Assuring that design infiltration rates are realized in finished subgrade excavations is an increasingly important element of site inspection and approval by local storm-water authorities as the use of on-site infiltration and low impact development practices proliferates.

Clogging

Site design to minimize clogging and routine maintenance to inspect and mitigate clogging are essential for the reliable performance of pervious concrete systems. As with all infiltration practices, good site design minimizes surface clogging by locating pervious concrete away from direct sources of particulate loading, and protecting the pavement by pretreating runon (e.g., with a vegetative filter strip), as feasible. The high infiltration rate of the pervious concrete pavement [commonly exceeding 1,000 cm/h (Bean et al. 2007b; Houle 2006)] rarely limits the performance of pervious concrete storm-water systems. Although some surface clogging can be tolerated without a significant loss of storm-water services, clogged pavements can increase the risk of freeze-thaw damage, and chronic sources of clogging demand prompt attention. Good practice requires routine inspection of the pavement surface for evidence of clogging and maintenance, as needed. Rapid assessment of the magnitude and extent of surface clogging, such as the quick drain test used by Delatte et al. (2007), provides simple consistent criteria to initiate pavement maintenance. Dry vacuum sweeping and pressure washing have been shown to restore up to 90% of the infiltration capacity of pervious concrete pavements (Wanielista et al. 2007).

Surface clogging is effectively managed through routine maintenance, but fine-grained particles can penetrate the full pavement and subbase and accumulate at the subgrade surface (Joung and Grasley 2008; Mata 2008; Siriwardene et al. 2007). The use of nonwoven geotextile between the subbase and the subgrade can exacerbate the development of a fine particulate layer that may significantly reduce exfiltration and lead to premature clogging failure. To reduce the risk of clogging by fine-grained particles at the subbase-subgrade interface, lining the bottom of infiltration structures with geotextile fabrics is not encouraged by the MDE or the Maryland State Highway Administration (MSHA). Instead, MDE and MSHA recommend incorporating a filter layer of quartz sand between the undisturbed soil and the stone subbase to reduce the risk of clogging failure. Alternate designs [American Concrete Institute (ACI) 2006] include a filter layer between the subbase and the soil, with a geotextile between the subgrade soils and the filter layer.

Drain Design

The drains in Tables 1 and 2 are characterized as a discrete number of vertical 2.54 cm (1 in.) diameter circular orifices. Parameterizing the under drains in this way also provides an estimate of the drainage area served by a single drain, offering design guidance in scaling drained systems to larger or smaller areas. In practice, a pragmatic drainage implementation might incorporate larger diameter drains (to minimize clogging and facilitate cleanout), with a restrictor plate over the outlet, engineered to precisely establish the design orifice area and invert elevation.

All computations in Tables 1 and 2 are based on a drainage area of 9,290 m^2 (100,000 ft^2). The 72-h drawdown criterion will be a binding constraint for drains that optimize infiltration. Reported drawdown times of less than 72 h could be further optimized, but were limited in these examples by the use of a discrete number of standard sized drains with a minimum orifice diameter of 2.54 cm. Designs requiring only one 2.54-cm drain for a 9,290-m^2 drainage area would still require at least one drain for a smaller drainage area. The 2.54-cm drain for a smaller area would result in greater proportional drainage resulting in a shorter drawdown time and a larger effective curve number. Scaling designs with one drain to smaller drainage areas would therefore be expected to yield lower hydrologic services and a higher effective curve number. For example, for soils with a minimum infiltration rate of only 0.13 cm/h, the design summarized in Table 1 calls for a 29.9-cm subbase and one 2.54-cm underdrain per 1,032.3 m^2 of drainage area. The design yields a drained drawdown time of 63 h with an effective curve number of 87.3. Drainage areas less than 1,032.3 m^2 still require at least one drain to satisfy the drawdown criterion. With a minimum drain diameter of 2.54 cm, smaller drained designs yield effective curve numbers of 91 for a drainage area of 464.5 m^2 (5,000 ft^2) and 95.2 for a drainage area of only 92.9 m^2 (1,000 ft^2). Higher curve numbers from smaller drainage areas are also accompanied by a thinner minimum subbase and shorter drawdown times, both reflecting the disproportionately larger discharge the single drain provides to smaller pervious concrete systems.

Design Strategy and Environmental Site Design

Although the design procedure has been developed using standard storm-water computations, the design strategy differs fundamentally from the common use of unified sizing criteria. Unified sizing criteria specifies hydrologic performance a priori as design criteria to effectively capture and treat runoff volumes for water quality, recharge, channel protection, and out-of-bank flooding. In contrast, the hydrologic performance of the pervious concrete system is *characterized*, rather than designed for, by the effective curve number that results from applying the design criteria to site-specific drainage and infiltration characteristics. The end result is a consistent design procedure that sizes pervious concrete systems for conservative freeze-thaw and drawdown reliability; hydrologic performance is a derived site-specific characteristic, rather than a prescriptive performance criterion that must be uniformly satisfied at all sites.

Decoupling design criteria and hydrologic performance fundamentally changes design and regulatory decision making in the choice and permitting of pervious concrete systems. For example, state and municipal storm-water guidance commonly discourages the use of infiltration practices, including pervious concrete, on hydrologic C and D soils. The design criteria described in this paper can be readily applied to pervious concrete systems on soils with very low infiltration rates. Resulting designs will likely entail thick subbases, substantial subbase drainage, and a high effective curve number, unambiguously quantifying the limited hydrologic services that can be realized on soils with limited infiltration capacity. For conventional unified sizing criteria, such systems would simply fail to satisfy all the required hydrologic design criteria. For ESD, the design criteria enable the utility and cost-effectiveness of using pervious concrete to become a value engineering decision, made in the context of overall site development constraints.

Limitations and Validation

The freeze-thaw design criterion is consistent with current practice and experience, but its cost-effectiveness and residual risk have not been systematically verified. One might expect risk-based freeze-thaw criteria (and the joint probability of large runoff-producing events and freezing conditions) to vary geographically with soils and climate [National Ready Mixed Concrete Association (NRMCA) 2004]. The freeze-thaw criterion provides storage to reduce the probability of pavement saturation. The occurrence of a design storm during freezing conditions is not, however, the only event that could result in freezing of saturated pavement. For any sequence of events that could saturate the pavement, greater storage reduces the probability the pavement will be saturated during freezing conditions, thereby reducing the freeze-thaw failure risk. Absent a rigorous predictive understanding of the relationship between climate variability and the reliability of pervious concrete freeze-thaw designs, a conservative hydrologic design criterion is adopted, acknowledging the inherent residual risk. Residual freeze-thaw risk may be managed by both the choice of design storm and the incorporation of additional overdrains. As experience and consistent performance information in different soils and climates continue to grow, the design procedure described here can be readily refined to reflect observed performance.

Conservative design assumptions provide a margin of safety for rational design, consistent with current practice and experience. The procedure provides designers and regulators with conservative criteria that can be consistently applied to both size and approve designs, and to quantify storm-water performance credits. The design procedure is parameterized by the recurrence interval for the design storm and the design drawdown time, implicitly defining the levels of freeze thaw and drawdown risk. Though illustrated here for the 10-year storm and 72-h drawdown time, more conservative designs can be specified systematically by choosing a longer design storm recurrence interval or shorter drawdown time. Design parameters can be expected to vary regionally reflecting differences in climate [e.g., dry freeze versus hard wet freeze zones (NRMCA 2004; PCA 2006)] and the local preferences of permitting authorities. The design procedure offers a consistent basis to transform these common risk-based parameters into consistent designs for pervious concrete storm-water systems.

Perhaps more important, the procedure provides a predictive performance-based framework for hypothesis-based performance monitoring and validation, uniformly applicable to both new systems designed for performance monitoring, and installed systems that have been carefully documented [such as those benchmarked by Delatte et al. (2007)]. Performance information from installed systems is generating the cumulative body of experience needed for validation and continual improvement of standard design procedures. The design procedure presented here represents an adaptable framework for hypothesis-based design and evaluation that can be used in practice, and revised and refined as knowledge and experience continue to grow.

Conclusions

This paper presents a procedure for the consistent design and hydrologic evaluation of pervious concrete storm-water management systems. Design parameters of subbase thickness and the size and elevation of drains are identified to satisfy basic operational criteria based on freeze-thaw risk and the timely drawdown of subbase storage. In contrast to current structural BMP design based on unified sizing criteria, the hydrologic performance of the pervious concrete system is characterized by an effective curve number, evaluated empirically from simulated routing of design storms. The procedure offers a consistent risk-based framework to size and quantify the hydrologic services of pervious concrete systems as integral components of ESD.

Quantifying hydrologic services by an effective curve number, offers a simple consistent metric that can be used to quantify storm-water credits and characterize the contribution of a pervious concrete system to the larger goal of restoring hydrologic services in ESD. The site-specific effective curve number enables designers, site planners, and landscape architects to evaluate the utility of pervious concrete storm-water systems as a value engineering decision in ESD, rather than as a prescriptive BMP technology specified by regulation. The criteria rationalize functional design and site-specific hydrologic performance. Combining reliable criteria for operational design and the evaluation of hydrologic performance provides a consistent framework to integrate the design of pervious concrete systems with conventional practice and emerging criteria for ESD.

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