ABSTRACT: Runoff from urban catchments depends largely on the amount of impervious surface and the connectivity of these surfaces to the storm sewer drainage system. In residential areas, pervious lawns can be used to help manage stormwater runoff by intercepting and infiltrating runoff from impervious surfaces. The goal of this research was to develop and evaluate a simple method for estimating the reduction in stormwater runoff that results when runoff from an impervious surface (e.g., rooftop) is directed onto a pervious surface (e.g., lawn). Fifty-two stormwater runoff reduction tests were conducted on six residential lawns in Madison, Wisconsin during the summer of 2004. An infiltration-loss model that requires inputs of steady-state infiltration rate, abstraction (defined here as surface storage, vegetation interception and cumulative total infiltration minus steady-state infiltration during the period prior to steady-state), and inundated area was evaluated using experimental data. The most accurate results were obtained using the observed steady-state infiltration rates and inundated areas for each test, combined with a constant abstraction for all tests [root mean squared (RMS) difference = 1.0 cm]. A second case utilized lawn-averaged steady-state infiltration rates, a regression estimate of inundated area based on flow-path length, and lawn-specific abstractions based on infiltration rate (RMS difference = 2.2 cm). In practice, infiltration rates will likely be determined using double-ring infiltration measurements (RMS difference = 3.1 cm) or soil texture (RMS difference = 5.7 cm). A generalized form of the model is presented and used to estimate annual stormwater runoff volume reductions for Madison. Results indicate the usefulness of urban lawns as a stormwater management practice and could be used to improve urban runoff models that incorporate indirectly connected impervious areas.

(KEY TERMS: best management practice; downspout; impervious; infiltration; model; pervious; lawn runoff; roof runoff; stormwater management.)


INTRODUCTION

Urbanization creates a network of impervious surfaces such as roads, driveways, sidewalks, and rooftops. These impervious surfaces are defined as connected if the impervious area drains directly to the storm sewer drainage system and disconnected if the impervious area first drains onto a lawn or other pervious area where infiltration can occur. Routing stormwater runoff from impervious surfaces onto pervious surfaces (i.e., disconnecting impervious surfaces) is
one low impact development technique that can help mitigate increases in stormwater runoff volume caused by urbanization. Quantifying the hydrologic disconnection of impervious surfaces has important implications for the management of runoff and the associated nonpoint source pollution.

The hydrologic connectivity of impervious surfaces is difficult to determine since it is dependent on the physical characteristics (e.g., vegetative cover, flow-path length, topography, soil) of intervening pervious areas. Additionally, hydrologic connectivity is dependent on rainfall duration and intensity and the relative sizes of the impervious and pervious areas. In a residential setting, lawns comprise a large amount of the pervious area. Investigations into the runoff response of lawns to direct rainfall have been conducted (e.g., Legg et al., 1995) and runoff from pervious-impervious systems have been evaluated experimentally in the laboratory (e.g., Shuster et al., 2008). However, the ability of lawns to hydrologically disconnect rooftops from the storm drainage system represents a different process. Rooftop drainage onto lawns via downspouts (run-on) occurs as a concentrated flow source and the runoff response to such run-on has received minimal attention. Alley and Veenhuis (1983) developed an empirical relationship between total impervious area and directly connected impervious area for an urbanized portion of Denver. In their hydrologic analysis of a residential area in Boulder, Lee and Heaney (2003) subtracted roof areas from their estimate of directly connected impervious area if the downspout outlet was not located on a directly connected surface. Pitt and Bozeman (1979) assumed that outfall runoff yield from rooftops was about 30% since most rooftops in their San Jose study area were not directly connected to the storm sewer system. Steinke et al. (2007) measured runoff from turf plots for three impervious/pervious ratios, however flow onto each turf plot occurred as sheet flow from the adjacent impervious surface. DeMaster (2002) measured lawn runoff in response to downspout run-on and considered slope, ground cover, soil texture, and development age as infiltration factors. None of these site factors showed a clear correlation to infiltration rate, though older sites had some tendency to infiltrate better than newer sites.

Understanding the role of lawns in disconnecting impervious surfaces has two important applications. First, such an understanding will aid in assessing the usefulness of lawns as an urban stormwater management practice. Second, urban runoff models are an important component of stormwater management and better representation of the hydrologic connectivity of impervious surfaces will allow for improved stormwater predictions. Therefore, the goal of this research is to better understand the practical extent to which urban residential lawns can infiltrate stormwater runoff that would otherwise flow into storm sewer systems. The objectives are to (1) measure runoff and infiltration resulting from concentrated run-on through a rooftop downspout onto residential lawns, (2) evaluate a simple infiltration-loss model for predicting stormwater runoff volume using experimental data and a range of model input parameters, and (3) use the model to determine the lawn flow-path length required to achieve various degrees of infiltration (i.e., hydrologic disconnection) and to assess the effectiveness of lawns as an urban stormwater management practice.

**MATERIALS AND METHODS**

Stormwater runoff reduction tests were conducted on six residential turf grass lawns in Madison, Wisconsin between June 22, 2004 and August 19, 2004. The lawns ranged in age from 5-50 years, slopes ranged from 0.04-0.22 m/m, and all soils were classified as loams (Table 1). Although the range of conditions investigated is somewhat narrow, thereby limiting the applicability of the results to other locations with significantly different lawn and soil characteristics, the methods presented herein provide a basis for similar trials in other locations and offer a framework for analysis. Lawns were selected based on the following criteria: (1) the existing downspout discharged onto the lawn, (2) the flow path was free of obstructions (e.g., trees), (3) the pervious flow path from the downspout was at least 6 m, (4) the slope along the flow path was uniform, and (5) the entire flow path contained sufficient grass cover (no bare patches). Of the lawns available for use in this study, only one met each of these five criteria. The remaining five lawns were selected because they met at least four of these criteria (Table 1).

Rooftop drainage onto each lawn (run-on) was simulated through a temporary downspout (used for easier access) placed near the actual downspout. Water was pumped from a 1.51 m$^3$ tank into the temporary downspout. A series of valves allowed control of the flow rate which was measured using a volumetric flowmeter. Flow discharged through the downspout with exit velocities and trajectories similar to those of the actual downspout and was allowed to flow freely across the lawn surface.

Flexible plastic lawn edging, inserted vertically into the lawn at a specified distance from the downspout, routed runoff to a collection bucket installed below the surface of the lawn. All soil-plastic interfaces along the edging and the collection bucket were sealed with bentonite to prevent preferential flow into the ground.
Runoff water was pumped from the collection bucket to a calibrated tipping bucket system to measure runoff rate and volume. A constant water level was maintained in the collection bucket by manually adjusting a gate valve. An energy dissipater was used to direct water into a small tipping bucket (static tip volume = 300 ml). A funnel located beneath the small tipping bucket then directed flow into a larger tipping bucket (static tip volume = 1,000 ml). The dual bucket system allowed low and high flow rates to be monitored with similar accuracy. Tips from both buckets were counted with reed switches and recorded with a CR-10 datalogger (Campbell Scientific, Logan, Utah). Runoff rate was recorded every minute throughout the test and tests were conducted until steady-state (runoff tip rates were constant for 15-20 min) was reached.

Two CS-616 soil moisture probes (Campbell Scientific) were positioned along the flow path and a soil moisture measurement was integrated over a 30 cm vertical depth. One probe was 1.8 m from the downspout and remained on-site to continuously monitor soil moisture. The second probe was temporarily installed 3.7 m from the downspout and only recorded soil moisture during a test.

One to three of the following flow-path lengths were evaluated on each lawn depending on the maximum lawn length available: 1.8, 2.7, 3.7 and 5.5 m (Table 1). Run-on application rates at each length were 0.23 m$^3$/hour, 0.68 m$^3$/hour, and 1.14 m$^3$/hour. The roof areas draining onto the lawns ranged from approximately 23.2 to 46.5 m$^2$. For an area of 46.5 m$^2$ and a one-hour duration, these rates correspond to rainfall depths (assuming no abstractions for the roof area; i.e., all rainfall becomes runoff) of 4.9 mm, 14.6 mm, 24.5 mm and respective recurrence intervals of approximately <2-month, 2-month, and 9-month for Madison (Huff and Angel, 1992). For an area of 23.2 m$^2$ the recurrence intervals are approximately <2-month, 1-year, and 10-year. Initial volumetric moisture contents ranged from 0.26-0.49, 0.26-0.52, 0.27-0.52 m$^3$/m$^3$, for run-on rates of 0.23, 0.68, and 1.14 m$^3$/hour, respectively.

Each test condition (combination of flow-path length and run-on rate) was run twice in order to measure runoff resulting from two antecedent moisture conditions. On all lawns, tests for the longest flow path were completed first so that barrier installation/removal did not affect the flow path. A total of 52 tests were completed. Inundated areas were determined by visual inspection at three foot intervals from the downspout throughout each test. Intermediate and final inundated areas were delineated with flags, the perimeters were surveyed, and the areas were determined.

Infiltration rates were also measured on each lawn using a standard double-ring infiltrometer (ASTM, 2002). Double-ring tests were conducted at the same locations as the soil moisture probes. The inner ring was 24.7 cm in diameter and the outer ring was 45.5 cm in diameter. One centimeter of water head (obtained from municipal water supply) was maintained throughout each test until the measured infiltration rate was constant for one hour. Soil cores (4 cm in diameter) were collected from the top 30 cm in 10-15 cm increments at three locations immediately after each double-ring infiltration test. One location was at the center of the double-ring (saturated) and two locations were 30 cm away from the outside ring (antecedent moisture content). Samples were weighed immediately after extraction, dried for at least 48 hours at 105°C, and weighed again to determine moisture content. Samples were analyzed for textural classification using the hydrometer method (Gee and Or, 2002).

### RUNOFF VOLUME REDUCTION MODEL

The infiltration-loss model evaluated to predict runoff depths ($D_{\text{runoff}}$) was...
where $D_{\text{runoff}}$ is the measured depth of run-on (total run-on volume/ final inundated area; cm), $D_{\text{infiltration}}$ is the estimated depth of water infiltrated (total infiltration volume/ final inundated area; cm), and $E$ is the error in estimating infiltration (cm). Since it is unlikely that individual lawn characteristics will be considered separately in regulating stormwater runoff for an urban development, data from all lawns and tests were combined and analyzed together. Analysis of the entire data set also allowed accounting for the amount of variability that can exist among urban lawns of similar soil texture.

The ability of Equation (1) to predict runoff depths was assessed using different input values for steady-state infiltration rate, abstraction (defined here as surface storage, vegetation interception, and cumulative total infiltration minus steady-state infiltration during the period prior to steady-state), and final inundated area (the wetted surface area of the lawn as a result of the test). The range of steady-state infiltration rate input values represents a progression from lawn/test specific values to more general values and includes (1) the measured rate for each test, (2) the average measured rate for each lawn, (3) the double-ring rate for each lawn, and (4) the rate for each lawn based on soil texture. Abstraction inputs include (1) a constant abstraction which is the average abstraction over all tests and (2) a lawn-specific abstraction based on a regression with lawn steady-state infiltration rate as the independent variable. Inundated area inputs include (1) the measured final inundated area for each test and (2) the estimated inundated area using a regression in which flow-path length is the independent variable.

**GENERALIZED RUNOFF VOLUME REDUCTION MODEL**

In order to evaluate a range of design storms and continuous precipitation data, a more generalized form of the stormwater runoff volume reduction model is advantageous. Such a model can be used to assess stormwater treatment via infiltration and to enhance existing urban runoff models that consider indirectly connected impervious areas. The generalized stormwater runoff volume reduction model allows for evaluation of different precipitation intensities and durations, ratios of contributing roof area to infiltrating lawn area, and infiltration rates. Run-on depth can be represented as

$$D_{\text{runoff}} = D_{\text{runon}} - D_{\text{infiltration}} - E,$$

where $D_{\text{runon}}$ is the precipitation depth (cm), $A_{\text{roof}}$ is the roof area (m$^2$), and $A_{\text{lawn}}$ is the lawn area (m$^2$). Combining Equations (1) and (2) yields

$$D_{\text{runoff}} = \frac{P(A_{\text{roof}} + A_{\text{lawn}})}{A_{\text{lawn}}} = P\left(1 + \frac{A_{\text{roof}}}{A_{\text{lawn}}}\right),$$

where $P$ is the precipitation depth (cm), $A_{\text{roof}}$ is the roof area (m$^2$), and $A_{\text{lawn}}$ is the lawn area (m$^2$). The abstraction depth for each test was determined as the difference between the steady-state infiltration rate multiplied by the storm duration and the measured infiltration depth. An average abstraction depth for each lawn was then determined. These average abstraction depths varied with steady-state infiltration rate according to:

$$I_a = 0.13I_{\text{ss,ave}} + 0.68 \quad R^2 = 0.49,$$

where $I_a$ is the average abstraction depth for each lawn (cm) and $I_{\text{ss,ave}}$ is the average steady-state infiltration rate for each lawn (cm/hour). Equation (4) indicates that for a noninfiltrating lawn (e.g., highly compacted, $I_{\text{ss,ave}} \approx 0$), some water ($\sim 0.68$ cm) will be lost through surface storage and vegetative interception.

**RESULTS AND DISCUSSION**

**Infiltration Rates**

The average measured steady-state infiltration rates generally increased with increasing run-on rate (Table 2). Other research suggests that infiltration rate increases with increased precipitation rate (Legg et al., 1995; DeBoer and Chu, 2001). DeMaster (2002) observed that steady-state infiltration rates for a run-on rate of 11 cm/hour averaged about 76% of the steady-state infiltration rates for a run-on rate of 22 cm/hour. With the exception of Lawns 1 and 2, the infiltration rates from the double-ring infiltrometer tests were greater than the observed infiltration rates during the stormwater runoff reduction experiments (Table 2). With the exception of Lawn 5, the infiltration rates for the newer (5-10 years old) lawns
were lower than the infiltration rates for the older (50 years) lawns.

**Runoff Volume Reduction Model**

Runoff depths were first predicted (Equation 1) using the measured steady-state infiltration rates \(I_{ss}; \text{cm/hour}\) which were determined by averaging infiltration rates (run-on rate minus runoff rate) over the last 10 min of each test. Infiltration rates were assumed constant throughout the duration of each test and the error term \(E\) in Equation (1) was assumed equal to zero. Although the steady-state infiltration rate does not fully represent decreasing infiltration rate with time, in practice and for design purposes lawn infiltration rate will often be determined from a double-ring infiltration test or based on soil texture, both providing an estimate of the steady-state infiltration rate. Additionally, if the transient infiltration is not otherwise accounted for, the steady-state infiltration rate provides for a conservative estimate of lawn runoff and ultimately the lawn flow-path length required for various degrees of infiltration. The measured final inundated area for each test was used to convert infiltration volume to depth. This depth of water infiltrated \(D_{\text{infiltration}}\) is both lawn and run-on rate specific and therefore represents a “best-estimate” for the range of lawns considered in this study. The root mean squared (RMS) difference between predicted and observed inundation depths was 1.6 cm (Figure 1A). Runoff depths were over-predicted by an average of 1.2 cm. This error likely resulted from the assumption of a constant steady-state infiltration rate throughout the entire test even though the observed infiltration during the early part of the test was higher. This error \(E = 1.2 \text{ cm}\), or abstraction, was applied to all tests which reduced the RMS difference between predicted and observed runoff depths to 1.0 cm (Figure 1B). Measured runoff depths ranged from 0 cm to 16.1 cm (median = 4.9 cm).

When the average measured steady-state infiltration rate for each lawn was used to predict runoff depth with the constant abstraction depth of 1.2 cm \(E = 1.2 \text{ cm}\), the RMS difference between predicted and observed runoff depths increased to 2.0 cm (Figure 1C). Use of the constant abstraction ignores lawn-to-lawn variability. However, using Equation 4 to estimate an average abstraction depth for each lawn did not improve the RMS difference between predicted and observed runoff depths (RMS = 2.0 cm; Figure 1D).

All of the previously discussed estimates for infiltration depth were based on final measured inundated area. In practice, inundated area will not be known \textit{a priori}. Therefore, intermediate and final inundated areas were analyzed with respect to flow-path length using linear, exponential, and power functions. The following power series regression (Figure 2) produced the lowest RMS difference (1.67 m²) between predicted and observed inundated areas and allows for estimation of inundated area given flow-path length (i.e., distance from the downspout):

\[
A = 1.2D^{1.26},
\]

where \(A (\text{m}^2)\) is the inundated area and \(D \text{ (m)}\) is the distance from the downspout. Using Equation (5) to estimate infiltration depth increased the RMS difference to 2.2 cm (Figure 1E).

Lawn infiltration rates are likely to be estimated using double-ring infiltrometer tests or based on soil textural classification. Using the average steady-state double ring infiltration rate for each lawn and Equations (4) and (5) resulted in a RMS difference between predicted and observed runoff depths of 3.3 cm (Figure 1F). Soils in each of the experimental lawns were classified as loams (Table 1). Rawls \textit{et al.} (1982) report hydraulic conductivity of saturated loam soils to be 1.32 cm/hour which is less than the minimum observed steady-state infiltration rate on

<table>
<thead>
<tr>
<th>Lawn</th>
<th>Average Steady-State Infiltration Rate for the Three Experimental Run-On Rates</th>
<th>Double-ring Infiltration Rate (cm/hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.23 m³/hour (cm/hour)</td>
<td>0.68 m³/hour (cm/hour)</td>
</tr>
<tr>
<td>1</td>
<td>0.3</td>
<td>0.6</td>
</tr>
<tr>
<td>2</td>
<td>2.4</td>
<td>3.5</td>
</tr>
<tr>
<td>3</td>
<td>4.5</td>
<td>7.4</td>
</tr>
<tr>
<td>4</td>
<td>5.0</td>
<td>5.3</td>
</tr>
<tr>
<td>5</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>6</td>
<td>1.7</td>
<td>2.1</td>
</tr>
</tbody>
</table>

*a* Lawn 6 was too steep to maintain horizontal ponding level in double-ring.

*Table 2. Steady-State Infiltration Rates for Each Run-On Rate and Double-Ring Infiltration Rates for Each Lawn.*
FIGURE 1. Predicted and Measured Runoff Depths Using (A) Measured Steady-State Infiltration; (B) Measured Steady-State Infiltration and Constant Abstraction (E = 1.22 cm); (C) Average Measured Steady-State Infiltration for Each Lawn and E = 1.22 cm; (D) Average Measured Steady-State Infiltration for Each Lawn and Lawn Specific Abstraction Using Equation (4); (E) Average Measured Steady-State Infiltration for Each Lawn, Lawn Specific Abstraction Using Equation (4), and Estimated Inundated Area Using Equation (5); (F) Double-Ring Infiltration for Each Lawn, Lawn Specific Abstraction Using Equation (4), and Estimated Inundated Area Using Equation (5); (G) Texture-Based Infiltration for Each Lawn, Lawn Specific Abstraction Using Equation (4), and Estimated Inundated Area Using Equation (5).
Lawns 2, 3, 4, and 6; within the range of observed infiltration rates on Lawn 5; and greater than the maximum observed infiltration rate on Lawn 1. Use of hydraulic conductivity as a surrogate for steady-state infiltration combined with Equations (4) and (5) yielded an RMS difference between predicted and observed runoff depths of 5.7 cm (Figure 1G), which is greater than the median runoff depth for all events (median = 4.9 cm).

Estimated Annual Runoff and Stay-On for Madison

Continuous Simulation. Stormwater runoff depths were estimated for a range of infiltration rates using the 1981 precipitation record for Madison. This data record represents a period of precipitation that produces runoff representative of long-term average conditions for use in stormwater management practice design (WDNR, 2004). Hourly precipitation depths were separated into individual storms based on having a minimum six-hour time interval without precipitation preceding and following a storm. Using this separation, there are 86 storms totaling 73.2 cm of rainfall. The minimum, maximum, median, and average storm event precipitation depths are 0.03, 6.6, 0.3, and 0.9 cm, respectively. The hourly rainfall intensity \(i\) for each storm was then determined.

The abstraction for the first storm \(I_{a,\text{max}}\) was determined using Equation (4). Initial abstractions for subsequent events were determined based on the available moisture storage at the end of the previous event and the time between the previous event and the start of the current event. If the precipitation depth was greater than the available storage depth at the beginning of an event, the available storage depth at the end of the event was assumed equal to zero. If precipitation depth was less than the available storage depth at the beginning of an event, the available storage depth at the end of the event was assumed equal to the initial abstraction minus the precipitation. Between storms, soil moisture was assumed to decrease exponentially with time (Linsley et al., 1982). Based on the available soil moisture storage \(I_a\) at the end of the previous event, the time \((\Delta t)\) for the moisture content of a saturated soil \((I_a = 0)\) to decrease such that \(I_a\) was available was determined by

\[
I_a = I_{a,\text{max}} \left(1 - e^{-\frac{\Delta t}{k}}\right),
\]

where \(k\) (hour) is a decay constant chosen such that 90\% of the maximum initial abstraction was available 72 hours after a storm that depleted the abstraction \((k = 31 \text{ hours})\). This time was added to the time between storm events, which allowed the abstraction at the beginning of the event \((I_a)\) to be determined using Equation (6) and \(\Delta t = \text{time between storm events plus the time for the moisture content of a saturated soil to decrease such that } I_a \text{ was available}\).

The lawn infiltration rate was assumed constant throughout the duration of each rainfall event. Runoff was equal to zero as long as cumulative precipitation for each event was less than the initial abstraction. Once cumulative precipitation exceeded the initial abstraction, hourly runoff depths were determined using Equation (3) with \(I_a = 0\). For the hour during which the initial abstraction was satisfied, the precipitation intensity \(i\) was determined by subtracting the initial abstraction from the cumulative precipitation and dividing by one hour. Hourly runoff depths for the 1981 data record were summed to determine the annual runoff depth. This annual runoff depth represents the average runoff depth with respect to the lawn area and was multiplied by \((A_{\text{lawn}}/A_{\text{total}})\) to obtain the average runoff depth with respect to the total area \((A_{\text{roof}} + A_{\text{lawn}})\).

Annual runoff depths are shown in Figure 3A for infiltration rates ranging from 0 to 10 cm/hour and ratios of roof area to lawn area ranging from 0 to 20. When using Figure 3, two limiting cases can be considered. One is the case of a noninfiltrating lawn \((I_a = 0 \text{ cm/hour})\). Runoff depth increases from 46 to 71 cm as the roof-to-lawn ratio increases from 0 to 20. For a roof-to-lawn ratio of 0 (no roof) and a noninfiltrating lawn, an abstraction of 0.68 cm...
(Equation 4) is assumed due to surface storage and interception. For a roof-to-lawn ratio of 20 (mainly roof area) the roof abstraction is assumed to be zero, while the abstraction for the much smaller lawn area is 0.68 cm, resulting in a combined abstraction of 0.03 cm. These differences in abstractions lead to the different runoff depths. The second limiting case is for a roof-to-lawn ratio of 0 (predevelopment case). The model suggests that no runoff is generated on a predevelopment site when infiltration rate exceeds 4.2 cm/hour. Stay-on is defined as the amount of lawn precipitation or run-on lost through infiltration and surface storage within the lawn and was computed by subtracting the runoff depth from the total precipitation depth (Figure 3B).

Limitations of the model are associated with the following assumptions: (1) the inundated area will continue to increase with distance (i.e., flow does not channelize); (2) rooftop abstractions are negligible (this assumption may be reasonable for a pitched roof, but may not apply to a relatively flat surface such as a flat roof or parking lot); (3) lawn infiltration rates are spatially and temporally constant, however these rates can vary throughout a storm and over small distances within a lawn; (4) the lawn abstraction depends only on the infiltration rate. The actual abstraction will vary according to other factors such as soil type, extent of compaction, antecedent soil moisture conditions, and vegetation cover and density.

**Stormwater Runoff Reductions (Stay-On).** In order to assess the usefulness of lawns as a stormwater management practice, postdevelopment stormwater stay-on depths (Figure 3B) were analyzed with respect to predevelopment conditions and with respect to discharging run-on directly onto a subsequent impervious surface (i.e., no controls). The ratio of postdevelopment to predevelopment stay-on (represented by a stay-on coefficient that ranges from 0 to 1) was determined by dividing the stay-on depth for a given infiltration rate and roof-to-lawn ratio by the stay-on depth for the same infiltration rate and roof-to-lawn ratio of 0 (predevelopment case). Except for the case of very high infiltration rates and low roof-to-lawn ratios, storm runoff depths, as expected, increase (stay-on coefficients decrease) as a result of development (Figure 4). As shown in Figure 4, for constant infiltration rate, as the roof-to-lawn ratio increases, less stay-on is maintained (i.e., stay-on coefficient decreases).

The State of Wisconsin’s performance standard, NR 151, is part of Wisconsin’s Administrative Code to regulate stormwater runoff in Wisconsin (WDNR, 2004). New residential and nonresidential developments are required to infiltrate 90 and 60% of the average annual predevelopment infiltration volume. The flow-path lengths required to maintain 90 and 60% of the predevelopment infiltration volume (stay-on coefficients = 0.9 and 0.6) were determined using the roof-to-lawn ratio (Figure 4) and Equation 5 for roof areas ranging from 9.3 to 92.9 m², and for infiltration rates ranging from 0 to 20 cm/hour (Figure 5A and 5B).

The increase in stay-on when rooftop runoff is routed onto a lawn (i.e., lawn as a stormwater management practice) with respect to stay-on...
when rooftop runoff is routed directly to a storm sewer (i.e., no stormwater management practice) was determined as

\[ SIF = \frac{D_{\text{stayon}}(I, R_{R/L}) (1 + R_{R/L}) - D_{\text{stayon}}(I, 0)}{D_{\text{stayon}}(I, 0)} \]  

where \( D_{\text{stayon}}(I, R_{R/L}) \) is the stay-on depth for a given infiltration rate \( I \) and roof-to-lawn ratio \( R_{R/L} \) (Figure 6). As an example, for the case of a roof-to-lawn ratio of 4 (e.g., 80% impervious, 20% pervious) and a lawn infiltration rate of 5 cm/hour, the stay-on depth \( D_{\text{stayon}}(5 \text{ cm/hour}, 4) \) is approximately 63.2 cm (Figure 3B) which is multiplied by \( 1 + R_{R/L} = 5 \) to obtain the equivalent stay-on depth over just the lawn area. \( D_{\text{stayon}}(5 \text{ cm/hour}, 0) \) is 73.2 cm (Figure 3B) and is the stay-on depth for the lawn assuming there is no run-on to the lawn, only direct precipitation, and rooftop runoff is routed directly to a storm sewer. The Stay-on Increase Factor (SIF) (Equation 7) is then 3.3, or approximately three times more annual stay-on is possible when rooftop runoff is directed onto the lawn rather than directly to the storm sewer.

SUMMARY AND CONCLUSIONS

Understanding the role of residential lawns in hydrologically disconnecting impervious surfaces is necessary for management and prediction of urban
stormwater runoff. We conducted 52 runoff volume reduction tests on residential lawns in Madison. Rooftop runoff was directed onto the lawns via a downspout and allowed to flow freely across the lawn. Measured infiltration rates increased as run-on rate increased. Inundated areas were represented by a power function with flow-path length as the independent variable. An infiltration-loss model that requires inputs of steady-state infiltration rate, abstraction that accounts for interception and the infiltration rate which is greater than the steady-state infiltration rate, and inundated area was evaluated using experimental data. As input parameter values progressed from lawn-test specific to the more general case, the RMS difference between predicted and observed runoff depths increased and exceeded the median measured runoff depth when the infiltration rate was determined from soil textural classification.

A generalized form of the stormwater runoff reduction model that requires inputs of precipitation intensity and duration, roof-to-lawn ratio, and steady-state infiltration rate is presented. The model was used to estimate annual lawn runoff and stay-on depths for Madison, Wisconsin by utilizing a precipitation record that produces stormwater runoff representative of long-term average conditions for the area. Runoff depths increased as the roof-to-lawn ratio increased and as the lawn infiltration rate decreased. Model results suggest that under predevelopment conditions, there is no annual runoff generation for lawn infiltration rates >4.2 cm/hour. The lawn flow-path lengths required to maintain 90 and 60% of predevelopment annual infiltration were estimated using the model and the power series regression for inundated area.

The stormwater runoff reduction model can be used to determine the viability of urban lawns as a stormwater management practice and has potential to be implemented into urban runoff models that consider indirect area runoff. Based on measured double-ring infiltration rates and the maximum lawn length evaluated in our study, one of the six lawns would meet the Wisconsin performance standard of infiltrating 90% of predevelopment annual infiltration volume for roof areas of ≤9.3 m², while two lawns would meet the standard for roof areas ≤55.7 m². In its current form, the model is not intended for evaluating rain gardens, infiltration basins, and other devices that also use storage to decrease stormwater runoff. However, additional storage abstractions could be incorporated.

FIGURE 6. Stay-On Increase Factor (SIF; Equation 7) for Infiltration Rates Ranging From 0 to 20 cm/hour and Roof-to-Lawn Ratios Ranging From 0 to 20.

ACKNOWLEDGMENTS

Funding for this research was provided by the Wisconsin Department of Natural Resources. The authors thank Kenneth Potter (University of Wisconsin, Madison), Judy Horwatich (USGS), and Roger Bannerman (WDNR) for their valuable input and also the anonymous reviewers who provided comments on this manuscript.

LITERATURE CITED


