A Non-dimensional Modeling Approach for Evaluation of Low Impact Development from Water Quality to Flood Control

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ABSTRACT

Regulations in the United States establish water quality protection requirements that typically are targeted at relatively small, frequent events, comprising the bulk of non-point source pollutant loading to receiving waters. Although water quality requirements vary from municipality to municipality, typical requirements include promoting infiltration to reduce runoff volume and peak flows, storage and release of runoff or some combination of infiltration and storage/release. Examples of such requirements include ordinances requiring development to maintain runoff rates and, in some cases, volumes at pre-development levels for up to a specified design event and/or requirements to capture, store and release runoff from frequent events.

Complying with these types of water quality requirements can be expensive, so it is understandable to question what benefit these requirements have for flood control. Flood control benefits of water quality facilities typically can be quantified using hydrologic and hydraulic calculations; however, there are important considerations that belie the simplicity of calculations, including ownership, operation and maintenance of facilities. These issues are especially important for on-site water quality facilities and “distributed” controls, which generally are not publicly owned and maintained.

This paper presents hydrologic and hydraulic modeling to explore water quality and flood control benefits of water quality facilities, especially infiltration-based Low Impact Development (LID) practices. The paper presents a method for calculating an Imperviousness Reduction Factor (IRF) that can be used to calculate effective imperviousness based on total site imperviousness. This paper demonstrates that while water quality facilities are important for smaller, more frequently occurring events and play a role in water quality and stream channel protection when it comes to larger flooding events, hydrologic benefits diminish and must be complemented with sound detention, conveyance and floodplain management policies and practices. Failure to recognize and plan for this fact will inevitably subject properties to higher than appropriate flood risk.

INTRODUCTION

Reducing the volume of runoff generated from development and redevelopment projects is fundamental to effective stormwater management. The ability to easily quantify volume reduction associated with minimizing directly connected impervious area (MDCIA), Low Impact Development (LID) practices and other Best Management Practices (BMPs) is important for evaluating the feasibility of these types of practices. One of the primary barriers to wider use of LID in the United States is the need for a relatively simple method for quantifying volume reduction benefits of LID practices (Earles et al. 2008).

The concepts discussed in this paper are dependent on the concept of Effective Imperviousness. The term "Effective Imperviousness" refers to impervious areas that contribute surface runoff to the drainage system. In engineering literature, this term is sometimes used interchangeably with "Directly Connected Impervious Area." For the purposes of this paper, "Effective Imperviousness" is more broadly defined, including portions of the Unconnected Impervious Area that contribute to runoff from a site. For small, frequently occurring events, the "Effective Imperviousness" is equivalent to Directly Connected Impervious Area since runoff from Unconnected Impervious Areas infiltrates into Receiving Pervious Areas; however, for larger events, the "Effective Imperviousness" is increased to account for runoff from Unconnected Impervious Areas that exceeds the infiltration capacity of the Receiving Pervious Area.

To evaluate the effects of MDCIA and other LID practices, the Urban Drainage and Flood Control District (UDFCD) has performed modeling using the United States Environmental Protection Agency (USEPA) Stormwater Management Model (SWMM) to develop tools for planners and designers, both at the watershed/master planning level, when site-specific details have not been well defined, and at the site level, when plans are at more advanced stages. This paper focuses on site-level analysis. Watershed/master planning level tools have been included in the UDFCD *Urban Storm Drainage Criteria Manual, Volume 3* (USDCM Volume 3), since the mid-2000's (UDFCD 1999, latest revision 2008) and are currently being revised as a part of an overall update to Volume 3 of the USDCM in 2010.

Conceptual Model for Volume Reduction BMPs

The hydrologic response of a watershed during a storm event is characterized by factors including shape, slope, area, imperviousness (connected and disconnected) and other factors (Guo 2006). Total imperviousness of a watershed can be determined by delineating roofs, drives, walks and other impervious areas within a watershed and dividing the sum of these impervious areas by the total watershed area. In the past, total imperviousness was often used for calculation of peak flow rates for design events and storage requirements for water quality and flood control purposes. This is a reasonable approach when much of the impervious area in a watershed is directly connected to the drainage system; however, when there are significant amounts of unconnected impervious area in a catchment, using total imperviousness will result in an overestimation of peak flow rates and storage requirements.

Unlike many conventional stormwater models, SWMM allows for more complex evaluation of flow paths through the on-site stormwater BMP layout. Conceptually, an urban watershed can generally be divided into four land use areas that drain to the common outfall point as shown in Figure 1. These four areas are: Directly Connected Impervious Area (DCIA), Unconnected Impervious Area (UIA), Receiving Pervious Area (RPA), and Separate Pervious

Area (SPA) (UDFCD 1999a).

A fundamental concept of LID 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 SWMM allows users to model overland flow draining from the upper impervious areas onto a downstream pervious area. As illustrated in Figure 1, the effective imperviousness is only associated with the cascading plane from UIA to RPA, while the other two areas, DCIA and SPA, are drained independently.

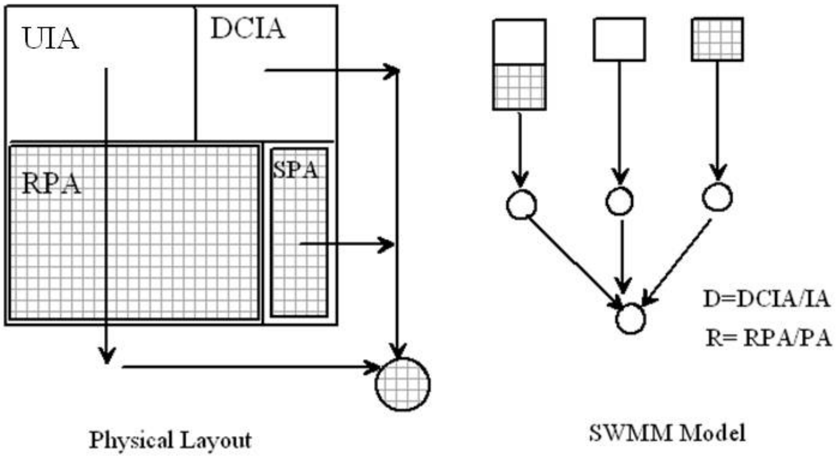


Figure 1. Four Component Land Use

For a LID site, the effective imperviousness is less than the total imperviousness. Aided by SWMM, effective imperviousness can be determined by a runoff-volume weighting method that accounts for losses along the selected flow paths. When designing a drainage system, design criteria that account for effective imperviousness can potentially reduce stormwater costs by reducing the size requirement of hard infrastructure to convey and/or store the design stormwater flows and volumes. To be practical, it is necessary to relate the effective imperviousness of a LID site to its area-weighted total imperviousness, because the surface-area map for a project site is typically available and total area-weighted imperviousness is a commonly calculated parameter.

QUANTIFICATION OF VOLUME REDUCTION

For site-level planning, whether at a conceptual level or a more advanced stage of design, volume reduction can be determined from SWMM modeling conducted by an experienced user. While it is possible to quantify volume reduction by varying inputs in SWMM including the fraction of impervious area directed to pervious areas, pervious area depression storage and other factors, design charts based on multiple SWMM runs can provide a useful tool for designers who do not wish to go to the effort or expense of detailed site-level modeling using SWMM.

This paper describes two options for quantification of volume reduction at the site level when these fractions have been identified:

- SWMM modeling using the cascading plane approach
- UDFCD Imperviousness Reduction Factor charts and spreadsheet

The Imperviousness Reduction Factor (IRF) charts presented in this paper were developed using a dimensionless SWMM modeling approach developed by Guo et al. (2010) that determines the effective imperviousness of a site based on the total, area-weighted, imperviousness and the ratio of the infiltration rate (saturated hydraulic conductivity), *f*, to the rainfall intensity, *i*. Because the Imperviousness Reduction Factor is based on cascading plane SWMM modeling, it will yield results that are generally consistent with creation of a site-specific SWMM model.

To apply either of the above methods, a project site must first be broken up into sub-watersheds based on topography and drainage patterns. For each sub-watershed, the areas of DCIA, UIA, RPA and SPA should be calculated. Sub-watersheds (and associated BMPs) will fall into one of two categories based on the types of BMPs used:

1. Conveyance-based—Conveyance-based BMPs include, but are not limited to, grass swales, vegetated buffers, pervious pavement systems without significant sub-surface storage and disconnection of roof drains and other impervious areas to drain to pervious areas (UDFCD 1999a). Conveyance based BMPs may have some incidental, short-term storage in the form of channel storage or shallow ponding but do not provide the Water Quality Capture Volume (WQCV) and/or flood-control detention volume.
2. Storage-based—Storage-based BMPs include bioretention/rain gardens, pervious pavement systems that provide the WQCV as sub-surface storage, extended dry detention basins and other BMPs that provide the WQCV and/or flood-control detention volume.

SWMM Modeling Using Cascading Planes

Because of complexities of modeling LID and other BMPs using SWMM, this alternative for site-level volume reduction analysis is recommended only for experienced users. The following list provides guidance for conveyance- and storage-based modeling:

- Each sub-watershed should be conceptualized as shown in Figure 1. Two approaches can be used in SWMM to achieve this:
  - Create two SWMM sub-catchments for each sub-watershed, one with UIA 100-percent routed to RPA and the other with DCIA and SPA independently routed to the outlet.
  - Use a single SWMM sub-catchment to represent the sub-watershed and use the SWMM internal routing option to differentiate between DCIA and UIA. This option should only be used when a large portion of the pervious area on a site is RPA and there is very little SPA since the internal routing does not have the ability to differentiate between SPA and RPA (i.e. the UIA is routed to the entire pervious area, potentially overestimating infiltration losses).
- Parameters for infiltration and depression storage are key input parameters for modeling LID. It is important to be realistic about infiltration parameters. When facilities are new, infiltration rates may be quite high; however, as facilities age and fine sediments penetrate into infiltration layers, the rate will decline. Therefore, the saturated hydraulic conductivity should not be overly-optimistic. For well drained sub-soils, a maximum value of 1 inch per hour is recommended to account for decaying infiltration over time and to be realistic about maintenance.
- For storage-based BMPs, there are two options for representing the WQCV:
  - The pervious area depression storage value for the RPA can be increased to

represent the WQCV. This approach is generally applicable to storage-based BMPs that promote infiltration such as rain gardens, pervious pavement systems with storage or sand filter basins. It should not be used when a storage-based BMP has a well defined outlet and a stage-storage-discharge relationship that can be entered into SWMM.

- The WQCV can be modeled as a storage unit with an outlet in SWMM. This option is preferred for storage-based BMPs with well defined stage-storage-discharge relationships such as extended detention basins.

These guidelines are applicable for EPA SWMM Version 5.0.018 and earlier versions going back to EPA SWMM 5.0. EPA is currently developing a version of EPA SWMM with enhanced LID modeling capabilities; however, currently, this new version is still undergoing testing and refinement.

Imperviousness Reduction Factor (IRF)

When UIA, DCIA, RPA, SPA and WQCV, if any, for a site have been defined, the IRF provides a relatively simple method for calculating effective imperviousness and volume reduction. Fundamentally, the IRF charts (and spreadsheet) are based on the following relationships.

For a conveyance-based approach:

$$K = Fct\left(\frac{F_d}{P}, A_r\right) = Fct\left(\frac{f}{I}, A_r\right) \qquad \text{Equation 1}$$

For a storage-based approach:

$$K = Fct\left(\frac{F_d}{P}, A_r, A_d\frac{WQCV}{P}\right) \qquad \text{Equation 2}$$

Where:

K = Imperviousness Reduction Factor = Effective Imperviousness/Total Imperviousness
F_d = Pervious area infiltration loss (in)
f = Pervious area infiltration rate (in/hr) corresponding to saturated hydraulic conductivity
P = Design rainfall depth (in)
I = Rainfall intensity (in/hr)
A_r = RPA/UIA
A_d = RPA
$WQCV$ = Water quality capture volume (watershed inches), and
Fct designates a functional relationship.

A full derivation of these expressions can be found in Guo et al. (2010). The results of cascading plane modeling based on these expressions are shown in Figure 2 for the conveyance-based approach and Figure 3 for the storage-based approach.

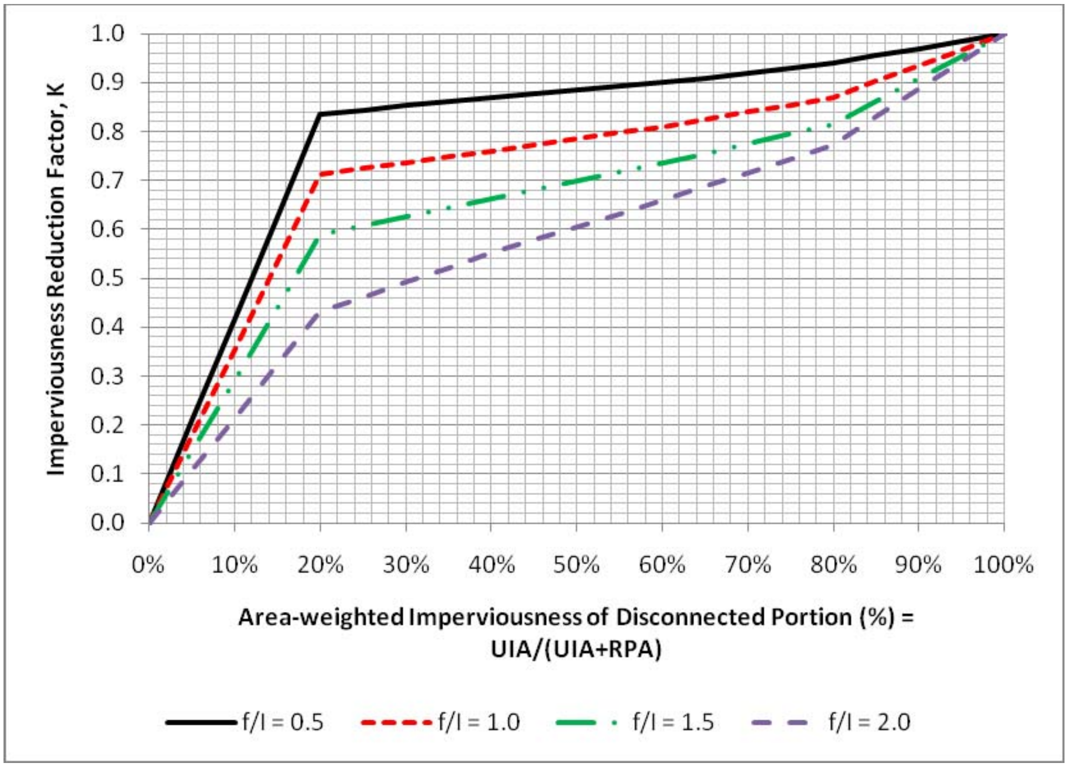


Figure 2. Conveyance-based Imperviousness Reduction Factor

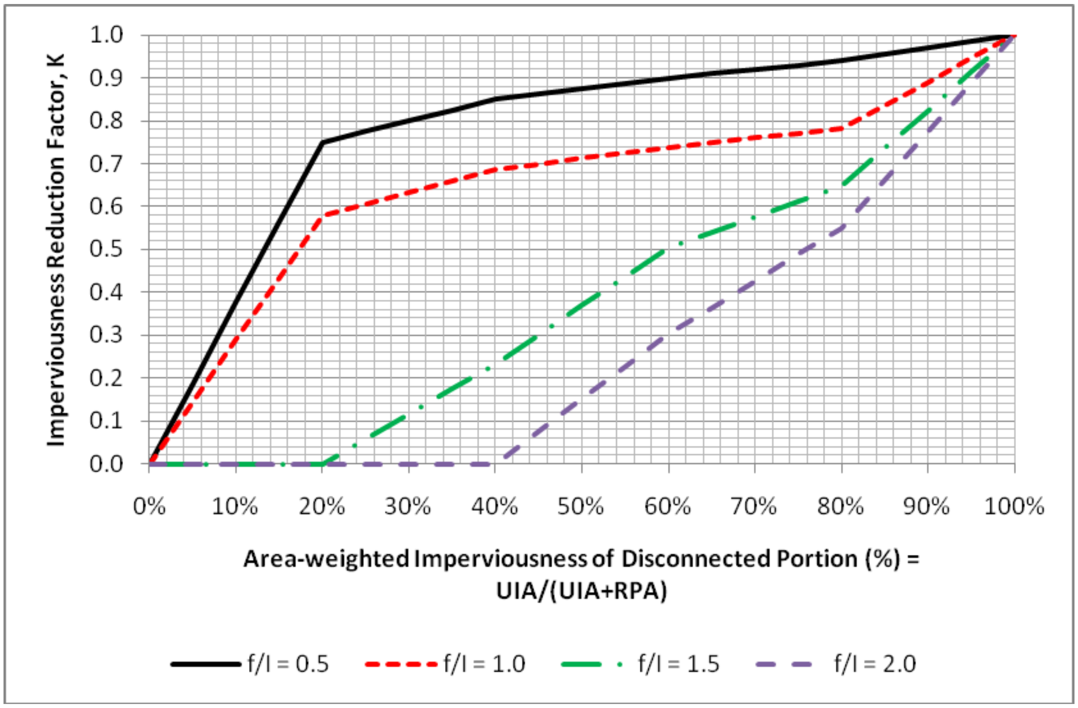
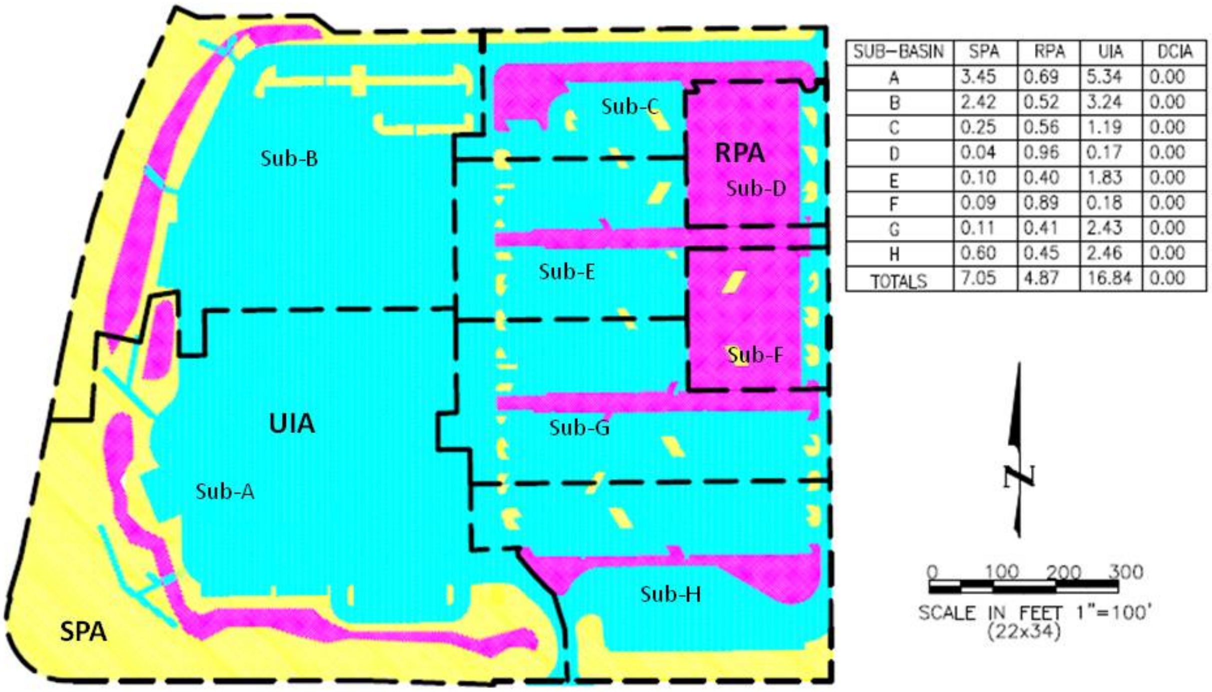


Figure 3. Storage-based Imperviousness Reduction Factor

Example Application

To implement the design charts shown in Figures 2 and 3, a spreadsheet was developed to calculate the IRF for a site plan. Spreadsheet inputs include fractions of UIA, DCIA, RPA and SPA; design rainfall; infiltration capacity of RPA and whether the sub-basin uses conveyance-based or storage-based BMPs. Calculations include the IRF for each input sub-basin as well as volume reductions for the water quality, major and minor events based on effective imperviousness.

The site chosen to demonstrate the spreadsheet IRF method is a commercial site in Aurora, Colorado that is one of the first sites in the metropolitan Denver area with widespread implementation of LID across the site. LID practices include pervious pavements, infiltration beds, and bioswales as well as more conventional BMPs such as extended dry detention basins on portions of the site. Figure 4 shows the site layout, conceptualized as the four area fractions. The total site area is approximately 29 acres with virtually no DCIA (areas are provided for each sub-basin in Figure 4).



SUB-BASIN	SPA	RPA	UIA	DCIA
A	3.45	0.69	5.34	0.00
B	2.42	0.52	3.24	0.00
C	0.25	0.56	1.19	0.00
D	0.04	0.96	0.17	0.00
E	0.10	0.40	1.83	0.00
F	0.09	0.89	0.18	0.00
G	0.11	0.41	2.43	0.00
H	0.60	0.45	2.46	0.00
TOTALS	7.05	4.87	16.84	0.00

Figure 4. Commercial Store Site Plan UIA, DCIA, RPA and SPA.

One-hour point rainfall totals for the Denver metropolitan area of 0.50 inches for the 3-month event, 1.55 inches for the 10-year event and 2.60 inches for the 100-year event were entered into the spreadsheet to evaluate the effects of the LID practices over a range of events. With the exception of only two sub-basins (A&B), storage-based BMPs were implemented on the site. The maximum infiltration rate specified for pervious areas in the spreadsheet was 1.0 inch per hour, representing the saturated hydraulic conductivity of the relatively sandy soils on site.

Table 1 presents the results of applying the IRF to calculate effective imperviousness. It is very important to note that the IRF is applied only to adjust the UIA. Effective imperviousness is calculated as follows:

$$Effective\ Imperviousness = \frac{UIA \times R + DCIA}{UIA + DCIA + SPA + RPA} \qquad \text{Equation 3}$$

with variables defined above.

Sub-basin ID	I_{total}	$I_{3\text{-month Effective}}$	$I_{10\text{-year Effective}}$	$I_{100\text{-year Effective}}$
A	56%	50%	54%	55%
B	52%	45%	50%	51%
C	60%	19%	54%	56%
D	15%	0%	11%	12%
E	79%	35%	74%	76%
F	16%	0%	12%	13%
G	82%	39%	79%	80%
H	70%	33%	67%	68%
Overall	59%	38%	56%	57%

Table 1. Effective Imperviousness for 3-month, 10-year and 100-year Events

The results in Table 1show that the effective imperviousness of the site is more than 20 percent lower than the total impervious area for the 3-month event. As would be expected, however, this effect diminishes for larger events and is only a 2% difference for the 100-year event when the rainfall intensity overwhelms the soil infiltration capacity.

The spreadsheet also uses effective imperviousness to project volume “credits” associated with LID practices. The spreadsheet calculates the water quality capture volume (WQCV) and 10- and 100-year detention storage volumes using empirical equations from the UDFCD *Urban Storm Drainage Criteria Manual* for total and effective imperviousness. The “credit” is the difference between the storage volumes calculated using total and effective imperviousness. Table 2 shows the results of WQCV and detention credit calculations.

Sub-basin ID	WQCV (ft^3) for I_{tot}	WQCV (ft^3) for I_{eff}	WQCV Credit (ft^3)	10-year Detention (ft^3) for I_{tot}	10-year Detention (ft^3) for $I_{10\text{-}yr\ eff}$	10-year Detention Volume Credit (ft^3)	100-year Detention (ft^3) for I_{tot}	100-year Detention (ft^3) for $I_{100\text{-}yr\ eff}$	100-year Detention Volume Credit (ft^3)
A	7723	7093	630	21313	20531	782	48303	47198	1106
B	4778	4349	429	12896	12325	572	29374	28550	824
C	1702	800	902	4759	4282	476	10738	10063	675
D	386	0	386	607	440	167	1301	1010	292
E	2702	1403	1299	7380	6960	420	16142	15605	537
F	403	0	403	649	476	173	1409	1107	302
G	3680	1906	1775	9812	9360	451	21311	20747	564
H	3509	2036	1473	9889	9401	488	21950	21300	650
Total	24884	17586	7298	67305	63776	3530	150528	145580	4949

Table 2. WQCV and Detention "Credit" Results

As a fraction of the total volume required, the greatest benefits are associated with the WQCV, with diminishing reductions in storage volume requirements for the 10- and 100-year events. It is notable that there are indeed reductions in detention volume requirements for these larger events; however, in terms of the overall detention volume required for the site, the credits amount to less than 6% of the total volume for the 10-year event and less than 4% of the volume for the 100-year event.

CONCLUSIONS

The method presented in this paper provides a methodology for calculating effective imperviousness based on factors including the fractions of UIA, DCIA, RPA and SPA on a project site; the design rainfall intensity; the infiltration rate of pervious areas, and water quality storage with extended release (WQCV). The procedures presented in this paper are based on modeling using USEPA SWMM, and a user familiar with SWMM can conduct site-level or watershed-level modeling to quantify benefits of LID practices and other BMPs.

The example provided illustrates application of the imperviousness reduction factor method and also quantifies volume "credits" associated with LID. While the impact of LID measures on effectiveness is quite prominent for frequently occurring events that are typically targeted for water quality purposes, these benefits diminish for larger events typically associated with storm sewer design and flood control.

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