EQUIVALENT IMPERVIOUSNESS FOR GRASS BUFFERS

By

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Over the years, many storm water best management practices (BMPs) have been developed to reduce the runoff volume and pollutant concentrations. In general, the concept of BMP takes the four following steps to dispose on-site storm water (USWDCM 2001): (1) to reduce runoff peaks and volumes by minimizing directly connected impervious areas (MDCIA), (2) to provide water quality capture volume (WQCV) for an on-site retention process, (3) to stabilize downstream banks and stream beds along the waterways, and (4) to implement BMPs for special needs for industrial and commercial developments within the tributary area. The principle behind MDCIA is twofold: to reduce impervious areas and to direct runoff from impervious surfaces over grassy areas to slow down runoff and promote soil infiltration. Draining paved areas onto porous areas can reduce runoff volumes, rates, pollutants, and cost for drainage infrastructure. Several approaches are used to reduce the effective imperviousness of a development site, including (1) the reduction of paved area, (2) an increase of porous pavement, (3) filtering runoff by grass buffers, and (4) infiltration by porous cascading planes.

Photo 1 Cascading Filtering System Along Highway

Under the concept of BMPs, creative site layout can reduce the paved areas. For example, the use of modular block porous pavement or reinforced turf in low-traffic zones such as parking areas and infrequently used service drives such as fire lanes can significantly reduce the site imperviousness. This practice can reduce the sizes of the downstream storm sewers and detention basins. BMP design methods are sensitive to the imperviousness percentage. For instance, the rational volumetric method or so called modified Federal Highways Administration method (FAA 1970, Guo 1999) for sizing small detention and retention volumes is highly dependent on the watershed imperviousness. Obviously, the area-weighted method has become inadequate for BMP designs. This paper applies kinematic wave theory to quantify the infiltration benefits. The *cascading-plane model* was developed to represent the physical layout of landscaping infiltrating beds or grass buffers. The result from the cascading-plane model was then compared with the *central-channel model* by which the runoff flows were separately generated by the pervious and impervious planes. Using the runoff volumes as the basis, this study produces a family curves to calculate the equivalent imperviousness for a specified MDCIA setting.

CASCADING-PLANE MODEL

A cascading landscape is to spread the runoff flow generated from the upper impervious plane onto the porous plane for additional infiltration loss. In this study, a model of two cascading planes shown in Figure 1a is derived to simulate the overland flow in series. The upstream plane is set to be 100% paved and the downstream plane is set to be 100% unpaved. Both planes are under the same rainfall event. Applying kinematic wave to the unit-width overland flow, the flow on a plane is described as (Woolhiser and Liggett in 1967; Morgali and Linseley in 1965; Guo 1998):

$$\frac{[I_e(t)+I_e(t+t)]}{2}X-\frac{[q(t)+q(t+\Delta t)]}{2}=\frac{V(t+\Delta t)-V(t)}{\Delta t} \tag{1}$$

$$I_e=I-f+\frac{q_i}{X} \tag{2}$$

$$V=Xd \tag{3}$$

$$q=\frac{1.49}{n}d^{\frac{5}{3}}\sqrt{S_o} \tag{4}$$

in which I_e= excess rainfall intensity in L/T, I = rainfall intensity in L/T, q = unit-width flow rate in L^2/T, V= unit-width storage volume in reach in L^2, *f* = infiltration rate in L/T, q_i = unit-width inflow from upper paved plane in L^2/T, X = length of reach in L, d = flow depth in L, n = Manning's roughness coefficient, S_o = slope for reach, t = time, and Δt = time interval. The values of all variables at time t serve as the initial condition. At time, t+Δt, the only unknown in Eq 1 is the flow depth, d, that can be solved simultaneously using Eq's.1 through 4.

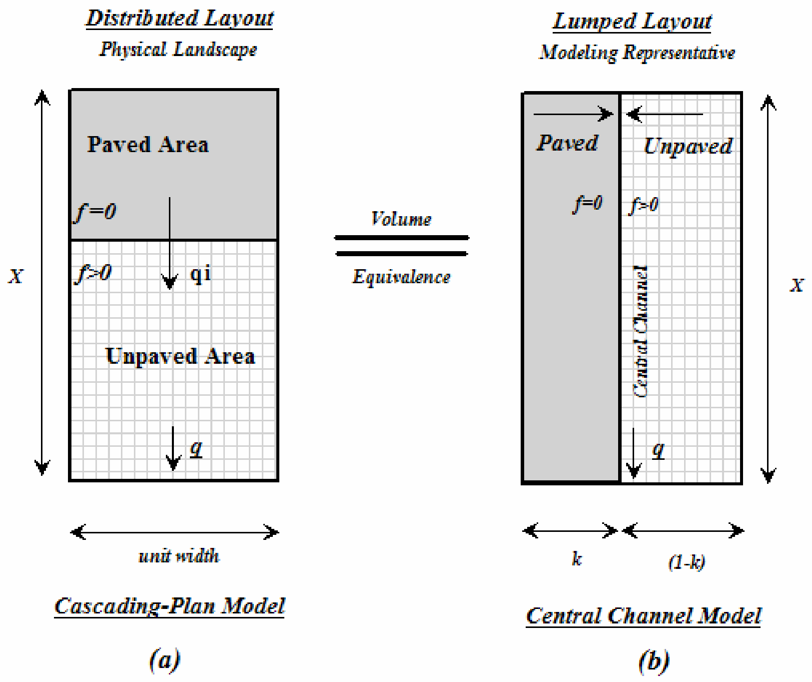

Figure 1 Illustration of Cascading and Channel Models

To apply Eq's 1 through 4 to the upper impervious plane, Eq. 2 has q_i = 0 and *f* =0 for all times. For the lower pervious plane, the inflow, q_i, is defined by the inflow hydrograph generated from the upper impervious plane. Having calculated the overland flow hydrograph at the outlet of the lower porous plane, the total runoff volume produced by this two cascading planes is calculated by (Guo 2004):

$$V_T=\sum_{t=0}^{t=T_b}q(t)\Delta t \tag{5}$$

in which V_T = total unit-width runoff volume in L^2, and T_b = base time of runoff hydrograph.

CENTRAL-CHANNEL MODEL

The area weighted method implies that an urban watershed could be divided into impervious and porous planes, and both planes could produce runoff flows separately and independently. This concept has been incorporated into SWMM5 (Rossman 2005) using a central channel to collect the runoff generated from an urban area. As illustrated in Figure 1b, the watershed is divided into left-paved plane and right porous-plane. Both planes are under the same rainfall, but they produce overland flows separately. At the outfall point, the resultant hydrograph is the sum of these two overland flows. As illustrated in Figure 1b, the flow length of the central-channel model is set to be equal to the total length of the cascading-plane model. The unit width is then divided into the left-paved and right-porous planes as:

$$W_i + W_p = 1 \tag{6}$$

where W_i = left-paved width, and W_p = right-porous width. Mathematically, the value of W_i is equivalent to the areal imperviousness percentage as:

$$W_i = k \tag{7}$$

$$W_p = 1 - k \tag{8}$$

where k = equivalent imperviousness percentage. In this study, Eqs 1 through 5 are separately applied to the left-paved and right-porous planes to generate overland flows. Knowing that the kinematic wave flow volume is linear to the plane width, the total runoff volume produced by the left-paved and right-porous planes is summed as:

$$V_T = W_i V_i + W_p V_p \tag{9}$$

in which V_i = left-paved runoff volume, V_P = right-porous runoff volume. Substituting Eq's 7 and 8 into Eq 9 yields:

$$k = \frac{V_T - V_P}{V_i - V_P} \tag{10}$$

Both the cascading-plane and central-channel models must produce the same runoff volume for a specified hydrologic condition. As a result, the equivalent imperviousness, k, can be determined by Eq's 7 and 10.

VOLUME-BASED IMPERVIOUSNESS CURVES

This study begins with the selected parametric values to test the numerical models. The final conclusion is produced by the normalized parameters to remove the scale effect. For instance, the numerical model was first tested for a uniform rainfall distribution at 2.53 inch/hr (64.87 mm/hr). The ratio, f/I, was set to be 0.50. The cascading system has an upper 200-foot (62 m) paved plane that drains onto on the lower 200-foot porous plane on a slope of 1.0%. As recommended (USWDCM, 2001), the Manning's n of 0.016 is applied to the upper paved plane and 0.05 is applied to the lower porous plane. Applying the same parameters to the central-channel model, the overland flows were separately produced by the left-paved and right-porous planes. These three hydrographs are plotted in Figure 2. The cascading system produced a unit-width runoff volume of 56.1 ft^2 (5.31 m^2) while the left-paved plane generated 84.1 ft^2 (7.96 m^2) and the right- pervious plane generated 31.4 ft^2 (2.97 m^2). Substituting these volumes into Eq 10, the equivalent imperviousness is calculated to be 0.46 for this case. In this study, a further investigation on the non-uniform rainfall distribution was also conducted using the 1-hr 100-yr rainfall distribution recommended for the Denver area in the State of Colorado (USWDCM 2001). Such a rainfall distribution is very similar to the 1-hour rainfall centered in the SCS 24-hour Type 2 curve. Figure 3 presents the results produced by the nonuniform rainfall distribution. The equivalent imperviousness using the hydrographs in Figure 3 was found to be 0.45 for f/I=0.50. As expected, the equivalent imperviousness is not sensitive to rainfall distribution because the runoff volume under a runoff hydrograph is mainly determined by the rainfall excess, not its time distribution.

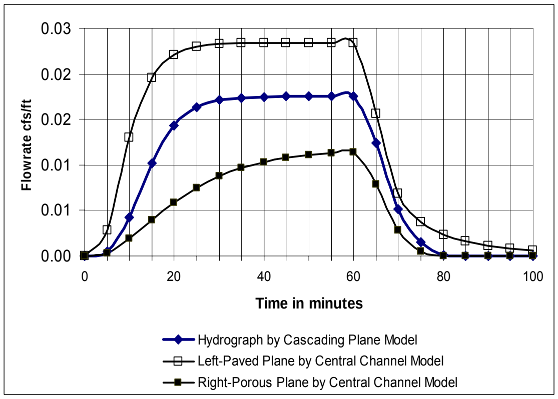

Figure 2 Hydrographs by Uniform Rainfall

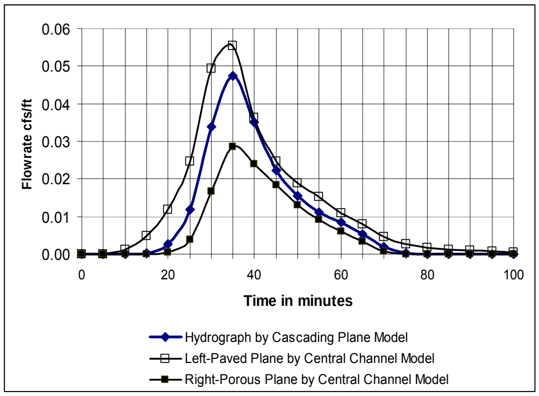

Figure 3 Hydrographs by Non-uniform Rainfall

With the aforementioned, a systematic approach was engaged to investigate a range of the design parameters. For instance, the impervious to previous area ratios, A_r, ranging from 0.25, 0.5, 1.0, 1.5, 2.0, to 3.0 and infiltration rate to rainfall intensity ratios, f/I. ranging from 0.25, 0.50, 0.75, to 1.0. The equivalent imperviousness ratios for various combinations are plotted in Figure 4. The normalized family curves are identified by the parameter of f/I. All curves vary from zero when the imperviousness area vanishes to unity when A_r becomes infinity or the imperviousness area becomes very large. At A_r = 1.0, the conventional area-weighted method defines the equivalent imperviousness to be 0.50. This study found that the equivalent imperviousness varies from 38.2% to 48.8% with respect to f/I ratio. As expected, the higher f/I ratio, the lower equivalent imperviousness. This study reveals that the conventional area-weighted method sets the limit for these family curves. Figure 4 implies that any cascading landscaping arrangement does increase the infiltrating benefits and can reduce the equivalent impervious ratio. Using Figure 4 as the data base, a non-dimensional regression equation was derived as:

$$k = 0.6197 A_r^{0.7065} e^{-(0.2881\frac{f}{I}+0.1759A_r)} \qquad \text{with } r^2 = 99.37 \qquad (11)$$

in which r^2 = correlation coefficient.

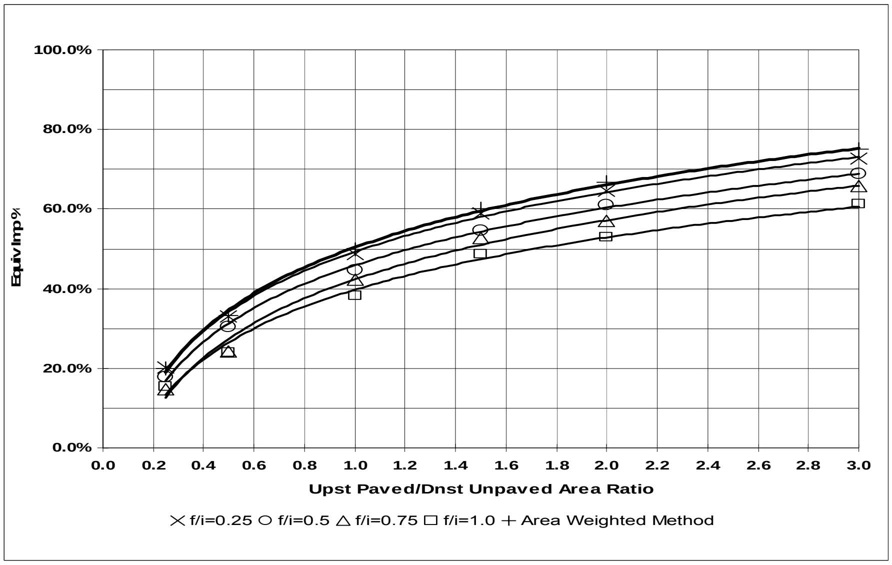

Figure 4 Equivalent Imperviousness for Various Conditions

CONCLUSIONS

Under the concept of storm water BMPs, a drainage system needs to cope with the full spectrum of runoff events. For instance, the natural stream needs to pass the major event, the sewer system must be adequate for the minor event, and the on-site BMPs have to accommodate more frequent micro events. Both lumped and distributed methods are jointly used to design a storm water quality and quantity control system. Hydrologic methods were developed with assumptions and limitations. It is important to establish the basis of consistency among methods. Otherwise, the entire system will fail to maintain the same risk level selected for the design (Guo 2002).

The latest developments in storm water BMPs demand the modeling technique to trace the foot prints of the runoff flow. Watershed imperviousness is a key parameter in urban hydrology. This study uses a cascading-plane model to represent the physical landscaping layout. Such a model was then compared with the central-channel model in which the runoff was separately generated by the pervious and impervious planes. Design curves were produced in this study to predict the imperviousness percentages for the cascading landscaping layouts. The conventional area-weighted method set the limits for these family curves. As expected, these curves vary between zero and unity, according to the infiltration to rainfall intensity ratio and the impervious to pervious area ratio. The higher the f/i ratio is, the lower the imperviousness percentage is.

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