

# Low Impact Development Benefit Quantification for Urban Stormwater Management

Jeffrey Y.C Cheng PhD, P.E

## Abstract:

Low impact development (LID) is an alternative comprehensive approach to urban stormwater management. It can be used to address a wide range of water quality issues, erosion control problem, and reduce capital cost of storm drainage system. The LID cascading layout has been widely apply on the new community development. And the Level Spreaders are commonly used in combination with riparian buffers as a stormwater Best Management Practice (BMP) in many parts of the developments. These systems have not been extensively studied in urban environments to determine the impact on the flow path, nor do level spreaders have a complete detailed design guideline. This paper provides the Kinematics wave cascading model and runoff volume analysis numerical techniques to model a low impact development layout system for the purpose of comparison between effective imperviousness and traditional area weight method imperviousness.

**Key words:** Low Impact Development, Imperviousness rate, Watershed, Level spreader, Kinematics wave, cascading plane, Stormwater quality.

## Introduction:

Urban stormwater quality problems result from urban growth and development. Without adequate environmental control practices, runoff pollution occurs when storm runoff washes the pollutants from urban landscapes and carries debris to receiving waters. Stormwater BMPs offer practical solutions to enhance the runoff filtering processes using various delivery and storage facilities.

Stormwater quality control BMP consider stormwater a natural resource and captures runoff through stormwater storage facilities including, wet ponds, wetlands, vegetative filters, and various infiltration practices. The concept of BMP takes the four following steps to manage on-site storm water (USWDCM 2001):

1. Reduce runoff peaks and volumes by minimizing directly connected impervious areas (MDCIA),
2. Provide water quality capture volume (WQCV) for an on-site retention process,
3. Stabilize downstream banks and stream beds along the waterways,
4. Implement BMPs for special needs for industrial and commercial developments within the tributary area.

The term LID refers to systems and practices that use or mimic natural processes that result in the infiltration, evapotranspiration or use of stormwater in order to protect water quality and associated aquatic habitat. (EPA, 2012)

Many BMPs are collectively utilized in LID which is a site design strategy. A relatively new concept, in stormwater management, LID was proposed by Prince George's County, Maryland, in the early 1990's (EPA, 1993). The goal of LID is to maintain or replicate the predevelopment hydrologic regime through the use of design techniques to, create a functionally equivalent hydrologic landscape. LID has been widely applied on the urban stormwater management in these recent years.

MDCIA is a commonly utilized strategy in LID. The principle behind MDCIA is twofold: to reduce impervious areas, and to direct runoff from impervious surfaces over grassy areas to slow down runoff and promote soil infiltration. Draining paved areas onto porous areas can reduce runoff volumes, rates, pollutants, and cost for drainage infrastructure (USWDCM, 2001). One example of the MDCIA technique is a level spreader which is a horizontal drain that releases storm runoff

through rows of holes to produce sheet flows onto a gently sloping, vegetated surface for infiltration. Level spreaders target solids removal through settling and interception by soil infiltration. In addition to stormwater quality enhancement, the level spreader system can also provide on site stormwater reuse.

The major function of level spreaders is to diffuse a concentrated stormwater flow onto an infiltrating bed or grass buffer area. Of increasing concern is how to estimate the infiltration impact on the total runoff generated from the paved catchment that flows onto the grassed infiltrating basin (EPA,1983). The basins imperviousness rate is primal key parameter to predict the entire basin runoff volume and peak runoff flow rate. In traditional area weight method, the imperviousness did not include the storm runoff flow path. This may cause the stormwater runoff volume to be over or underestimated. To evaluate the imperviousness base on the runoff volume, the effective imperviousness is introduced. This paper presents a numerical model to trace the cascading overland flows with consideration of infiltration volume. With known rainfall volume, infiltration volume and system outflow volume, the effective imperviousness rate can be calculated.

### Level Spreader System

As illustrated in Figure 1, a level spreader system has three major components: Impervious stormwater catchments basin (catchments basin), storm drainage system with level spreader, and pervious infiltration beds. (Hathaway and Hunt 2006), the design criteria for level spreader design are varied according to the purpose of the application. The design parameters consider the drainage area upstream of the level spreader's location, storm design volume, erosion impacts and overflow bypass. The following is the summary of the design considerations for a level spreader:

1. How to convey the concentrated storm runoff from catchment basin into the level spreader structure
2. The inflow must be dissipated before it enters the level spreader.
3. The flow is distributed throughout a long linear shallow trench or behind a low berm.
4. Water then flows over the berm/ ditch, theoretically, uniformly along the entire length.
5. The design of the level spreader must take into consideration site specific conditions such as topography, vegetative cover, soil and other geologic conditions. If diffused flow is not attainable based on site conditions they should not be used.

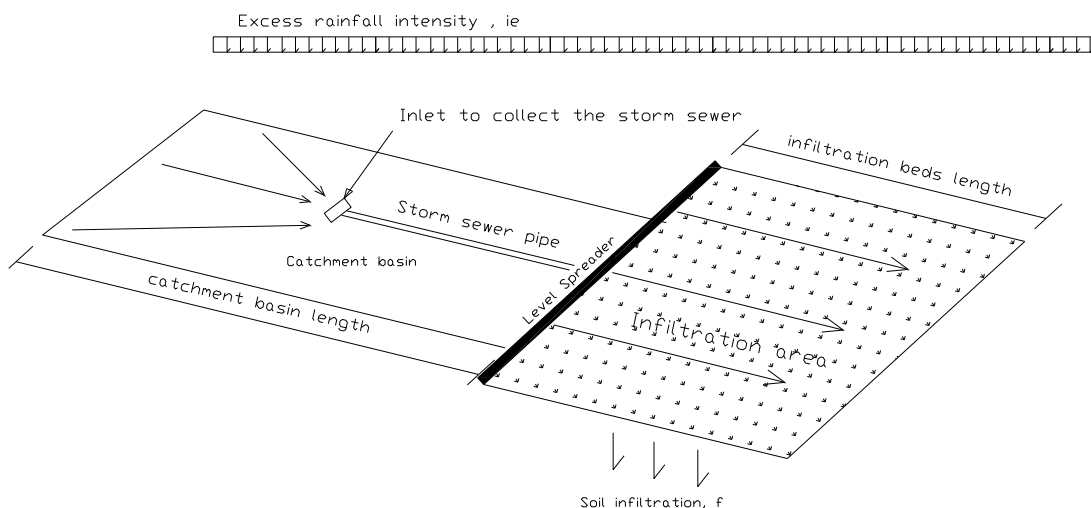


Figure 1, Level spreader system

### 1. Storm catchment basin (catchment basin)

The storm catchment basin upstream of the level spreader receives precipitation and collects runoff. Storm drainage system carries the storm flow to the level spreader and then diffuses it onto the downstream (Driscoll, 1989). In most cases, the catchment basins usually have high imperviousness rate (near to 100%) with a small amount of infiltration and depression volume capacity.

### 2. Level Spreader

As Figure 2 shows below, the level spreader structures are similar to concrete street inlets. The only difference between the two is that the street inlets collect runoff during a storm event but level spreaders spread the runoff as sheet flow during the storm. During a major event, the storm runoff will flow through both the spreader and storm drainage pipe. In order to reduce the erosion effect to the downstream infiltration beds, level spreader structure transforms the concentrate flow into diffusive sheet flow with a control flow velocity.

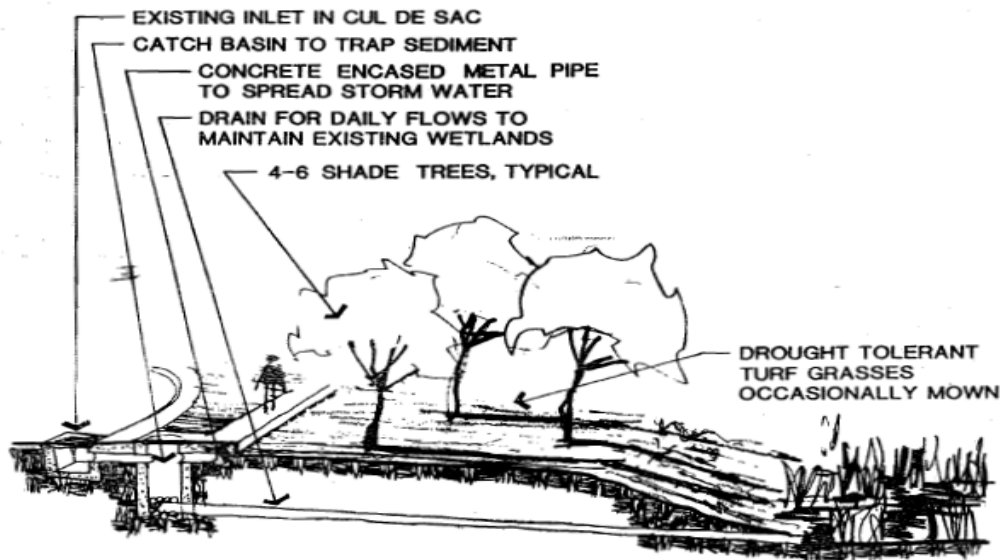


Figure 2, Typical Section Storm Water Spreader

As the rule of thumb, the spreader must evenly spread the runoff in the pipe. A simple design is to use a slotted CMP drain pipe shown in Figure 3. The major functions of level spreader are providing energy dissipation for the storm flow; reduce the flow velocity to protect infiltration basin erosion, convert the concentrated storm flow shown in Figure 4 from drainage pipe into uniform sheet flows for evenly diffusion onto the infiltrating beds.

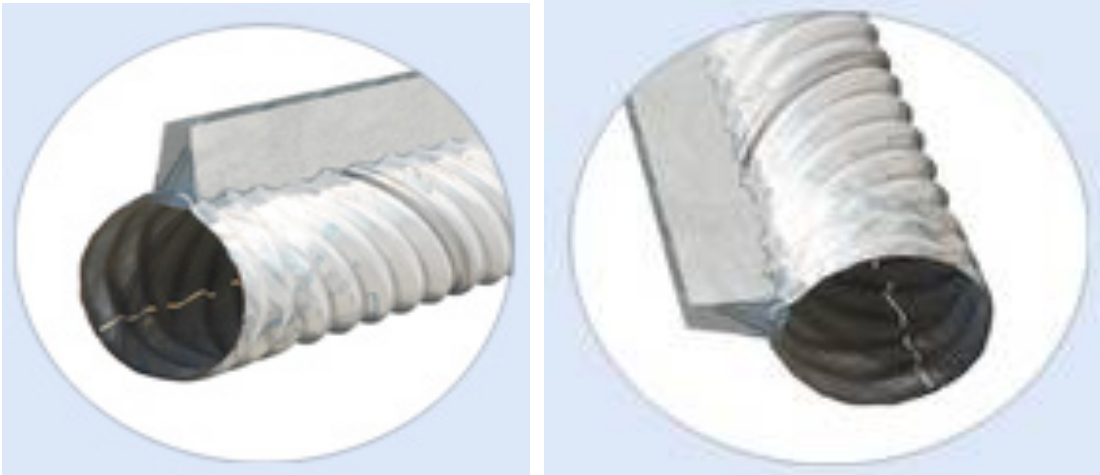


Figure 3 Typical CMP Drain pipe

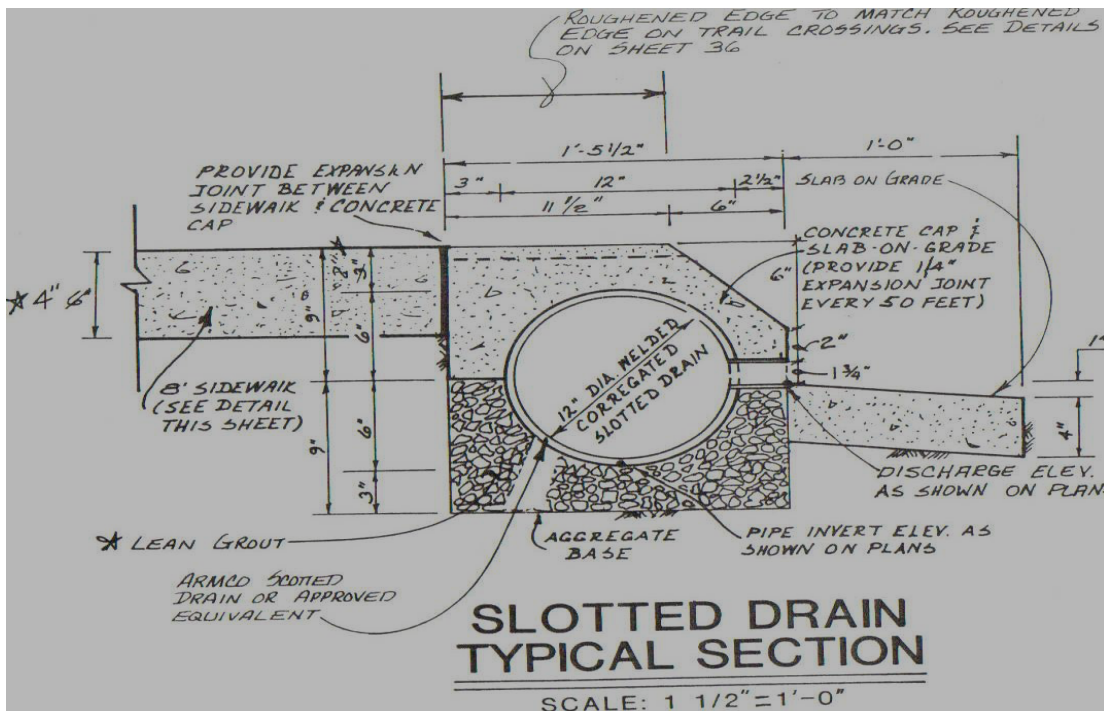


Figure 4, a detail cross section for spreader structure

### 3. Infiltration beds

After the stormwater passes over the level spreader lip, it enters the riparian buffer, often simply called the buffer. As the stormwater passes through the buffer vegetation, some of the water infiltrates and recharges to groundwater. Ideally, the buffer will remove sediment and nutrients from runoff before it reaches the stream. Additionally, the infiltration bed needs high infiltration capacity soil to allow the upper catchment basin's storm outflow recharge to ground water.

### CASCADING-PLANE MODEL

The cascading-plane model is a distributed approach that is often used for BMP designs when the flow paths and landscape are defined shown in Figure 5. In current practice, the micro-

hydrology studies under the MDCIA concept demand an in-series flow system while the macro-hydrology approaches such as the rational method relies on a lumped parameter derived by the area-weighted method (Guo, 2004). In this study, the cascading-plane model was applied to the specified level spreader layout to calculate the runoff hydrograph after the cascading process. In this paper, the effective imperviousness percentage is defined by the runoff to rainfall volumes. It is expected that the cascading layout will produce a low effective imperviousness percentage than the area-weighted method.

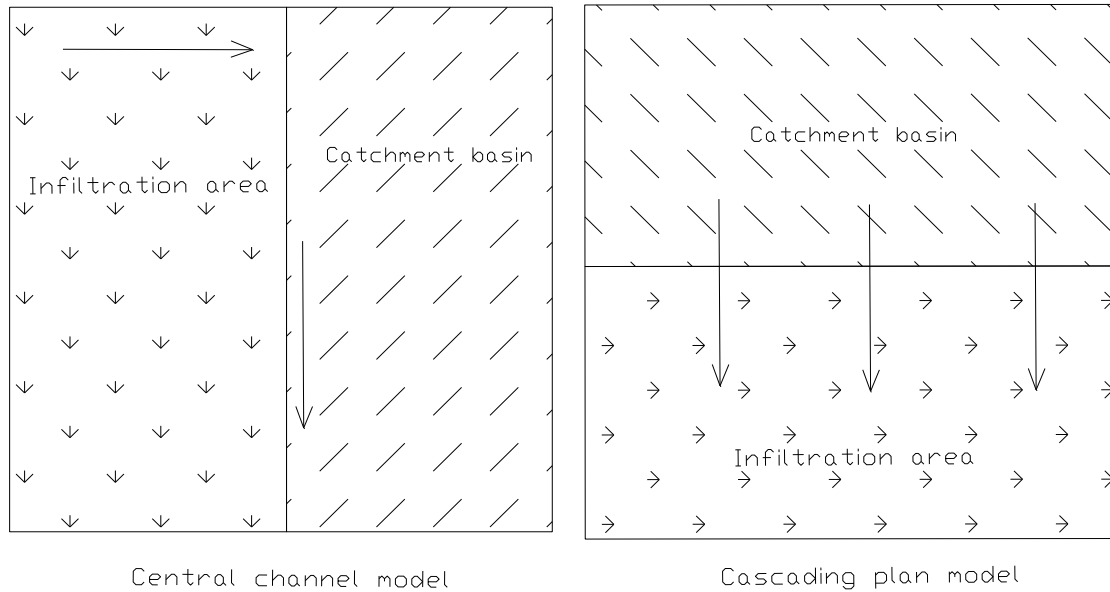


Figure 5, Central channel model and cascading plane model

The function of a cascading landscape is to spread the runoff flow generated from the upper impervious plane onto the porous plane for additional infiltration (Guo, 1993). In this study, a model of cascading planes shown in Figure 5 is derived to simulate the overland flow through cascading planes. The upstream plane (catchment basin) is set to be 100% paved and the downstream plane (infiltration beds) is set to be 100% unpaved with grass. Both planes are under the same rainfall event.

The continuity equation which describes the volume balance of inflow and outflow volumes within a finite time interval is written as:

$$(Q_2 - Q_1)\Delta t + (A_2 - A_1)\Delta x = 0 \quad (1)$$

in which  $Q_1$  is the flow at cross section 1,  $Q_2$  is the flow at cross section 2,  $A_1$  is the cross section area 1,  $A_2$  is the cross section area 2,  $\Delta t$  is the time different during flow travel,  $\Delta x$  is the flow travel distance..

Applying the kinematic wave theory to the unit-width overland flow, the flow on a plane is described as (Woolhiser and Liggett in 1967; Morgali and Linseley in 1965; Guo 1998):

$$\frac{\partial q}{\partial x} + \frac{\partial y}{\partial t} = i_e \quad (2)$$

in which  $q$  is the lateral flow runoff,  $y$  is the flow depth,  $i_e$  is the rainfall excess.

The rainfall excess is calculated as:

$$i_e = i - f \quad (3)$$

in which  $i$  is the rainfall intensity (L/T) and  $f$  is the soil infiltration rate (L/T)

Re-arranging Eq 2 yields the finite difference form as:

$$\frac{\Delta Q}{\Delta x} = I_e - \frac{\Delta Y}{\Delta t} \quad (4)$$

For each time step, the average values shall be used. Eq 4 is thus converted into:

$$\frac{\bar{Q} - \bar{Q}_i}{\Delta x} = \bar{I}_e - \frac{Y(t + \Delta t) - Y(t)}{\Delta t} \quad (5)$$

Re-arranging Eq 5 yields:

$$\bar{I}_e \Delta x + \bar{Q}_i - \bar{Q} = \frac{Y(t + \Delta t) - Y(t)}{\Delta t} \Delta x \quad (6)$$

Since the surface detention is the storage volume under the water surface profile. Eq 6 essentially depicts the change rate of the storage volume in the unit-width surface. When  $i_e = 0$ , Eq 7 is reduced to the general hydrologic equation of continuity that states:

$$I - O = \frac{dS}{dt}; \text{ Inflow rate} - \text{outflow rate} = \text{change rate of storage volume} \quad (7)$$

Considering that the representative values for each time interval is the average, Eq 7 becomes:

$$\frac{I_e(t + \Delta t) + I_e(t)}{2} \Delta x + \frac{Q_i(t + \Delta t) + Q_i(t)}{2} - \frac{Q(t + \Delta t) + Q(t)}{2} = \frac{Y(t + \Delta t) - Y(t)}{\Delta t} \Delta x \quad (8)$$

Open channel flow is described by Manning's equation as:

$$Q = \frac{1.49}{n} AR^{2/3} S^{1/2} \quad (9)$$

in which Q is the channel flow discharge rate, n is the Manning channel surface roughness number, A is flow cross section area, R is hydraulic radius and S is channel slope (Chow, 1988). Considering the unit-width flow, the flow area A is replaced by the flow depth Y as:

$$Q(t + \Delta t) = \frac{1.49}{n} [Y(t + \Delta t)]^3 \sqrt{S_o} \quad (10)$$

Numerically, for each time step, the relationship between flow runoff Q(t+Δt) and flow depth Y(t+Δt) can be solved by Equation's 9 and 10.

### Storm catchments basin

The upper impervious plane or catchment basin in the cascading system doesn't receive any inflow, thus  $Q_i(t + \Delta t) = Q_i(t) = 0$  and infiltration is ignored since we assume the impervious rate is 100% the catchment basin should not allow any infiltration into groundwater ( $f=0$ ). Aided by Eq 4, Eq 9 is reduced to:

$$\frac{I(t + \Delta t) + I(t)}{2} \Delta x - \frac{Q(t + \Delta t) + Q(t)}{2} = \frac{Y(t + \Delta t) - Y(t)}{\Delta t} \Delta x \quad (11)$$

The boundary condition for the upper plane includes:

$$Y(t) = 0 \quad \text{at } x=0 \text{ (upper boundary) for all times} \quad (12)$$

The initial condition for the storm catchments plane is dry bed defined as:

$$Y(x) = 0 \text{ at } t=0 \text{ everywhere} \quad (13)$$

With Equation, 11 and 10, flow runoff  $Q(t+\Delta t)$  and flow depth  $Y(t+\Delta t)$  can be solved.

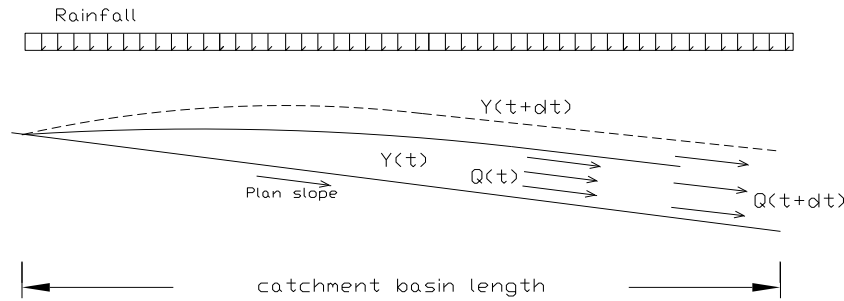


Figure 6,  
Catchments  
basin's flow  
profile  
**Infiltration**

### beds

For the lower infiltration beds, the inflow,  $Q_i$ , is defined by the outflow hydrograph generated from the upper impervious plane. And the beds will allow the infiltration into the ground ( $f > 0$ ), the equation 3 and 4 can be rewritten as:

$$\frac{\partial q}{\partial x} + \frac{\partial y}{\partial t} = I - f + Q_i \quad (14)$$

And equation 5 can be re-write as

$$\frac{\Delta Q}{\Delta x} = I - f + Q_i - \frac{\Delta Y}{\Delta t} \quad (15)$$

Since  $I_e = I - f$ , from the equation 9 and 10 can be applied for infiltration beds, with two known equations and two un-known, flow runoff  $Q(t+\Delta t)$  and flow depth  $Y(t+\Delta t)$ . The flow runoff and flow depth can be found. Having calculated the overland flow hydrograph at the outlet of the lower porous plane, the total runoff volume produced by these two cascading planes is calculated by (Guo 2004):



$$V_T = \sum_{t=0}^{t=T_b} q(t)\Delta t \quad (16)$$

In which  $V_T$  = total unit-width runoff volume, and  $T_b$  = base time of runoff hydrograph.

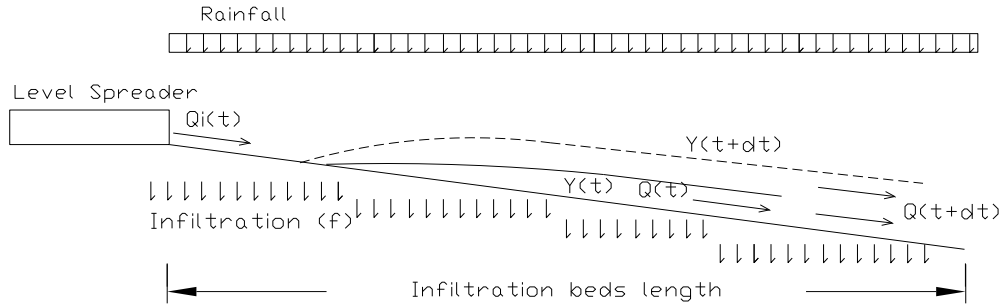


Figure 7, Infiltration beds cascading profile

#### Runoff volume and effective imperviousness

All volumes in the model must follow the mass balance principle. As:

$$V_T - V_f - V_o - V_s = 0 \quad (17)$$

In which  $V_T$  = total unit-width runoff volume,  $V_f$  = infiltration volume through the lower beds area,  $V_o$  = entire level spreader outflow volume, and  $V_s$  = the storage volume, which is the storm runoff residual on both the upper and lower basins.

The total rainfall volume for entire level spreader system can be presented as the following

$$V_T = \sum_{t=0}^{t=T_b} I(t) \cdot A \quad (18)$$

In which  $I(t)$  is the rainfall depth for each time step

And the total outflow volume for entire system is

$$V_o = \sum_{t=0}^{t=T_b} Q_{out}(t)\Delta t \quad (19)$$

In which  $Q_{out}(t)$  is the stormwater runoff rate in each time step for entire level spreader system.

With the equation 17, 18 and 19, the total infiltration volume for runoff discharge into groundwater can be described as

$$V_f = \sum_{t=0}^{t=T_b} [I(t) \cdot A - Q_{out}(t)\Delta t] - V_s \quad (20)$$

To evaluate the level spreader system land imperviousness, from the storm runoff volume point view the effective imperviousness for the level spreader cascading system is defined as:

$$I_{effective} = \frac{V_o}{V_T} \quad (21)$$

Traditional area weight method for imperviousness can be calculate as (USWDCM, 2001)



$$I_{\text{area-weight}} = \frac{\sum_1^n I_n A_n}{A} \quad (22)$$

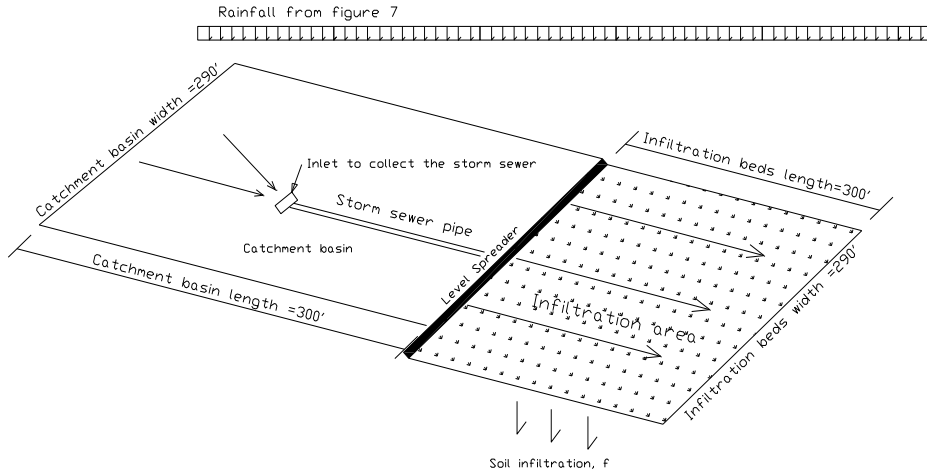


Figure 8, case study for the level spreader system

### Case study

In order to determine the effectiveness of a level spreader, this paper suggests calculating the effective imperviousness for the cascading system and comparing this to the traditional area weight method imperviousness.

As show above, in figure 8, a level spreader system has an upper 300-foot paved asphalt concrete parking lot that drains onto on the lower 300-foot grass infiltration beds with 290 ft of level spreader on a continue slope of 1.0% shown in figure 6. As recommended for asphalt concrete surface, the Manning's n of 0.016 is applied to the upper paved plane and 0.05 is applied to the lower infiltration beds area.

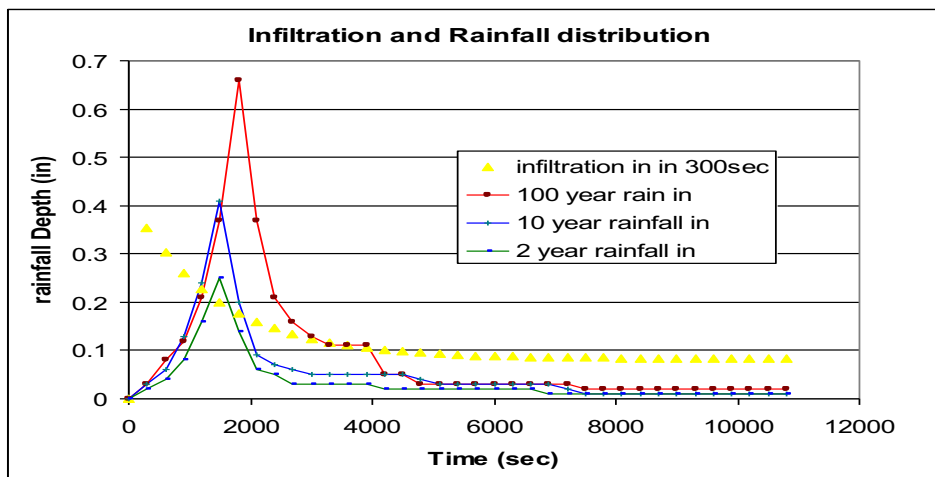


Figure 9, Rainfall distribution for level spreader system case study.

To demonstrate the relationship of the rainfall intensity, rainfall depths and soil infiltration, this paper uses 1.15 to 3.51 inch of total rainfall depth and three different soils for infiltration. The entire rainfalls are distributed in three hours or 10800 seconds (see above Figure 9). Lower

infiltration bed's soil infiltration rates have been classified as sand soil, sand and clay mix soil and clay only soils and the infiltration factor and volume are presented in table 1. The infiltration rates are distributed base on Horton infiltration model, (USWDCM 2001).

NRCS Hydrologic Soil Group	Infiltration (inches per hour)		Decay
	Initial— $f_i$ (in/hr)	Final— $f_o$ (in/hr)	Coefficient— $a$
A	5.0	1.0	0.0007
B	4.5	0.6	0.0018
C	3.0	0.5	0.0018
D	3.0	0.5	0.0018

Table 1, Soil infiltration, base on the NRCS hydrologic group classification, A is sandy soil, B is clay and sandy mix and C & D are clay.

With the cascading numerical model calculation, the total rainfall volume, infiltration volume and outflow volumes of the level spreader system can be calculated. These volumes are presented in table 2. As table 2 presents, site infiltration volumes show minor increases which correspond to rainfall depth increases. This phenomena indicates that the urbanization impact is greater in high frequency, low intensity rainfall events (minor design events), and less in low frequency, high intensity rainfall events (major design events).

Total Rainfall depth (inch)	Total Rainfall Volume (cf)	Total Infiltration Volume (cf)	Outflow Volume from Upper basin (cf)	Total outflow volume from entire level spreader system (cf)
3.28	47626	14274	23284	33028
1.98	28750	12268	14021	17431
1.27	18440	10854	9222	7550

Table 2, Total Volumes of Level Spreader System for Sand/Clay mix (Type B) soils.

The main purpose of this paper is to make the comparison between the traditional area weight method of imperviousness and effective imperviousness, by calculating these rates at different volumes. As Figure 10 shows, the area weight method imperviousness has no effect to rainfall depth and the rate remains the same at 50%. The effective imperviousness rate with total rainfall depth has a positive ratio. With lower rainfall intensity events, the effective imperviousness rates are lower than when calculated with the traditional area weight method.



Figure 10, infiltration basin picture

As the Figure 10 shows, the level spreader provides some irrigation function for the grass area (infiltration beds); the picture shows that the grasses close to the level spreader are greener than the other grass areas.

### Conclusion

In stormwater management, watershed imperviousness is a primal parameter in urban hydrology to evaluate the storm runoff rate and volume. This study uses a cascading-plane model to represent the physical landscaping layout and use the runoff volume to evaluate the effective imperviousness. The cascading model for the level spreader provides a new methodology to analyze the basin imperviousness. Under the traditional area weight method concept, the impervious rate for the case study should remain constant at 50% since the impervious area is equal to pervious area. With the cascading model however, the effective imperviousness can be represented from 14% to 81%, based on different rainfall depth and different soil infiltration rates. For a high frequency but low intensity rainfall event, the traditional area weight method over estimate the storm runoff volume. The main reason for the traditional area weight method to overestimate storm runoff is that the method does not consider the basin's flow path and ignores the additional soil infiltration volume when overflow passes over the pervious surface area.

This study introduces the effective imperviousness rate, and provides the cascading model was successful at representing the physical behaviors in terms of runoff and infiltration of the level spreader system.

During the numerical modeling, this study found that part of the runoff generated from the upper impervious basin was intercepted by lower infiltration beds at an early stage of rainfall event. This causes the total system outflow to be less than area weight method estimate. This paper also found that the effective imperviousness calculated by the cascading model is much less than traditional area weight method in most of low intensity but high frequency event cases.

Additionally, the latest developments in stormwater management encourage reducing development land imperviousness rate by changing the site plan layout. In this study, the level spreader system was introduced to reduce the imperviousness rate under the MDCIA concept by

direct runoff from impervious surfaces over grassy areas to slow runoff and promote soil infiltration. The use of an infiltration bed with a level spreader system is frequent in soils with good water infiltration capacity. The correct design of level spreader system depends greatly on the accuracy in determining the volume of water from storm catchments basin.

If the catchments basin has any low points however, the flow will tend to concentrate. This concentrated flow with high flow velocity may cause an erosion problem. By installing a spreader structure, the concentrated flow can be diffused into sheet flow and decrease flow velocity to reduce erosion.

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