Guo, James C.Y. Guo, Blackler, E G, Earles, A, and MacKenzie, K (2010) "*Catchment Effective Imperviousness for Stormwater On-site Conveyance and Storage Designs*" accepted for publication on ASCE J. of Engineering Hydrology,(Feb, 2010).

Guo, James C.Y. (2008) *Runoff Volume-Based Imperviousness Developed for Storm Water BMP Designs*", ASCE J. of Irrigation and Drainage Engineering, Vol 134, No 2, April.

INCENTIVE INDEX FOR STORMWATER LOW IMPACT DESIGNS

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Abstract: In practice, the challenge of storm water low-impact-development (LID) design is often related to how to quantify the effectiveness of a LID layout. In this study, the watershed imperviousness was chosen as a basis to evaluate the performances of various LID designs. Often, LID designs apply cascading planes to drain the runoff flow from the upstream impervious area onto the downstream pervious area. In this study, the conventional area-weighting method is revised with a pavement-area-reduction factor (PARF) to produce the effective imperviousness. PARF is employed as an incentive index to quantify the on-site runoff volume reduction and cost-savings from down-sized sewers. Two sets of PARF are derived; conveyance-based and storage-based LID designs. The conveyance-based LID approach is to drain runoff flows on various porous surfaces while the storage-based LID approach is to temporarily store runoff flows in an on-site basin. For a specified LID layout, the PARF provides a consistent basis to translate the infiltration and storage effects into the reduction on the area-weighted imperviousness. The non-dimensional governing equation derived in this paper indicates that the PARF depends on the ratio of the soil infiltration rate to rainfall intensity, the ratio of receiving pervious area to upstream impervious area, and the on-site stormwater storage capacity. The PARF serves as a basis for the engineers, planners and/or developers to select a LID design and also for regulatory agencies to assess meritorious credits for cost savings.
Key words: Stormwater, LID, BMP, Urban Catchment, Imperviousness, Runoff

INTRODUCTION

The hydrologic response of a catchment during a storm event is characterized by the catchment's shape, slope, area, and percent imperviousness (Booth and Jackson 1997). Many studies indicate that the percent imperviousness of a catchment is an important and sensitive parameter in analyzing the effects of urbanization of stormwater runoff (Kuichling 1889, Arnold and Gibbons 1996). In current practice, the catchment imperviousness is determined by the area-weighted method, which implies that the impervious and pervious portions of the catchment are drained through two independent flow paths to the watershed outlet. For instance, the Rational Method was developed to relate the peak runoff to the impervious area in the catchment using the area-weighted runoff coefficient (Lee and Heaney 2005). Recently, designers are considering low impact development (LID) practices that route stormwater flows through vegetated beds and landscaping areas for additional infiltration losses. With a LID layout, stormwater generation is flow path dependent since impervious-area runoff is routed to pervious areas. With the increased infiltration losses from the cascading flow process, the catchment's effective imperviousness percent must be determined by weighting the runoff volumes generated from the pervious and impervious areas (Guo 2008). Effective imperviousness represents the on-site runoff volume reduction due to the additional infiltration losses; it is also an important consideration for stream stability and quality of aquatic habitat (Booth and Jackson 1997). Separating connected impervious areas by a pervious area is not a recent addition to drainage designs. Minimization of directly connected impervious areas (MDCIA) can significantly reduce peak flow rates, runoff volumes, and the potential negative effects on urban stormwater quality and quantity (Lee and Heaney 2003). Although a LID layout may incur a higher cost for additional on-site infiltrating facilities, it can, in return, decrease the peak flood flows and reduce the sizes of the downstream drainage facilities. When facing the selection among various LID designs, the engineer needs simple guide to quantify the LID effectiveness on runoff volume reduction. In this study, the effective imperviousness is chosen as the incentive index for comparison and selection among various LID designs.

In this study, the Stormwater Management Model, Version 5 (SWMM5) supported by the United States Environmental Protection Agency (USEPA) is adopted to simulate the runoff flow routing from the upstream impervious area over the downstream pervious area (Rossman 2009). This internal routing scheme in SWMM5 allows the user to model the cascading flows through the catchment. The calculated runoff volumes from the pervious and impervious areas can serve as a basis to consistently determine the effective imperviousness percents for various LID designs in an urban watershed. In general, LID designs are classified into two types: porous pavements on the flow paths and infiltrating basins at the low points. Both are intended to reduce the developed runoff volume by the infiltration through the sub-base soil-media. The non-dimensional equations derived in this paper indicate that LID effectiveness, in terms of storm runoff volume reduction, depends on the ratio of soil infiltration rate to rainfall intensity, the ratio of pervious receiving area to upstream impervious area, and on-site stormwater storage capacity. Two sets of design charts are separately produced for conveyance-based and storage-based LID designs. This simple method converts the area-weighted imperviousness to volume-weighted effective imperviousness for the specified design parameters. Effective imperviousness can serve as a basis for the engineer, planner and/or land developer to select a LID design and also for the regulatory agency to evaluate volume reduction and potential credits identified in terms of reductions in storage requirements for the WQCV, minor and/or major events.

CASCADING FLOW MODEL FOR EFFECTIVE IMPERVIOUSNESS

Unlike many conventional stormwater modeling techniques, SWMM5 allows for more complex evaluation of flow paths through the on-site LID layout. Conceptually, an urban catchment can generally be divided into four various land-use areas that drain to the common outfall point as shown in Figure 1.

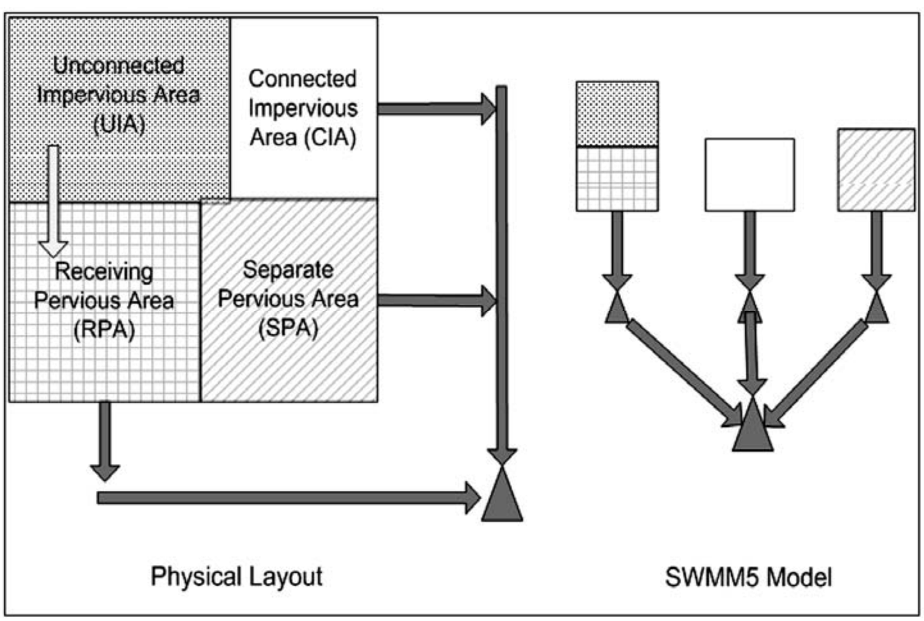

Figure 1 Four-Component Land-Use Model

The 4-component land use model consists of 3 draining flow paths, including: Directly Connected Impervious Area (DCIA) draining onto the street, Unconnected Impervious Area (UIA) draining onto Receiving Pervious Area (RPA), and Separate Pervious Area (SPA) draining to the street (UDFCD 2010). In this study, UIA is also referred to as an effective impervious area that is the tributary area to a porous area (Woo and Burian 2009). As reported (Government of Western Australia, 2005), the purpose of minimizing effective imperviousness is to reduce the transportation of pollutants to receiving water bodies and to retain the post development hydrology as close as possible to the pre-development hydrology. A LID layout is to route runoff generated from the UIA onto the RPA to increase infiltration losses. To model the stormwater flows through a LID site, it is necessary to link flows through their physical flow paths to take into consideration additional depression storage and infiltration losses over the pervious landscape. One of the more recent developments in SWMM5 allows users to model overland flow draining from the upper impervious areas onto the downstream pervious area. This feature is accomplished using two parameters, including *subarea-routing options* and *percent routed* as catchment attributes in SWMM5. There are three options for sub-area routing, including: (1) *conventional outlet* to collect two independent flow paths from pervious and impervious areas, (2) *impervious outlet* to drain the overland flow from the pervious area onto the impervious area, and (3) *pervious outlet* to route the overland flow from the impervious area onto pervious area.

As illustrated in Figure 1, the site has three independent flow paths, including the cascading flow path from UIA to RPA, and two directly connected flow paths for DCIA and SPA. The tributary areas for the cascading plane and the entire site are calculated as:

$$A_C = A_{UIA} + A_{RPA} \tag{1}$$

$$A_T = A_C + A_{DCIA} + A_{SPA} \tag{2}$$

where A_C = area for cascading plane, A_{UIA}=unconnected impervious area, A_{RPA} =receiving pervious area, A_T = site area, A_{DCIA} =directly connected impervious area, and A_{SPA} =separate pervious area. Using the conventional area-weighted method, the lumped model for this catchment would have an imperviousness percent as (Woo and Burian 2009):

$$I_{SA} = \frac{A_{DCIA} + A_{UIA}}{A_T} \tag{3}$$

where I_{SA} = conventional site imperviousness. Eq (3) ignores the additional infiltration loss over the cascading plane. As a result, Eq (3) fails to evaluate the effectiveness of a LID design and provides no incentive to encourage stormwater best management practices (BMP's). In this study, it is recommended that a discrete model shown in Figure 1 be developed using the SWMM5 computer model to collect the runoff flows from three paths draining to the outlet point. This discrete flow model offers a volume-weighting basis to compute the effective imperviousness for the cascading plane. As a result, the site imperviousness percent, with an incentive index, can be weighted as:

$$I_{SE} = \frac{I_E A_C + A_{DCIA}}{A_T} \tag{4}$$

where I_{SE} = site effective imperviousness percent, I_E = effective imperviousness percent for the cascading plane. As indicated in Eq (4), the incentive index depends on the effective imperviousness along the cascading flow path. In practice, the land use map is readily available for calculating the area-weighted imperviousness at the project site (Chabaeva et al. 2009). By definition, the area-weighted imperviousness for the cascading plane is calculated as:

$$I_A = \frac{A_{UIA}}{A_C} \times 100 = \frac{100}{1 + \frac{A_{RPA}}{A_{UIA}}} = \frac{100}{1 + A_r} \quad (5)$$

where I_A = area-weighted imperviousness percent for cascading plane and A_r = ratio of downstream A_{RPA} to upstream A_{UIA}. To be convenient, the approach developed in this study is to relate the effective imperviousness for the cascading plane to its area-weighted imperviousness by a reduction factor as:

$$I_E = K I_A \quad (6)$$

where K = pavement area reduction factor (PARF). As aforementioned, the runoff volume reduction can be achieved using conveyance-based LID or storage-based LID designs. In this study, two sets of PARF are derived using the non-dimensional approach that will convert the area-weighted imperviousness into its effective imperviousness for the specified cascading flow condition. The non-dimensional approach can significantly reduce the number of computer test runs when generating the database for development of design charts (Blackler and Guo 2009).

CONVEYANCE-BASED EFFECTIVE IMPERVIOUSNESS

A conveyance-based cascading plane is designed to use porous pavements, grass swales, vegetated buffers, infiltrating beds, or landscaping filters to receive the stormwater from roof drains or/and impervious areas (UDFCD 1999). Under the cascading effect, the effective imperviousness is weighted by the runoff volumes as (Guo and Cheng 2008):

$$V_C = (100 - I_E) V_C^{\ 0} + I_E V_C^{\ 100} \quad (7)$$

$$V_C^{\ 100} = P A_C \quad (8)$$

$$V_C^{\ 0} = (P - F) A_C \quad (9)$$

where V_C = runoff volume produced from cascading plane as designed *[L^3]*, $V_C^{\ 0}$= runoff volume produced from cascading plane as if it is all pervious *[L^3]*, $V_C^{\ 100}$ =runoff volume produced from cascading plane as if it is all impervious *[L^3]*, *P* = design rainfall depth *[L]*, and *F* = infiltration loss *[L]* on pervious area. Re-arranging Eq (7) yields:

$$I_E = \frac{V_C - V_C^{\ 0}}{V_C^{\ 100} - V_C^{\ 0}} \times 100 \quad (10)$$

Eq's (7), (8), and (9) imply that there exists a relationship among the four variables as:

$$K = Fct(\frac{F}{P}, A_r) = Fct(\frac{f}{i}, A_r) \quad (11)$$

In which *f* = infiltration rate on pervious surface *[L/t]*, and *i* = average rainfall intensity [L/t], and *Fct* is the expression of the function relationship between the dependent and independent variables. Eq (11) indicates that a conveyance-based PARF is directly related to: (1) ratio of infiltration rate to rainfall intensity, and (2) ratio of RPA to UIA. In this study, Eq 11 was tested using Denver's 2-hr design rainfall distribution (UDFCD 2001). This 2-hr rainfall distribution is similar to the central, most intense portion of the SCS Type II 24-hr rainfall curve (Guo and Harrigan 2009). To be practical, the ratio of f/i was set to vary from 0.5 to 2.0 and the range of A_r is set to cover the area imperviousness from zero to 100%. The values for PARF are solved by numerical iterations for various cascading flow conditions modeled by SWMM5. The conveyance-based PARF derived in this study is presented in Figure 2. It can be seen that the conveyance-based PARF varies between 0.3 for low imperviousness and 1.0 for high imperviousness. This implies that the cascading LID layout cannot completely compensate the increased runoff volume due to the catchment development.

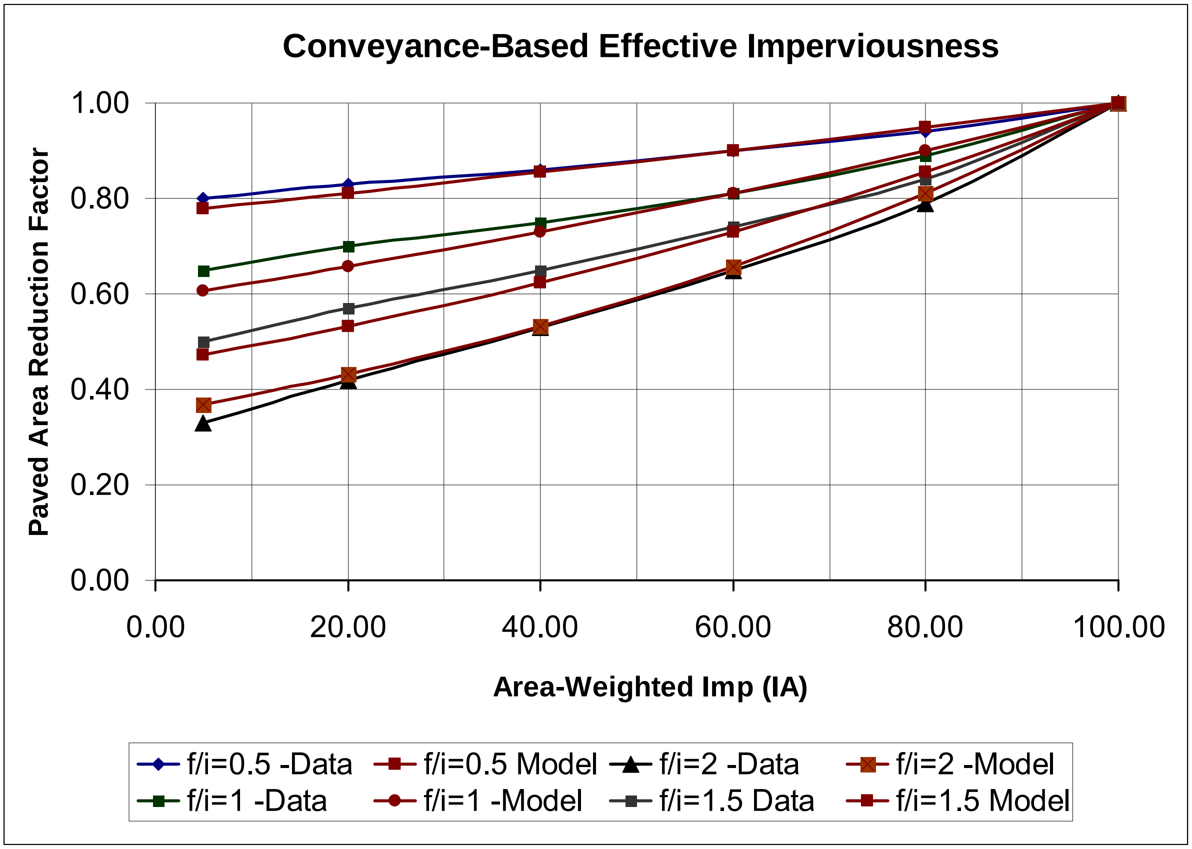

Figure 2 Conveyance-based Pavement Area Reduction Factor

For convenience, a regression model was derived from the data base generated from the SWMM5. The regression equation was formulated to have K=1 at
I_A =100% as:

$$K = e^{\left[-0.0052\,(100-I_A)\frac{f}{i}\right]} \qquad (12)$$

Although all test parameters were selected from the Denver hydrologic region, the non-dimensional form should be applicable to other regions when using localized f/i and A_r ratios.

STORAGE-BASED EFFECTIVE IMPERVIOUSNESS

A storage-based LID layout is designed to employ rain gardens, extended dry detention basins, constructed wetland basins, and infiltrating basins (Guo and Hughes 2001). Often an on-site storage basin is sized for a storm water quality control volume (WQCV) that is equivalent to the 3- to 4-month rainfall event depth (Roesner et al. 1996). The WQCV is determined by the catchment imperviousness and the local rainfall characteristics. WQCV is derived using the concept of diminishing return on the runoff volume capture curve between the WQCV and the effectiveness of the storm water quality enhancement (Guo and Urbonas 1996). Based on the long-term continuous rainfall and runoff analyses conducted for several major metropolitan areas across the United States, an empirical equation was derived for calculating the WQCV (ASCE WEF Manual Practice 23, 1998):

$$\frac{WQCV}{P_m} = aC + b \tag{13}$$

$$C = 0.91\,I^3 - 1.19\,I^2 + 0.78\,I \tag{14}$$

In which WQCV = water quality capture volume per catchment area [L], C= runoff coefficient, I = imperviousness of the tributary area, 0≤ I ≤1.0, P_m = local average event rainfall depth [L] (Driscoll et al. 1989, EPA Report 1983), and a and b are empirical coefficients, as listed in Table 1, that depend on the basin's drain time selected for a target sediment removal rate (Guo and Urbonas 1996).

Drain Time	Coefficient a	Coefficient b	Correlation Coefficient
hours	A	b	R^2
12-hr	1.360	-0.034	0.80
24-hr	1.619	-0.027	0.93
48-hr	1.983	-0.021	0.84

Table 1 Coefficients for WQCV

In this study, the effects of the WQCV storage are factored into the calculation of the effective imperviousness for a LID layout. An approach similar to the derivation of conveyance-based PARF is derived to account for the WQCV stored at an on-site basin. With an on-site WQCV basin, Eq (7) is revised to include the on-site WQCV. After the normalization, the effective imperviousness ratio for a storage-based BMP is derived as:

$$V_C = (1 - I_E)V_C^{\,0} + I_E V_C^{\,100} - WQCV \tag{15}$$

Eq (12) implies that the functional relationship exists among three parameters as:

$$K = Fct(\frac{F}{P}, A_r, \frac{WQCV}{P}) = Fct(\frac{f}{i}, A_r, \frac{WQCV}{P}) \tag{16}$$

Eq (16) indicates that a storage-based PARF is related to: (1) the ratio of infiltration rate to rainfall intensity, (2) the area ratio between A_{RPA} and A_{UIA}, and (3) the on-site WQCV. As indicated in Eq (13), WQCV depends on the local event-average rainfall depth. For this study, the City of Denver, Colorado was chosen as the example to develop the design charts for storage-based PARF. The average event rainfall depth for the City of Denver is 0.41 inch (Driscoll et al. 1989). As recommended, rain gardens or landscaping WQCV basins are designed to have a drain time of 12 hours (UDFCD 1999b). In this study, the WQCV for the assigned tributary area imperviousness is determined using Eq's (13) and (14). To operate SWMM5, the WQCV is then modeled as an additional surface depression loss, rather than a complicated reservoir routing. SWMM5 is a useful tool to warrant the conservation of runoff volumes during the computation. A design chart as shown in Figure 3 was derived for the storage-based PARF using Denver's WQCV. It shows that when the ratio, *f/i,* exceeds 1.2, the cascading plane with a WQCV basin can infiltrate the entire surface runoff volume from the cascading plane. Since the WQCV is localized, a similar approach can be repeated using the local WQCV with the aid of Eq's (13) and (14).

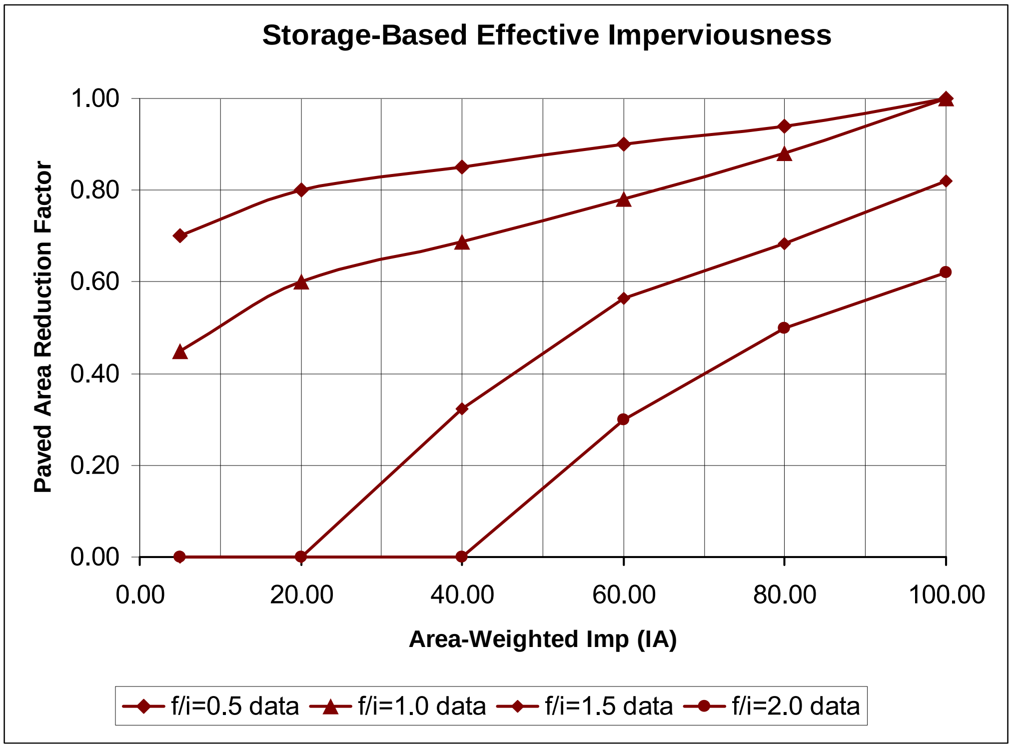

Figure 3 Storage-Based Pavement Area Reduction Factor

DESIGN EXAMPLES

The purpose of PARF is to establish a basis for the engineer to quantitatively evaluate various conveyance- or storage-based LID designs without performing the detailed modeling. In this study, the development of an 80 by 80-m site in Figure 4 is investigated.

For the purpose of runoff volume reduction, the site is to be developed with the front roof downspout draining onto the porous parking lot in front of the building, and the rear roof downspout is directly connected to an inlet. The alternatives for this project is with and without a WQCV basin in the landscaping grassed areas. From the land-use map and grading plan, the three flow paths can be identified as shown in Figure 5, including two sewer lines and one grass swale draining to the basin. For this case, the area components are: A_{DCIA}=1200 m^2, A_{UIA}=2700 m^2, A_{RPA} = 2000 m^2, and A_{SPA} =500 m^2. The ratio of rainfall intensity to infiltration rate is: f/i = 1.3 for this case. Without the use of conveyance-based PARF, the conventional area-weighted method, Eq (3), will define the site area-weighted imperviousness percent as:

$$I_{SA} = \frac{3900}{6400} \times 100 = 61\%$$

As discussed before, the conventional method does not include any incentive for a LID layout. According to Eq's (4), (12), and (3), the effective percent imperviousness for the cascading plane in this case is calculated as:

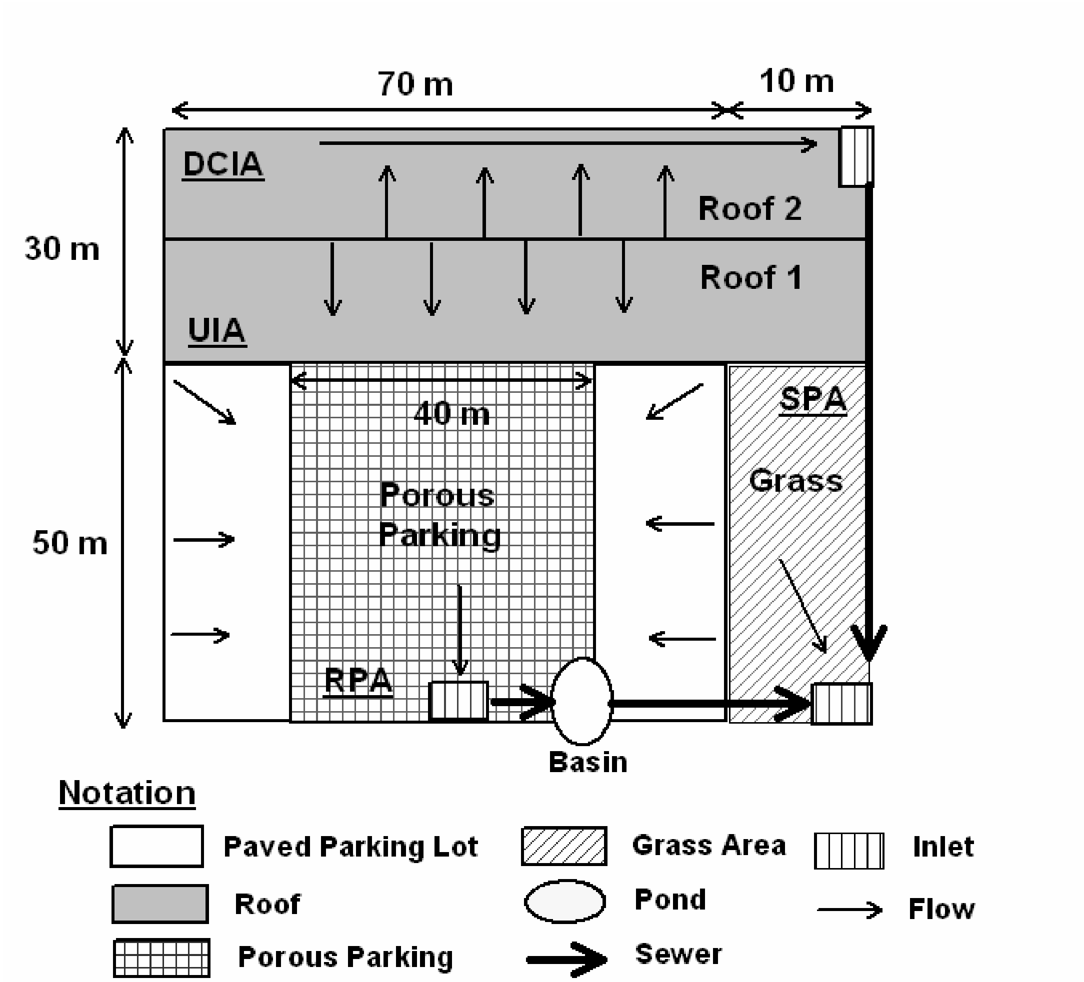

Figure 4 Example of LID Site

$$I_A = \frac{100}{1+\frac{2000}{2700}} = 57\%$$ for the cascading plane

$$K = e^{[0.0052(100-57)\frac{1}{1.3}]} = 0.74$$ (or read Figure 2 with *f/i* = 1.3)

$$I_E = 0.74 \times 57\% = 42.7\%$$

Using Eq (3), the site imperviousness percent is calculated as:

$$I_{SE} = \frac{42.7\% \times 4700 + 1200}{6400} = 50\%$$

For this case, the difference between I_{SA} and I_{SE}, or 11% in site difference, is the incentive for the LID stormwater management. Furthermore, a WQCV basin with a drain time of 12 hours can be added to the cascading plane. As determined, the cascading plane has an area-imperviousness percent of 57%, substituting $I=0.57$ to Eq (14) to find the runoff coefficient, C, as:

$C = 0.91\,(0.57)^3 - 1.19\,(0.57)^2 + 0.78 \times 0.57 = 0.23$ for the cascading plane

$\frac{WQCV}{0.41} = 1.36 \times 0.23 - 0.034 = 0.0.27$ or WQCV=0.11 inch or 2.90 mm per watershed.

This WQCV basin will store an additional runoff depth of 2.90 mm. With f/i = 1.3 and I_A =57% , the storage-based PARF is 0.61 from Figure 3. The effective imperviousness percent for the cascading plane is calculated as:

$$I_E = 0.61 \times 57\% = 35.0\%$$

The effective imperviousness percent for the site is:

$$I_{SE} = \frac{35.0\% \times 4700 + 1200}{6400} = 45.0\%$$

For this case, the area-weighted imperviousness percent for the site is calculated as 61% under the conventional drainage layout. With a LID layout, the proposed cascading landscape can improve the hydro modifications down to 50%. For an additional on-site WQCV basin, the site effective imperviousness is further reduced to 45%. It means that the downstream sewers or flood detention basins can be down-sized with $I_{SE} = 45\%$ as the effective imperviousness after the development. The method presented in this study provides a consistent base to quantify the LID effort to compensate the required hydro-modifications in the man-made drainage systems. The reduction in the site imperviousness percent can be translated into cost-savings,

CONCLUSIONS

This paper presents a runoff volume-based approach that converts the area-weighted watershed imperviousness into its volume-weighted effective imperviousness for a cascading plane. The cascading plane is then incorporated into a four-component land use model. The normalized dimensional analyses indicate that the pavement-area-reduction-factor (PARF) can serve as an index to quantify the runoff-reduction percentages at different levels of a stormwater LID effort. Two sets of pavement-area-reduction-factor (PARF) are developed to quantify the effectiveness of stormwater LID effort. PARF depends on the ratio of the infiltration rate to rainfall intensity, the ratio of receiving pervious area to upstream, disconnected impervious area, and the on-site storage capacity (WQCV).

Conveyance-based PARF's are sensitive to the f/i ratio for all conditions. As f/i increases, the higher PARF becomes. The additional infiltration benefit over the cascading plane diminishes as A_r decreases. Storage-based PARF's are sensitive to both localized WQCV and f/i ratio. The ratio of f/i represents different porous pavements and infiltrating beds. This study presents a simple methodology that can attach an incentive index to LID designs. The non-dimensional PARF derived in this study allows the engineers, planners and/or developers to quantify the construction cost savings or property tax credits in terms of reduced storage requirements for on-site WQCV and decreased sewer sizes for minor and/or major systems. T

The four-component land use model is a basic layout that has been adopted by the Denver metropolitan stormwater design manuals (UDFCD 2010). This approach has been tested by more than 20 site plans proposed in Denver's area. It was confirmed that the design charts, Figures 2 and 3, well agree with the complicated SWMM5 computer model. Of course, more research is needed to verify this approach by field data. In case of complicated site plan, the SWMM computer model can be employed to include as many cascading planes as designed to simulate the run-on flow that run from an impervious area or a pervious area with a certain land cover and soil type to another/other pervious area with different land covers and soils. Figures 2 and 3 are developed with one cascading plane that covers most of applications.

REFERENCES

ASCE WEF (1998), Joint Task Force of the Water Environment Federation and the ASCE “Urban Runoff Quality Management” WEF Manual of Practice No. 23 Alexandria Va. And Reston, Va.

Arnold, Jr. C.L. and Gibbons, C.J. (1996) “Impervious Surface Coverage: the emergence of a key environmental indicator” J. Am. Plan. Assoc., 62(2), 243.

Blackler, G. and Guo J. C. Y. (2009) “Least Cost and Most Efficient Channel Cross Sections” j. Irrig. Drain. Eng. 135(2), 248-251.

Booth, Derek B. and Jackson, Rhett C. (1997) “Urbanization of Aquatic Systems Degratdation Threshols, Stormwater Detention, and the Limits of Mitigation” J. American Water Resources Association. Vol 22 No. 5.

Chabaeva A., Civco J. and Hurd J. (2009) “Assessment of Impervious Surface Techniques” J. Hydrologic Engineering 14(4) 377-387.

Driscoll, E.D., Palhegyi, G.E., Strecker, E.W. and Shelley, P.E. (1989). “Analysis of Storm Events Characteristics for Selected Rainfall Gauges Throughout the United States”. U.S. Environmental Protection Agency, Washington, D.C.

EPA Report, (1983) “Results of the Nationwide Urban Runoff Program”, Final Report, U.S. Environmental Protection Agency, NTIS no. PB84-185545, Washington D.C.

Government of Western Australia (2005). Report on “Decision Process for Stormwater Management in Western Australia”, Department of Environment and Swan River Trust.

Guo, James C.Y. and Harrigan, Kelly (2009). “Conservative Design Rainfall Distribution”, ASCE J. of Hydrologic Engrg. Volume 14, Issue 5, pp. 528-530 (May 2009).

Guo, J. C.Y. and Cheng, J.Y.C. (2008) “Retrofit Stormwater Retention Volume for Low Impact Development”, ASCE J. of Irrigation and Drainage Engineering, Vol 134, No. 6, December.

Guo, J. C.Y. (2008) “Volume Based Imperviousness for Storm Water Designs” J. Irrig. and Drn. Eng. Vol 134 (2) 193-196.

Guo, James C.Y. and Urbonas, Ben. (2002). “Runoff Capture and Delivery Curves for Storm Water Quality Control Designs,” ASCE J. of Water Resources Planning and Management, Vol 128, Vo. 3, May/June.

Guo, James C.Y. and Hughes, William. (2001). “Runoff Storage Volume for Infiltration Basin,” ASCE J. of Irrigation and Drainage Engineering, Vol 127, No. 3, May/June.

Guo, J. C.Y. and Urbonas, Ben (1996). "Maximized Detention Volume Determined by Runoff Capture Rate,” ASCE J. of Water Resources Planning and Management, Vol 122, No 1, Jan.

Kuichling, E. (1889). "The Relation between Rainfall and the Discharge of Sewers in Populous Districts," Trans. ASCE, Vol 20, pp 1-56.

Lee, J.G., Heaney, J.P., (2003) “Estimation of Urban Imperviousness and its Impacts on Storm Water Systems” J. Water Resources Planning and Management, 129(5), 419-426.

Roesner, Larry, Urbonas, Ben, and Guo, James C.Y., (1996). "Hydrology for Optimal -Sizing of Urban Runoff Treatment Control System", J. of Water Quality International, London, SW1H9BT, UK, February.

Rossman L. A (2009) “Storm Water Management Model User’s Manual Version 5.0” Water Supply and Water Resources Division National Risk Management Research Laboratory. Cincinnati, OH. Chp 3. Pg 34.

UDFCD (2010) “Urban Stormwater Drainage Criteria Manual, Volume 3” Urban Drainage and Flood Control District, Denver, CO. Chp 3 – Pg SQ-14.

UDFCD (2001) “Urban Stormwater Drainage Criteria Manual, Volume 1” Urban Drainage and Flood Control District, Denver, CO. Chp 4 – Pg RA-4.

Woo S. H. and Burian S. J. (2009) “Determining Effective Impervious Area for Urban Hydrologic Modeling” J. Hydrologic Engineering 14(2), 111-120.

Notations

a = empirical coefficient
A_C = area for cascading plane
A_{DCIA} =Directly Connected Impervious Area
A_r = ratio of downstream RPA to upstream impervious area (UIA)
A_{RPA} =Receiving Pervious Area
A_T = site area
A_{SPA} =Separate Pervious Area
A_{UIA}=Unconnected Impervious Area
b= empirical coefficient
C= runoff coefficient
F = infiltration loss on pervious area *[L]*
f = infiltration rate on pervious surface *[L/t]*
Fct = expression of the function relationship
i = average rainfall intensity [L/t]
I = imperviousness of the tributary area, $0 \leq I \leq 1.0$
I_A = area-weighted imperviousness percent for cascading plane
I_E = effective imperviousness percent for the cascading plane
I_{SA} = site area-weighted imperviousness
I_{SE} = site effective imperviousness
K = pavement area reduction factor (PARF)
P = design rainfall depth *[L]*
P_m = local average event rainfall depth [L]
V_C = runoff volume produced from cascading plane as designed $[L^3]$
V_C^0= runoff volume produced from cascading plane as pervious $[L^3]$,
V_C^{100} =runoff volume produced from cascading plane as impervious $[L^3]$
WQCV = water quality capture volume per catchment area [L]