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PRESERVATION OF WATERSHED REGIME FOR LOW IMPACT DEVELOPMENT

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Abstract: Low impact development (LID) allows for greater development potential with less environmental impacts using on-site distributed storm water controls that achieve a good balance among conservation, growth, ecosystem protection, and public safety. The qualitative statement of the ultimate goal for LID can serve as guidance for engineering designs, but it is inadequate for comparison and selection among the innovative alternatives. This paper presents an innovative method by which the long-term runoff statistics are employed as the basis to quantify the impact of the development on the watershed hydrologic regime. In this study, the standard LID detention volume is defined by the stormwater storage volume required to preserve the pre-development mean and standard deviation for runoff volume population. Consequently, a detention basin is considered oversized if the after-detention runoff volume population has a lower mean flow while the undersized counterpart produces a mean runoff volume higher than that under the pre-development condition. This simple but quantifiable method is very useful for detention alternative comparisons, and can serve as a guide to retrofit an existing detention basin, according to the proposed LID initiative.

Key words: Low Impact, Watershed, Hydrologic Regime, Detention Basin.

INTRODUCTION

Low Impact Development (LID) for storm water management is a micro-scale on-site design strategy with a goal of maintaining or replicating the predevelopment hydrologic regime (LID-Practice, 2003). The natural hydrologic functions of storage, infiltration, and ground water recharge, as well as the volume and frequency of runoff flows are maintained using integrated and distributed controls, including minimization of directly connected impervious area and on-site stormwater retention and detention. In practice, the qualitative goal for a LID strategy may be translated into various functional landscapes that act as on-site stormwater facilities while the selection among different LID alternatives should be compared on a quantitative scale. Although several on-site hydrologic methods have been developed for event-based analyses (LID-Hydro Analysis 1999), the ultimate goal of a LID design is in fact to warrant the preservation of the hydrologic regime (LID-Strategy, 1999). It is an increasing concern about the needs of a simplified method by which a LID design can be quantitatively evaluated for a full spectrum control of runoff population. For instance, as reported by the US Environmental Protection Agency (EPA), more research is needed to quantify the environmental benefits of LID techniques, including the reduction of runoff volumes and pollutant loadings to downstream waters (EPA 2007).

In general, LID techniques are aimed at the entire land use management with emphasis on the controls of micro events such as 3-month to 2-yr events (Roesner et al. 1996). In conjunction with the conventional approach, the minor and major floods can be conveyed and mitigated through a large, centralized drainage network. At the outfall point of the watershed, a stormwater detention basin is an effective means to reduce the runoff releases. The conventional approach for stormwater detention is to focus on the control of the design flow release that is defined by the local drainage criteria or the downstream existing drainage capacity. Under the LID concept, the release from a LID detention basin should be dictated by the preservation of the pre-development hydrologic condition. The operation of a LID detention basin is often adjusted by the pre-selected drain time over 24 to 72 hours using perforated plates or risers. As a result, the focus of LID detention design has shifted to control the runoff volume over a specified drain time (EPA 2006), For instance, the flush volume and the water quality control volume were developed as a response to stormwater volume and quality control (Guo and Urbonas 1996).

A LID design is to restore the natural storage and infiltration. The design process always involves the selection of a storage volume among alternatives. On top of the qualitative descriptions such as longer flow time and more infiltration, it is necessary to quantify the impact on the watershed hydrologic regime. In this study, a simplified approach is derived to evaluate LID detention alternatives based on the statistics of the long-term after-detention runoff volume population. Using the pre-development runoff volume statistics as the basis, a standard LID detention volume (SLID-DV) is derived to compensate the runoff increase due to the development. In comparison, any storage volume greater than the SLID-DV is considered oversized because it results in short base flows in the stream. On the other hand, an undersized case creates frequent high flows that will erode and scour the stream. The SLID-DV can also serve as a basis to retrofit an existing detention basin for a desirable LID operation.

WATERSHED DEVELOPMENT

A watershed is considered as a system that produces runoff as a response to rainfall. During a storm event, the rainfall amount and distribution loaded to the watershed are transformed into the runoff depth after abstracting the hydrologic losses. The distribution of pervious and impervious areas in a watershed is one of the most important key factors used in the distributed control technique developed for the low impact stormwater management. For simplicity, the storm water modeling procedure divides the watershed into two subareas: pervious and impervious. The total volume produced by a rainfall event is expressed as (Guo and Cheng 1998):

$$V = PA - F(1-K)A \tag{1}$$

In which V = runoff volume, P =rainfall volume selected for the design event, F = hydrologic loss, K = imperviousness percentage, and A = watershed area. Applying the concept of runoff coefficient, Eq. (1) is equivalent to

$$V = PA - P(1-C)(1-K)A \tag{2}$$

In which C = runoff coefficient. Eq. (2) is written for the conservation of water volume in [L^3]. For convenience, Eq. (2) is converted into the unit of depth per watershed as:

$$Q = P[C + K(1-C)] \tag{3}$$

In which *Q* = runoff depth in depth per watershed. After the development, the watershed has more paved area. For a specified design event, the runoff depths under the pre- and post-development conditions are calculated as:

$$Q_e = P[C_e + K_e(1-C_e)] \tag{4}$$

$$Q_n = P[C_n + K_n(1-C_n)] \tag{5}$$

The subscripts, *e and n*, are used to represent the pre- and post-development parameters. Based on EPA NURP data (EPA 1983), the relationship between C and K is derived by a regression analysis as (Guo and Urbonas 1996):

$$C = 8.58 \times 10^{-7} K^3 - 7.80 \times 10^{-5} K^2 + 7.74 \times 10^{-3} K + 0.04 \tag{6}$$

Eq. (6) is an increasing function or implies that the higher impervious percentage in the watershed results in more runoff volume.

STANDARD DETENTION VOLUME

The low impact technique is aimed at restoring the predevelopment hydrologic functions. The innovative approach is to integrate various distributed stormwater controls into the on-site stormwater micro-management designs. Every landscape and infrastructure feature is designed to be multifunctional to convey and store stormwater. The overall effort is to minimize the increase of runoff due to the development.

$$\Delta Q = Q_n - Q_e \tag{7}$$

in which ΔQ = increase of runoff volume in depth per watershed after development. Substituting Eq.'s (4) and (5) into Eq. (7) yields:

$$\Delta Q = P[(C_n - C_e) + K_n(1 - C_n) - K_e(1 - C_e)] \tag{8}$$

To mitigate the hydrologic impacts of land use, a stormwater detention basin is often incorporated into the on-site landscape to store the excess storm runoff.

$$Q_d = Q_n - D_o \tag{9}$$

In which Q_d = after-detention runoff volume and D_o = runoff volume reduction due to the storage effect. Substituting Eq. (7) into Eq. (9) yields

$$Q_d = Q_e + \Delta Q - D_o \tag{10}$$

Under the LID concept, the integrated stormwater management approach is to mimic the predevelopment condition by compensating for losses of rainfall abstraction through micro-scale detention and infiltration facilities. Therefore, the ultimate goal for Eq. (10) is:

$$Q_d = Q_e \tag{11}$$

Eq. (11) implies the ultimate operation of the micro-scale detention is to compensate the runoff volume increase as:

$$D_o = \Delta Q \tag{12}$$

According to Eq 8, the runoff volume increase, ΔQ, depends on the design rainfall depth, P. Consequently, Eq. (12) should be utilized to calculate 2-, 5-, 10-, 50-, and 100-yr detention volumes. The ideal LID detention basin should be constructed with multiple layers to warrant the full-spectrum runoff control. In this study, this most effective storm water detention portrayed in Eq. (12) is referred to as the standard LID detention volume (SLID-DV) (Booth 1990). Aided by Eq 8, the SLID-DV for the design frequency is defined as:

$$D_o = \Delta Q = P[(C_n - C_e) + K_n(1 - C_n) - K_e(1 - C_e)] \tag{13}$$

in which D_o= SLID-DV in depth per watershed for the design frequency defined by the rainfall, P. A SLID-DV is the standard storage volume to mimic the pre-development hydrologic condition. Of course, an existing detention basin can be oversized or undersized relative to the SLID-DV or Eq. (12). Obviously, an oversized detention basin will result in insufficient base flows to the downstream stream. On the contrary, an undersized detention basin will result in a high overflow risk and prolonged base flows that may cause stream banks saturation and erosion (Guo 2002).

IMPACT ASSESSMENT

Not every on-site detention basin is a SLID-DV. For an existing detention basin that deviates from its SLID-DV, aided by Eq. (7), the after-detention release is reduced to:

$$Q_d = Q_n - D_R = Q_e + \Delta Q - D_R \qquad (14)$$

In which D_R = existing detention volume in depth per watershed. Since the rainfall population is dominated by a large number of smaller ones (Guo and Urbonas 2002), it is reasonable to assume that the after-detention runoff volume population in Eq. (14) is distributed as (Chow et al. 1998):

$$Q_d = \overline{Q}_d + ZS_d \qquad (15)$$

In which $\overline{Q}_d$ = mean of after-detention runoff volume, Z = frequency factor, and S_d = standard deviation of after-detention runoff volume population. Eq 15 is the generalized statistical model that can be further divided unto various probabilistic distributions, depending upon the frequency factor. For instance the frequency factors for the normal distribution are symmetric with Z=0 at the mean. In practice, Eq 15 is employed to produce various probabilistic graph papers. For a set of sample data, the selection of the most suitable probabilistic model depends on if the data can appear to be a straight line on the graph paper. Equating Eq.'s (14) to (15) yields:

$$\overline{Q}_d + ZS_d = Q_e + \Delta Q - D_R \qquad (16)$$

Eq. (16) has two unknowns: $\overline{Q}_d$ and S_d that depict the mean and standard deviation for the after-detention runoff volume distribution. In practice, a detention basin is shaped to control a couple of major events. For instance, the bottom layer of a flood control basin is sized for the 10-year event while the upper portion is sized to accommodate the 100-year event (USWCM 2001). A water-quality basin is often designed using the 2- and 5-year events because the morphology of the receiving stream is shaped by the effective flows. The 5- and 10-year storm events are often selected for local basin designs. With two design events, the two unknowns in the flow regime equation, Eq. (16) can be solved as:

$$\overline{Q}_d + Z^U S_d = Q_e{}^U + \Delta Q^U - D_R{}^U \qquad (17)$$

$$\overline{Q}_d + Z^L S_d = Q_e{}^L + \Delta Q^L - D_R{}^L \qquad (18)$$

In which the superscript, U, represents the design frequency for the upper layer of the detention basin, and L represents the design frequency for the lower layer of the detention basin. Solving Eq.'s (16) and (17) simultaneously produces the value of standard deviation for the post-development watershed regime as:

$$S_d = \frac{\Delta q_e + \Delta q - \Delta d_r}{\Delta z} \quad (19)$$

$$\Delta q_e = Q_e{}^U - Q_e{}^L \quad (20)$$

$$\Delta q = \Delta Q^U - \Delta Q^L \quad (22)$$

$$\Delta d_r = D_R{}^U - D_R{}^L \quad (21)$$

$$\Delta z = Z^U - Z^L \quad (23)$$

Both the standard deviation and mean for the after-detention release can serve as a quantifiable basis to assess the development impact on the watershed hydrologic condition. For instance, an oversized detention process will decrease the mean runoff volume, and an undersized will increase the mean runoff volume. A negative standard deviation implies that the basin results in a large number of low flows while a positive standard deviation means more high flows. Eq 19 also indicates that the standard deviation and mean for the after-detention runoff volume distribution remain unchanged if $D_R = D_o = \Delta Q$. Namely;

$$S_d = S_e = \frac{\Delta q_e}{\Delta z} \text{ when } D_R = D_o \quad (24)$$

In which S_e = standard deviation for pre-development runoff volume population

DESIGN SCHEMATICS

The Cherry Creek community in the City of Aurora, Colorado is a residential development dedicated to the preservation of natural water environment. The watershed upstream of Cherry Creek has been developed from its area imperviousness of 15% to 65%. The remedy to the increased urban runoff is a detention basin built with its storage volume composed of 0.85 inch per watershed for the 10-year event and 1.18 inch per watershed for the 100-year event. The method developed in this study is employed to evaluate the impact of this development to the watershed hydrology.

The one-hr precipitation depths at the basin site are 1.61 and 2.60 inches for the 10- and 100-year events respectively. The Gumbel distribution has been tested and found to be suitable for the runoff volume distribution at the site. The Gumbel frequency factor is calculated as:

$$Z^T = -\frac{\sqrt{6}}{\pi}\left\{0.5772 + \ln\left[\ln\frac{T}{(T-1)}\right]\right\} \quad (25)$$

in which Z^T = frequency factor for T-year return period and T = return period in years. Eq. (25) produces $Z^{10} = 1.305$ and $Z^{100} = 3.137$. Substituting K_e = 15% into Eq 6 results in $C_e = 0.14$. Similarly, $C_n = 0.45$ for K_n = 65%. Table 1 summarizes the design parameters for this case.

T	P	Z^T	Q_e	Q_n	D_0	D_R	Q_d
year	Inch		inch	inch	inch	inch	inch
		Eq 25	Eq 4	Eq 5	Eq 13	Given	Eq 16
10	1.61	1.305	0.30	1.30	1.00	0.94	0.36
100	2.60	3.137	0.48	2.10	1.62	1.57	0.53

Table 1 Design Parameters for Design Example

The runoff volume statistics for this case are calculated by Eq.'s (19) and (16) for the after-detention condition as:

S_d = 0.09 inch and $\overline{Q_d}$ = 0.24 inch.

Aided by Eq. (24), the runoff volume statistics for the pre-development condition are:

S_e = 0.10 inch and $\overline{Q_e} = 0.17$ inch

In which $\overline{Q_e}$ = mean of pre-development runoff volume population. For this case, the mean of the runoff volume distribution increases after the development. Therefore, it is concluded that the existing detention volume is undersized relative to the 10-year SLID-DV: $D_o^{10} = 1.00$ and the 100-yr SLID-DV: $D_o^{100} = 1.62$ inch per watershed as shown in Table 1. Furthermore, the standard deviation decreases. It implies that the post-development watershed produces higher flows more frequently. This case reflects the typical alterations to the hydrologic regime after the development, including the increased runoff volume, flow frequency, duration, and peak runoff rate (Booth 1990). Of course, this detention basin can be re-shaped to change its performance. Repeating the same process, the following alternatives to retrofit this basin are evaluated in Table 2 as:

Cases	D_R^{10} Inch	D_R^{100} Inch	D_R^{10}/D_o^{10}	D_R^{100}/D_o^{100}	S_d/S_e	$\overline{Q}_d/\overline{Q}_e$	Comments
Existing	0.94	1.57	0.94	0.97	0.90	1.41	Undersized
Alternative 2	1.05	1.69	1.05	1.04	0.90	0.82	Oversized
Alternative 3	0.94	1.69	0.94	1.04	0.30	1.88	Mixed
SLID-DV	1.00	1.62	1.00	1.00	1.00	1.00	Exact

Table 2 Statistics of Runoff Depths under Various Detention Operations

As listed in Table 2, the SLID-DV is able to mimic the pre-development hydrologic regime. On a Gumbel plot, Eq. (15) is linear with the standard deviation to be the slope and the mean to be the intercept at T = 2.33 yr. As illustrated in Figure 1, the existing runoff-frequency line is consistently above the SLID-DV line because the basin is undersized. On the contrary, the frequency line for Alternative 2 stays below the SLID-DV line because the basin is oversized. As a result, Alternative 2 consistently produces inadequate base flows in the stream. The frequency line for Alternative 3 crosses the SLID-DV line because it is a mixed case. The undersized 10-year detention results in higher base flows that can saturate the stream banks to cause erosion and scour. The oversized upper storage volume can well control the extreme events, but it produces high outflows for minor events. The method presented in this paper provides a simple but quantifiable base to evaluate various stormwater detention alternatives for a full-spectrum control of runoff releases.

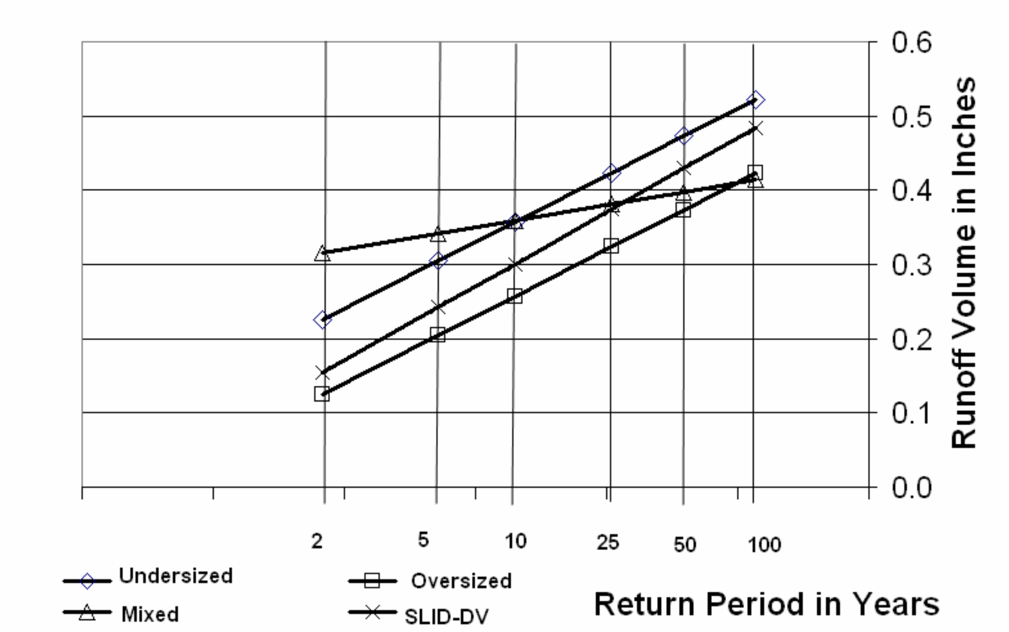

Figure 1 Impact on Hydrologic Regime using Gumbel Distribution

CONCLUSION

It takes years for a watershed to establish its hydrologic equilibrium. After a development, it also takes years to detect the change in the watershed hydrologic regime. During the planning stage, it is necessary to employ a quantifiable method to compare different alternatives and then make a final selection for the watershed development. This paper offers an easy site-based approach that utilizes the long-term runoff volume statistics as the indicator to evaluate various storm detention alternatives for low impact development.

In case that the LID design is to aim at the control of extreme events, the Gumble probabilistic distribution can be employed to quantify the runoff volume increase and the required detention volume; otherwise the exponential probabilistic distribution should be used for the full spectrum control of runoff flows. Using the pre-development runoff frequency curve as the basis, the paper presents a simplified method to evaluate the effectiveness of stormwater detention. For instance, an increase in the mean runoff volume implies a case of inadequate stormwater detention while a decrease in the mean runoff volume implies a case of oversized. The standard detention volume is defined by the increase of the runoff volume due to the watershed development.

An existing flood control detention basin is often constructed to control its 10- and 100-yr releases determined by the downstream drainage capacity. During an urban renewal process, an existing detention basin needs to be retrofitted to meet the purpose of the LID for the site. Different release alternatives should be developed for the basin to control the full-spectrum storm events. The method presented in this paper is very useful to compare alternatives, according to the new LID initiative. Although this method provides approximations to the long-term runoff statistics, it does not exclude the necessity of a detailed impact study using the long-term storm water simulation.

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