

Retrofitting Stormwater Retention Basin

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ABSTRACT: The concept of Low Impact Development (LID) applies decentralized on-site runoff source control to storm water management. LID is an integration of bio-retentions and vegetal landscapes to maintain catchment's hydrologic and ecological functions. In current practice, the LID implementation is quantified for the specified watershed development. During the dynamic development process, the existing LID facilities have to be improved according to the incremental changes in the watershed. This paper presents an on-site hydrologic approach to relate the required incremental storm water retention volume to the alteration of surface imperviousness in the tributary area. This approach allows the storm water retention volume to be tailored according to the stage of the watershed development. Cumulatively, the total storage volume can be achieved through multiple stages of the watershed development. The incremental retention volume is found to be related to the local average event rainfall depth. Design charts were produced and normalized by the local average rainfall event depth for generalized applicability.

INTRODUCTION

The ultimate goal for LID is to mimic the site's pre-development hydrology. LID increases on-site hydrologic loss and delays peak flows. Essentially, LID is to create a post-development condition that is hydrologically similar to its pre-development condition (Coffman 2001). Low Impact Development (LID) is an innovative stormwater management approach that applies infiltration, filtering, storage, evaporation, retention measures to manage the excessive storm water due to the development. According to the site specifics, LID applies an integrated concept to dispersing, conveying, treating, and disposing storm water at the source of rainfall. Almost all components of the urban environment have the potential to serve as an element in the integrated LID management, including rooftops, parking lots, vegetal beds, sidewalk landscape, and median depression (EPA 2006a, 2006b, 2006c).

One of the key factors in urban hydrology is the area imperviousness percentage that serves as an indicator to reflect the development density. The higher imperviousness percentage, the more increase in runoff. Numerous storm water Best Management Practices (BMPs) have been developed using area imperviousness as the basis to size the devices (Guo 1999). Storm water control facilities designed by the imperviousness-based storm water approach are often subject to continuous improvements because the watershed is always developed through multiple stages. Therefore, it is imperative that the on-site hydrologic methods be revised or newly developed to use the incremental imperviousness as the key factor.

This paper presents an attempt using the alteration in imperviousness as an index to determine the increase of the on-site storm water retention volume for LID designs. The design schematics can directly estimate the retrofit retention volume when the watershed is further developed.

RETENTION AND IMPERVIOUSNESS

The area-weighted method has been recommended for calculating the percentage of imperviousness in a tributary area. Such a procedure works well for a macro hydrologic study at

the level of master drainage planning, but it fails for micro hydrologic studies when detailed on-site flow paths and surface depression become significantly important. For instance, the area weighted method can not fairly assess the impacts of bio-retentions using permeable pavements, tree box planters, and disconnected downspouts. This is because additional infiltration losses due to the flow paths onto porous pavements have been ignored in the macro hydrologic approach. From the hydrologic point of view, watershed imperviousness has a direct impact on the storm water runoff volume generation. Referring to Figure 1, the runoff volume produced by an event from the tributary area is:

$$V = PA - F(1 - K_a)A \quad (1)$$

in which V = runoff volume in depth per watershed, P = rainfall volume in depth per watershed, A = tributary area, F = infiltrating amount in depth of watershed, K_a = post-development imperviousness ratio between zero and unity. To reduce the development impact on storm water runoff, a retention basin is often installed for runoff quality and quantity control. The operation of a storm water storage basin divides the on-site runoff release into *direct runoff release* and *extended runoff release*. The direct runoff is so designed that it mimics the pre-development condition. Therefore, the runoff volume with a retention basin operation can be divided into:

$$V = PA - F(1 - K_e)A + D_oA \quad (2)$$

In which K_e = pre-development imperviousness ratio, D_o = retention volume in mm per watershed. For convenience, the rainfall volume unit, depth/watershed or mm, is adopted to quantify runoff volumes in this study.

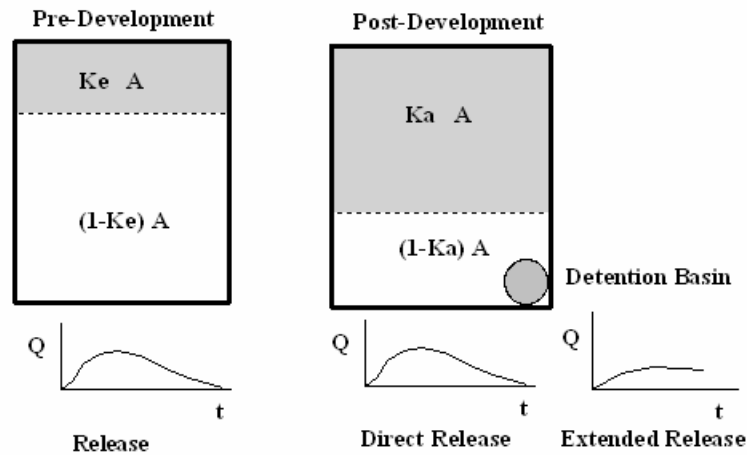


Figure 1 Comparison between Pre- and Post-Development Conditions

Equating Eq's (1) to (2) yields

$$K_e = K_a - \frac{D_o}{F} \quad (3)$$

Eq 3 implies that the storm water retention volume can be interpreted as a reduction on the watershed imperviousness. When $K_e=0$ or no pavement under the pre-development condition, Eq (3) depicts the natural surface depression volume, D_v , before the development.

$$D_o = FK_a = D_v \quad \text{when } K_e=0 \quad (4)$$

Under the LID's concept, the required storm water retention volume can be calculated by re-arranging Eq 3 as:

$$D_o = (K_a - K_e)F \quad (5)$$

According to the rational method (Guo 2001), the pre-development hydrologic loss is expressed as:

$$F = (1 - C_e)P_o \quad (6)$$

in which C_e = pre-development runoff coefficient, and P_o = design rainfall depth, Substituting Eq 6 into Eq 5 yields:

$$D_o = (1 - C_e)(K_a - K_e)P_o \quad (7)$$

Eq (7) defines the *retrofit retention volume* that is the minimum storm water storage volume required for the alteration in watershed imperviousness. Such a retention volume was also referred to as "standard volume" that was discussed, but not quantitatively defined in the previous studies (Booth and Jackson 1997, Booth 1990). In current practice, a storm water detention basin is often sized to meet the historical release rates and a retention basin is designed for the storm water quality control volume (USWDCM 2001). These criteria may equip the watershed with an *over-sized* basin that stores more runoff than needed, or an *undersized* basin that releases more runoff than needed. A retrofit retention volume defined in this paper is to be equal to the incremental runoff volume due to the change of watershed imperviousness. Neither the major event nor the minor event is appropriate to Eq 7 because a retention basin shall be designed to cope with micro events or the continuous rainfall record (Guo 2002, Guo and Urbonas 2002).

RETROFIT RETENTION VOLUME

There are many recommendations on modeling the distributions of complete rainfall records, such as exponential distribution (Bedient and Huber, 1992), one-parameter Poisson distribution (Wanielista and Yousef, 1993), and two-parameter model of Gamma distribution (Woolhiser and Pegram, 1979). In this study, the one-parameter exponential distribution is adopted to fit the complete rainfall depth distribution (Guo 2002).

$$f(P) = \frac{1}{P_m} e^{-\frac{P}{P_m}} \quad (8)$$

In which $f(P)$ = frequency of rainfall event depth, P , and P_m = average rainfall event depth. The non-exceedence probability for Eq 8 is derived as:

$$C_v = Prob(0 \leq P \leq P_o) = 1 - e^{-\frac{P_o}{P_m}} \quad (9)$$

where C_v = runoff capture rate between zero and unity, and $Prob (0 \leq P \leq P_o) =$ non exceedence probability for an event rainfall depth, P , not to exceed the design rainfall depth, P_o . In practice, the non-exceedence probability is also termed runoff capture rate for storm water BMP designs (Guo and Urbonas 2002). Re-arranging Eq 9 yields:

$$\frac{P_o}{P_m} = \ln(1 - C_v) \quad (10)$$

Substituting Eq 10 into Eq 7 yields:

$$\frac{D_o}{P_m} = (C_e - 1)\Delta K \ln(1 - C_v) \quad (11)$$

in which ΔK is the difference of imperviousness percentages in Eq 7.

$$\Delta K = K_a - K_e \quad (12)$$

The application of Eq 11 begins with the selection of the target runoff capture rate, C_v . As recommended, the maximized value for runoff capture rate is approximately 75 to 85% (Guo 2002, Guo and Urbonas 1996). Secondly, Eq 11 demands the information about the watershed incremental development in terms of ΔK . Eq 11 applies the incremental imperviousness as the index that reflects the watershed development stages. When the watershed is developed from the stage, K_e , to K_a , Eq 11 estimates the incremental runoff volume and suggests the retrofit storm water storage. The previous studies applied the watershed imperviousness, K_a , as the index to determine the required retention storage volume (Guo and Urbonas 1996). A major improvement by Eq 11 is to define the retrofit volume based on the incremental imperviousness before and after the development, i.e. ΔK . Of course, Eq 11 is reduced to an imperviousness-based approach when $K_e = 0$. To compare with the previous study (Guo and Urbonas 1996), Eq 11 is reduced to the special case with $K_e = 0$ and $C_v = 0.80$ as:

$$\frac{D_o}{P_m} = 1.61(1 - C_e)K_a \quad \text{for } C_v = 0.8 \text{ and } K_e = 0 \quad (13)$$

For convenience, the EPA NURP data (EPA 1983), was used to calibrate the relationship between runoff coefficients and impervious percentages as:

$$C = 0.858K^3 - 0.780K^2 + 0.774K + 0.04 \approx 0.774K + 0.04 \quad (14)$$

in which $K =$ watershed imperviousness percentage between 0 and 1.0. For instance, $K_e = 0$, Eq 14 results in $C_e = 0.04$. Aided by Eq 13, Eq 12 becomes

$$\frac{D_o}{P_m} = 1.99C_a - 0.08 \quad \text{for } K_e = 0, C_e = 0.04, \text{ and } C_v = 0.8 \quad (15)$$

Eq 14 is a special case directly derived from the concept of on-site LID. This special case is amazingly similar to the best-fitted equations developed using 15- to 40-year continuous rainfall data recorded at Denver, CO, Boston, MA, Tampa, FL, Sacramento CA, Cincinnati OH, Seattle, WA, and Phoenix AZ. Guo and Urbonas (1996) reported that the best-fitted equation derived from the long-term continuous records as:

$$\frac{D_o}{P_m} = aC_a + b \quad (15)$$

As shown in Table 1, the coefficients of a and b vary with respect to the basin drain time. The empirical formula, Eq 15, has been recommended for determining the water quality control volumes by ASCE Practice Manual 87 and WEF Practice Manual 23 (1998).

Drain Time	Runoff		Volume
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

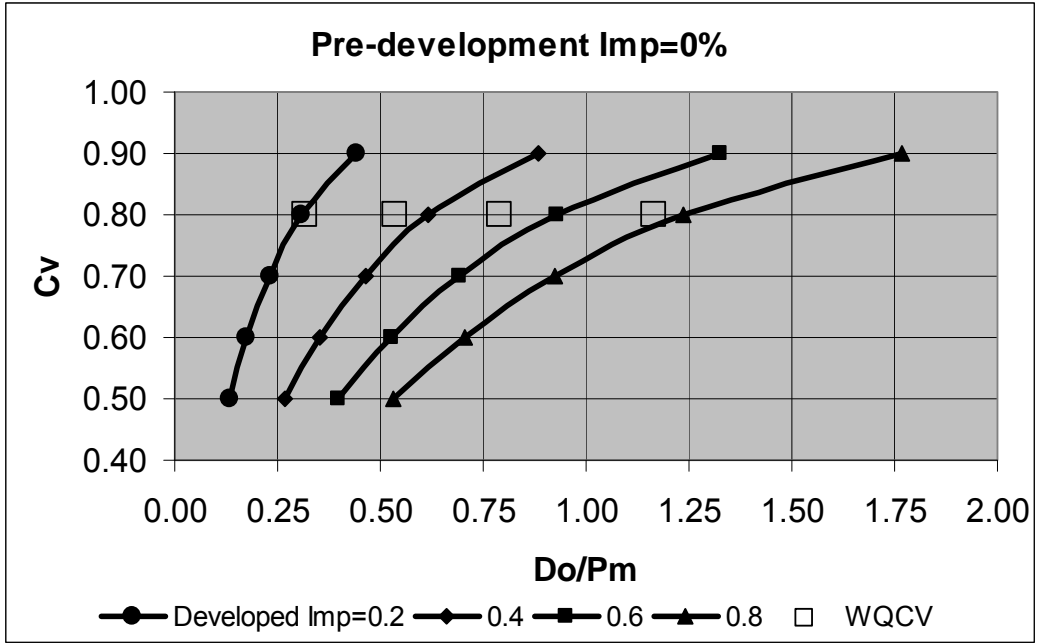
(Table 1 Best-fitted Coefficients for Storm Water Quality Control Volume)

In comparison, the coefficients in Eq 14 more closely agree to the cases with a longer drain time. It implies that to mimic the natural depression storage, the retrofit retention process prefers a drain time of 24 to 48 hours. The goal of LID is more than the peak flow reduction. In order to preserve the watershed regime, Eq 11 suggests that the runoff volume increase is rather related to ΔK than K_a . Secondly, watershed developments are staged. Eq 11 provides a quantifiable measure to estimate the incremental runoff volume between two consecutive stages. In current practice, the retention volume is sized under the assumption that the watershed is developed from its historical to fully developed condition. Eq 11 allows the storm water management plan to be tailored through multiple stages scheduled for the watershed development. And the total retention volume can be continuously built up through several stages of watershed development.

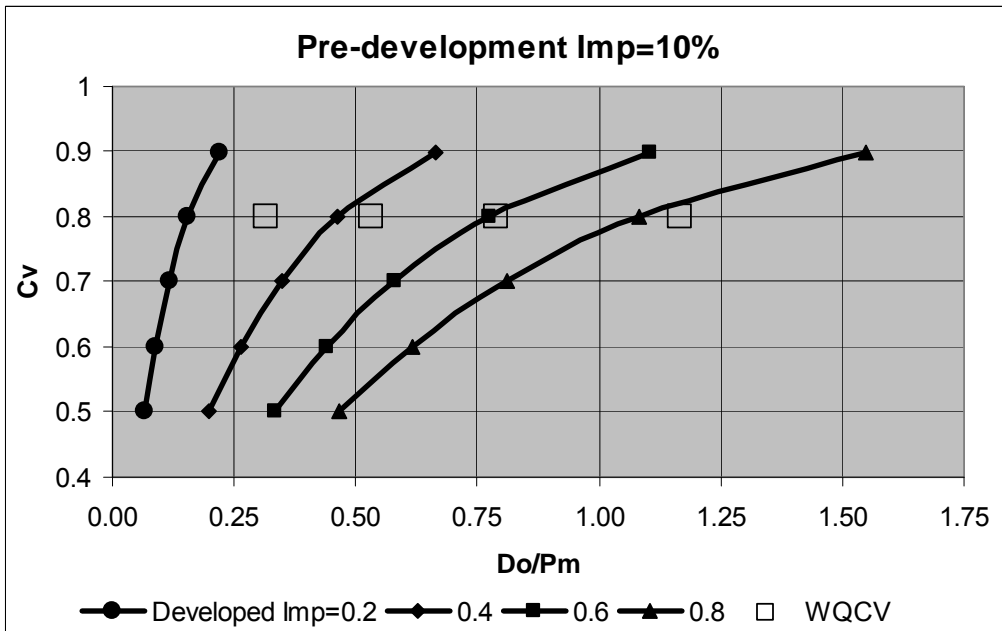
DESIGN SCHEMATICS

To apply Eq 11 to an engineering design, it is necessary to first define the watershed pre-development condition. In this study, the imperviousness of a natural watershed is considered to vary within a narrow range such as zero to 10%. As indicated in Eq 11, the on-site retrofit retention volume has to be designed for a target runoff volume capture rate. As aforementioned, the maximized basin storage volume is to capture 80% of runoff events without overtopping. Any basin volume greater than 90% of rainfall depth population will have to deal with extreme events. Any basin volume less than 50% of runoff population will be too small to avoid overtopping. For convenience, the design charts produced in this study cover the range of runoff capture rates from 0.5 to 0.9 for K_e =zero and 10% respectively. The retrofit runoff volumes are plotted for K_a =20, 40, 60, and 80%. As expected, the retrofit retention volume increases with respect to ΔK . And the case with K_e =0% demands a higher retrofit volume than that with K_e =10%.

According to Eq 11, both charts were plotted using the normalized variables: D_o/P_m , and C_v . To apply Eq 11 to a project site in the continent of USA, the local average rainfall depth, P_m , can be read off from Figure 4 developed from the previous EPA study (Driscoll et al. 1989)



(Figure 2 Stormwater Retrofit Volume for 0% Pre-Development Condition)



(Figure 3 Stormwater Retrofit Volume for 0% Pre-development Condition)

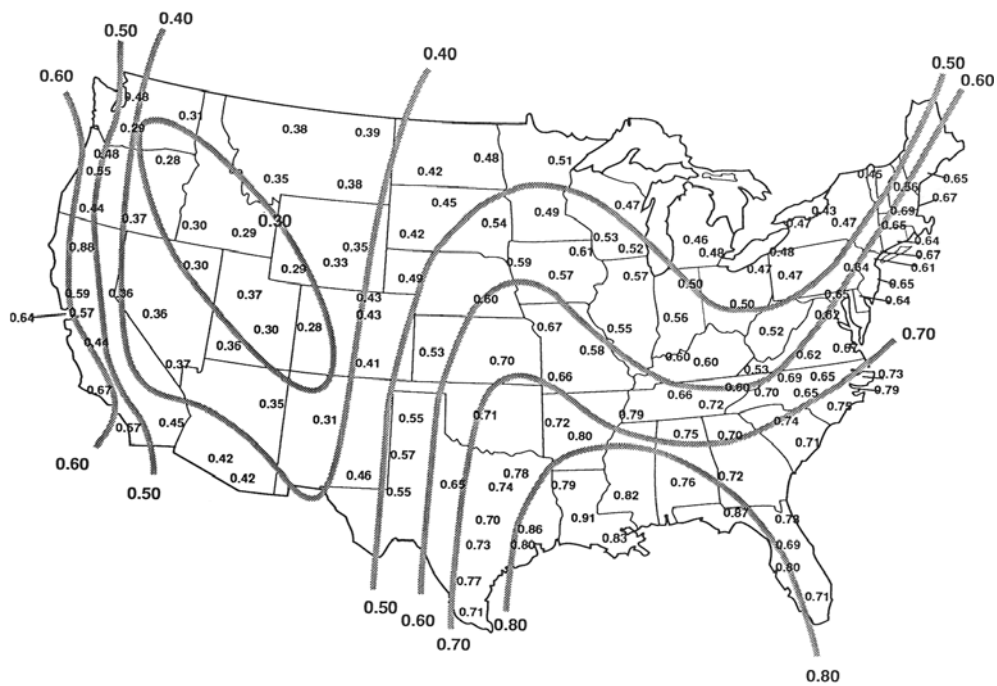


Figure 4 Average Rainfall Event Depths in United States (Driscoll et al. 1989)

CONCLUSION

Low Impact Development is an environmentally sound technology and economically sustainable approach to addressing the adverse impacts of urbanization. The creative devices and approaches developed to manage runoff close to its source demands on-site hydrologic methods that can quantify the differences between flow paths and on-site storage treatments. Based on the retrofit concept, this paper presents an on-site based method for determining the storm water retention volume.

The on-site retention retrofit volume depends on the on-site development density and target runoff volume capture rate. The higher the post-development imperviousness percentage is, the more the storm water retention volume will be for urban retrofits. Eq 11 defines the on-site retrofit or standard retention volume. Using a larger basin than the retrofit volume, it is a case of oversized storm water retention that may cause water rights issue. On the contrary, a smaller basin is an under-sized case that may transfer flooding damage to the downstream properties. Of course, when $K_e=0$, the retrofit retention volume is to mimic the natural depression storage capacity.

The method in this paper also allows the engineer to pre-select the level of storm water capture for treatment. The higher the runoff capture rate, the more the retention volume. At a runoff volume capture rate between 75 and 85%, this method produces comparable on-site retention requirement to the current design procedures recommended for storm water quality control volumes. The major benefit for using this method is to take on-site specifics and development phases into consideration. Figure 2 and 3 are normalized by the local average rainfall depth and can be transferable to various geographic areas.

APPENDIX I: REFERENCES

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APPENDIX II: Notations

a = empirical coefficient for determining water quality control volume

b = empirical coefficient for determining water quality control volume

A = tributary area

C = runoff coefficient

C_e = pre-development runoff coefficient

C_a = post-development runoff coefficient

C_v = runoff capture rate between zero and one.

D_o = retention volume in mm per watershed

D_v = natural surface depression

F = infiltrating amount

$f(p)$ = frequency of rainfall event-depth

K_a = post-development imperviousness ratio

K_e = pre-development imperviousness ratio

ΔK = difference of imperviousness percentages

K = percentage of watershed imperviousness

P = rainfall depth

P_o = design rainfall depth

P_m = average rainfall event-depth

$Prob(0 \leq P \leq P_o)$ = non-exceeding probability

r^2 = correlation coefficient

V = runoff volume depth