

# Storm Water Extended Release for Low Impact Development

By

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**ABSTRACT:** Storm water detention has been widely used for on-site runoff release control. The required storm water detention volumes are often determined by the pre-selected release rates for various design events. When a low release rate is selected, the basin stores more storm water volume than required and it results in an insufficient base flow for the downstream habitats. When a high release is selected, the prolonged basin operation may cause erosion to downstream stream bed and banks. Balancing the tradeoffs, this paper presents a method by which the required detention volume can be determined by urbanization retrofits. The method considers the change of imperviousness, design rainfall depth, watershed hydrologic losses as the design factors. Although the procedure is simple, it well agrees with the design criteria derived from sophisticated computer simulations.

**Keywords:** stormwater, low impact development, BMPs, detention, retention, imperviousness, urban retrofits

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## **INTRODUCTION**

The hydrologic equilibrium of a watershed evolves from the long-term stability of climate, surface runoff, groundwater, and natural landscape. Urban development changes the spatial and temporal distributions of surface runoff and results in a new hydrologic balance for the watershed (Booth and Jackson 1997). The impervious areas in a catchment increase runoff rates and volumes. To mitigate the urbanization impacts on the watershed regime, the practice of extended releases using storm water detention systems can control the release rates, but it results in longer duration of high flows that saturate and erode the downstream stream banks. Contrast to the conventional storm water approaches, Low Impact Development (LID) employs various measures at the source of rainfall, including: (1) minimization of directly connected impervious area (MDCIA) to disperse runoff, (2) decrease of paved area to reduce peak runoffs and volumes, (3) low impact development to decentralize runoff volumes, and (4) applications of best management practices (BMPs) to dispose runoff into hydrologically functional landscape such as rain gardens, bio-detention systems, filter/buffer strips, grassed swales, and infiltration trenches (EPA 2006a, 2006b).

The basic principle of LID is to design the on-site storm water facilities that can mimic the predevelopment condition. LID is an attempt to control the on-site runoff rate, volume, frequency, duration, and quality. The major parameter to achieve these goals is the allowable release rate. Using a high release rate, the detention volume becomes under-sized; as a result, the system does not provide adequate treatment to storm water captured. On the other hand, using a low release rate, the detention basin becomes over-sized; consequently the extended operation induces continuous erosion to the downstream stream banks (Guo 2002). Understanding the trade-off between upstream runoff detention and downstream stream aquatic balance, it is imperative that the on-site detention volume be fairly determined based on the concept of urban retrofits. This paper presents an on-site approach using the hydrologic loss and the catchment imperviousness as the design parameters for determining the proper storm water release rate from the developed catchment. This study suggests that the allowable release rate be the quantifiable basis to evaluate the hydrologic benefits of a creative LID or to compare the alternatives among various LID's.

## **DETENTION VOLUME BY URBAN RETROFIT**

Before the development, the hydrologic losses in a watershed are mainly composed of interception, soil infiltration, and depression storage. LID often involves the concept of bio-detention using permeable pavements, tree box planters, and disconnected downspouts to increase on-site runoff disposal. The runoff volume generated under the post-development condition can be modeled as:

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

in which  $V_a$  = runoff volume after development,  $P$  = rainfall depth,  $A$  = tributary watershed area,  $F$  = hydrologic loss,  $K_a$  = post-development imperviousness ratio. Similarly, the runoff volume generated before the development can be estimated as:

$$V_e = PA - F(1 - K_e)A \quad (2)$$

In which  $K_e$  = imperviousness ratio for pre-development condition. The difference between Eq's 1 and 2 is the storm water detention volume as:

$$V_d = F(K_a - K_e)A \quad (3)$$

In which  $V_d$  = runoff detention volume. Eq 3 defines the retrofit detention volume that is required as the minimum storm runoff storage volume in order to balance the negative impacts due to the watershed development. In the previous study, the concept of retrofit detention volume was also referred to as "standard detention volume", but it was not quantifiably defined (Booth 1990). Of course, a watershed can have an *over-sized* or *under-sized* detention volume, depending on the local design criteria and the runoff capture rate pre-selected for storm water quality control (Guo and Urbonas 2002).

## **DETENTION VOLUME BY RELEASE**

Runoff storage volume is sensitive to rainfall excess, but it is not sensitive to the time distribution. The Federal Highways Administration suggests that the storm water detention volume be the difference between rainfall excess and outflow volume (FAA 1970). As illustrated in Figure 1, the rainfall excess volume is equal to:

$$V_i = C_a IT_d A \quad (4)$$

in which  $V_i$  = rainfall excess volume equal to the trapezoidal inflow hydrograph. i.e. area abcd in Figure 1,  $C_a$  = post-development runoff coefficient,  $I$  = design rainfall intensity,  $T_d$  = design rainfall duration, and  $A$  = watershed area. The outflow hydrograph can be approximated by the linear rising hydrograph with the specified release rate (Malcom 1982 and Guo 1999). The outflow volume, area "aed" in Figure 1, is equal to:

$$V_o = \frac{1}{2} Q_a (T_d + T_c) \quad (5)$$

where  $V_o$  = outflow volume,  $Q_a$  = allowable release, and  $T_c$  = time of concentration of watershed. The difference between Eq's 1 and 2 is the storm water detention volume that can be calculated as:

$$V_d = [C_a IA - \frac{Q_a}{2} (1 + \frac{T_c}{T_d})] T_d \quad (6)$$

In practice, the rainfall duration selected for detention design is often significantly longer than the time of concentration of the watershed. Therefore, Eq 6 can be reduced to

$$V_d = [C_a IA - \frac{Q_a}{2}] T_d \quad \text{when } T_c/T_d \Rightarrow \text{zero} \quad (7)$$

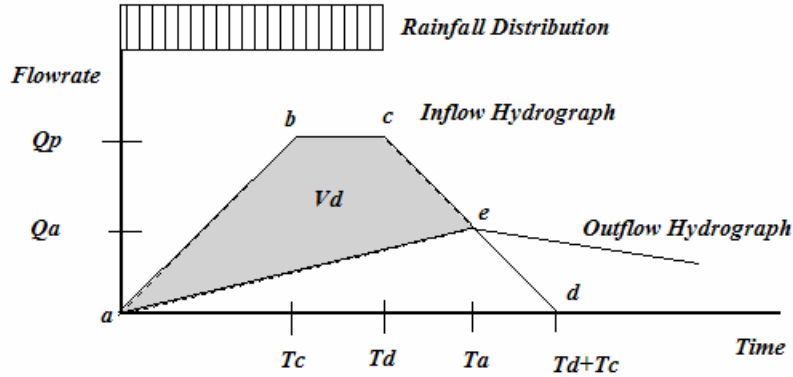


Figure 1 Detention Volume by Allowable Release Rate

In this study, Eq 7 defines the required detention volume based on the allowable release rate. Eq 7 satisfies the volume continuity between the inflow and outflow hydrographs. It produces a valid solution after the entire watershed becomes the contributing area, i.e.  $T_d > T_c$  (Guo 2001).

### **DETERMINATION OF RELEASE RATE**

Eq 3 defines the on-site runoff detention volume calculated for the specific LID in terms of pre- and post-development conditions. Eq 7 calculates the detention storage volume by the allowable release determined by the volume balance. Equating Eq 7 to Eq 3 yields:

$$Q_a = 2[C_a I - \frac{F}{T_d} (K_a - K_e)] \quad (8)$$

For convenience, Eq 8 can be further converted to

$$\frac{q}{i} = 2(C_a - \frac{f}{i} \Delta K) \quad (9)$$

$$q = \frac{Q_a}{A} \quad (10)$$

$$f = \frac{F}{T_d} \quad (11)$$

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

In which  $q$  = extended release expressed in runoff depth per watershed,  $f$  = hydrologic loss rate,  $\Delta K$  = imperviousness difference between pre- and post-conditions. In this study, Eq 9 defines the standard or retrofit release rate (Booth 1990). Hydrologically, the retrofit release compensates the runoff increase due to the change in the watershed imperviousness. Of course, a detention system can be over-released using a higher rate than Eq 7 or under-released using a lower rate than Eq 7.

### **DESIGN SCHEMATICS**

Eq. 9 has three independent variables, including  $C_a$ ,  $f/i$ , and  $\Delta K$ . Both  $C_a$  and  $\Delta K$  are related to the post-development imperviousness. For convenience, the EPA NURP data was used to calibrate the relationship between runoff coefficient and impervious ratio as (EPA 1983, Guo and Urbonas 1996):

$$C = 0.858K^3 - 0.780K^2 + 0.774K + 0.04 \approx 0.774K + 0.04 \quad (13)$$

Eq 13 is plotted in Figure 2. For the purpose of practicality, the ratio of  $f/i$  is set to vary from 0.1 to 0.6. The difference,  $\Delta K$ , between the pre- and post-development impervious ratio is set to vary between 0.15 to unity. With aforementioned variables, Fig 2 presents the relationship among change in imperviousness, release rate, and hydrologic losses. As expected, the higher ratio of  $f/i$ , the less ratio of  $q/i$ . All curves in Fig 2 exhibit the nature that  $q/i$  linearly increases with respect to  $\Delta K$  when  $\Delta K$  is small, and then the relationship becomes exponential when  $\Delta K$  is greater than 0.60.

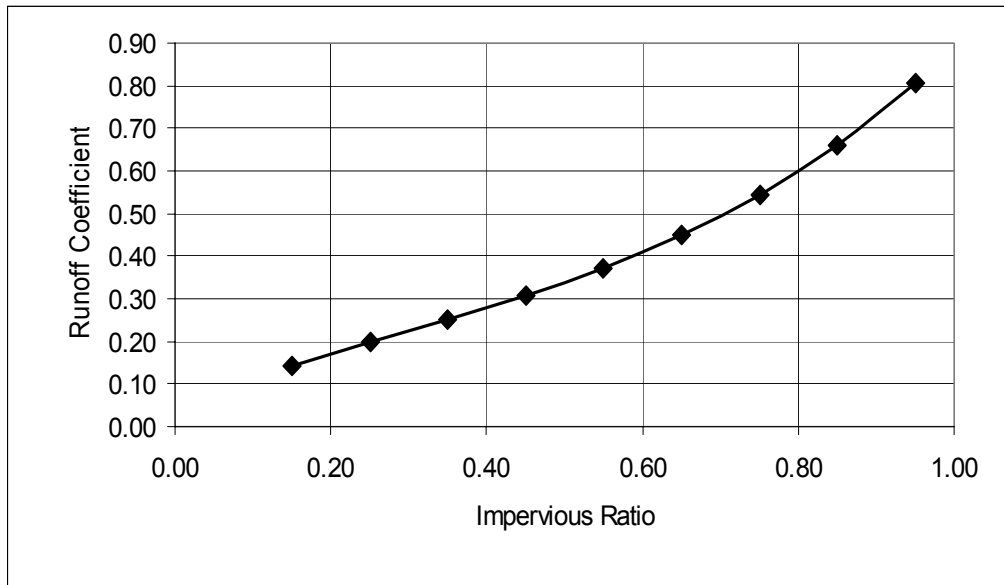


Figure 2 Imperviousness Ratios versus Runoff Coefficient

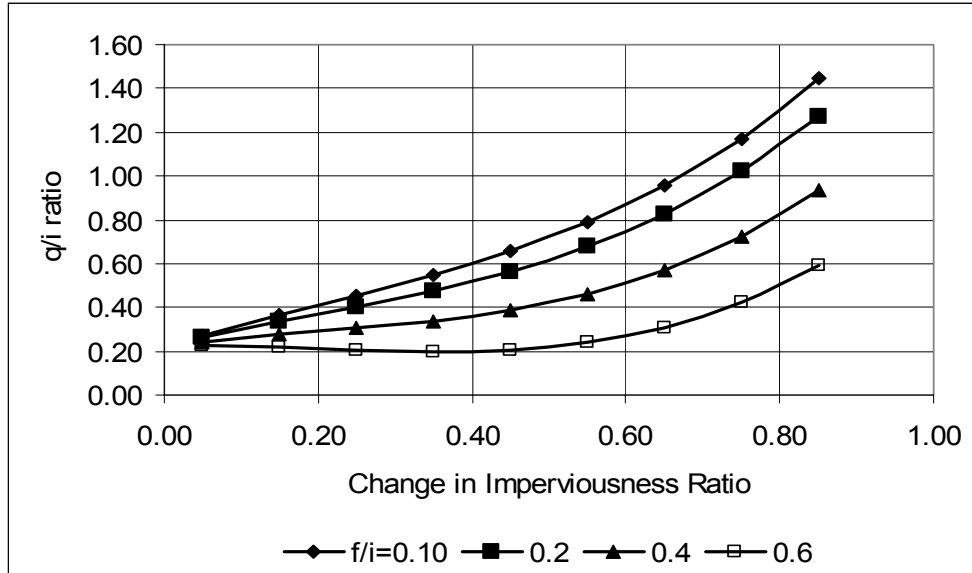


Figure 3 Stormwater Unit Releases versus Imperviousness Ratios

**DESIGN EXAMPLE**

The design example used in this paper is located in Denver, Colorado. The pre-development condition for this watershed has 5% impervious area. The developed imperviousness is 75%. Therefore, for this case,  $\Delta K=0.70$ . Using Fig 2, the post development runoff coefficient is found to be  $C_a=0.54$  for  $K_a=75\%$ . Considering that the two-hour 100-year rainfall depth for the Denver area is 2.99 inches, the design rainfall intensity is:

$$i = \frac{2.99}{2.0} = 1.50 \text{ inch/hr}$$

According to USWDCM (2001), the infiltration loss for Type C soils is recommended to be 0.5 inch/hour. Substituting the design variables into Eq 9 yields the 100-year release as:

$$\frac{q}{i} = 2(0.54 - \frac{0.50}{1.50} * 0.70) = 0.61 \text{ or } q = 0.93 \text{ inch/hr or } 0.93 \text{ cfs/acre.}$$

Repeat the above procedure, Table 1 presents the 10-, 50, and 100-year release rates for  $K=75\%$  or  $\Delta K = 70\%$ . USWDCM (2001) recommends that the 100-year release is 1.0 cfs per acre and 10-year release is 0.30 cfs/ace for Type C soils. These recommended release rates were derived from numerous computer simulations, and the average value for high density developments was then chosen for design. Such average values do not reflect the on-site specifics and progressive changes in the watershed development. For instance, when a lower density development such as  $K=55\%$  or  $\Delta K = 50\%$ , is chosen for the example watershed, Figures 2 and 3 indicate that the 100-year release is reduced to  $q/i=0.41$  or  $q = 0.62 \text{ cfs/acre}$  as shown in Table 1. As a result, the recommended design release rate at 1.0 cfs/acre becomes over-released (USWDCM 2001). Often, a watershed is developed through several stages over a period of time. At each stage, the release shall be tailored according to its current LID design. Table 1 presents the range of release rates for various combinations between design events and watershed imperviousness ratios.

Watershed Condition	Change in Watershed Imperviousness $\Delta K$	Return Period			Return Period		
		10-yr	50-yr	100-yr	10-yr	50-yr	100-yr
Impervious Ratio	Runoff C	$f/i$			$I \text{ in/hr}$		
		0.54	0.41	0.33	0.93	1.21	1.50
		$q/i$			q cfs/ac		

0.95	0.81	0.90	0.65	0.87	1.01	0.60	1.05	1.52
0.85	0.66	0.80	0.46	0.66	0.79	0.43	0.80	1.18
<b>0.75</b>	0.54	0.70	0.33	0.51	0.62	<b>0.31</b>	<b>0.62</b>	<b>0.93</b>
0.65	0.45	0.60	0.25	0.40	0.50	0.24	0.49	0.75
0.55	0.37	0.50	0.21	0.33	0.41	0.19	0.40	0.62
0.45	0.31	0.40	0.19	0.29	0.35	0.17	0.35	0.53
0.35	0.35	0.25	0.30	0.26	0.30	0.28	0.31	0.46
0.25	0.25	0.20	0.20	0.23	0.26	0.19	0.28	0.39
0.15	0.15	0.14	0.10	0.20	0.22	0.09	0.24	0.32

Table 1 Retrofit Release Rate According to Post Development Condition.

## **CONCLUSION**

1. This study presents an on-site hydrologic method for storm water best management practices and low impact designs. The post-development release depends on the change of watershed imperviousness, hydrologic loss, and design rainfall. Eq 9 is derived to determine the retrofit detention volume. In practice, Eq 9 can be applied to 2- to 100-year events. The detention basin is then shaped for multiple events.
2. Between the existing and future conditions, the urbanization process is often implemented through multiple phases. Eq 9 allows the engineer to tailor the incremental storm water detention volumes over the period of time during the watershed development.
3. Similar to the rational method, the applicability of Eq 9 is limited to a tributary area less than 150 acres. A low impact design is aimed at on-site storm water disposal, as a result, the post-development release rate can be so significantly reduced that Eq 9 may yield zero release for a frequent event such as 2-year event. When  $\Delta K$  increases to close to unity, the release rate increases exponentially with respect to  $\Delta K$ .

## **APPENDIX I: REFERENCES**

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## **APPENDIX II: Notations**

A = tributary area

$C_a$  = post-development runoff coefficient

$f$  = hydrologic loss rate

I = design rainfall intensity

$K_a$  = post-development imperviousness ratio.

$K_e$  = imperviousness ratio for pre-development condition

$\Delta K$  = imperviousness difference between pre- and post-conditions

L = hydrologic loss

P = rainfall depth

$Q_a$  = allowable release

q = unit release per unit area

V = runoff volume,

$V_d$  = detention volume

$V_i$  = rainfall excess volume

$V_o$  = outflow volume

$T_d$  = design rainfall duration

$T_c$  = time of concentration of the watershed