Low-Impact Development Hydrologic Analysis

- *Site Planning*
- *Hydrology*
- *Distributed IMP Technologies*
- *Erosion and Sediment Control*
- *Public Outreach*

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LOW-IMPACT DEVELOPMENT HYDROLOGIC ANALYSIS

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LOW-IMPACT DEVELOPMENT HYDROLOGIC ANALYSIS

CHAPTER 1. INTRODUCTION

1.1 OBJECTIVES

The purpose of this document is to provide low-impact development (LID) hydrologic analysis and computational procedures used to determine low-impact development stormwater management requirements. The hydrologic analysis presented is based on the Soil Conservation Service (SCS) TR-55 hydrologic model (SCS,1986).

Design concepts are illustrated by the use of runoff hydrographs that represent responses to both conventional and low-impact development. Low-impact development site planning and integrated management practices (IMPs) are defined and categorized into components of low-impact development objectives. Computational procedures for determining IMP requirements are demonstrated through design examples.

The process for developing low-impact development hydrology is illustrated in Figure 1.1. This figure lists the sequential steps and the sections in the manual where the methods to calculate or determine the specific requirements are provided.

1.2 KEY HYDROLOGIC PRINCIPLES

This section of the report provides an overview and general description of the key hydrologic principles involved in low-impact development, and provides guidance on the hydrologic analysis required for the design of low-impact development sites. The key hydrologic principles that are described include: precipitation and design storm events, rainfall abstractions, surface runoff, and groundwater recharge and flow.

Precipitation and Design Storm Events. Data for precipitation, including both snow and rain, are used in site planning and stormwater design. Precipitation occurs as a series of events characterized by different rainfall amount, intensity, and duration. Although these events occur randomly, analysis of their distribution over a long period of time indicates that the frequency of occurrence of a given storm event follows a statistical pattern. This statistical analysis allows engineers and urban planners to further characterize storm events based on their frequency of occurrence or return period. Storm events of specific sizes can be identified to support evaluation of designs. Storms with 2- and 10-year return periods are commonly used for subdivision, industrial, and commercial development design.

The 1- and 2-year storm events are usually selected to protect receiving channels from sedimentation and erosion. The 5- and 10-year storm events are selected for adequate flow conveyance design and minor flooding considerations. The 100-year event is used to define the limits of floodplains and for consideration of the impacts of major floods.

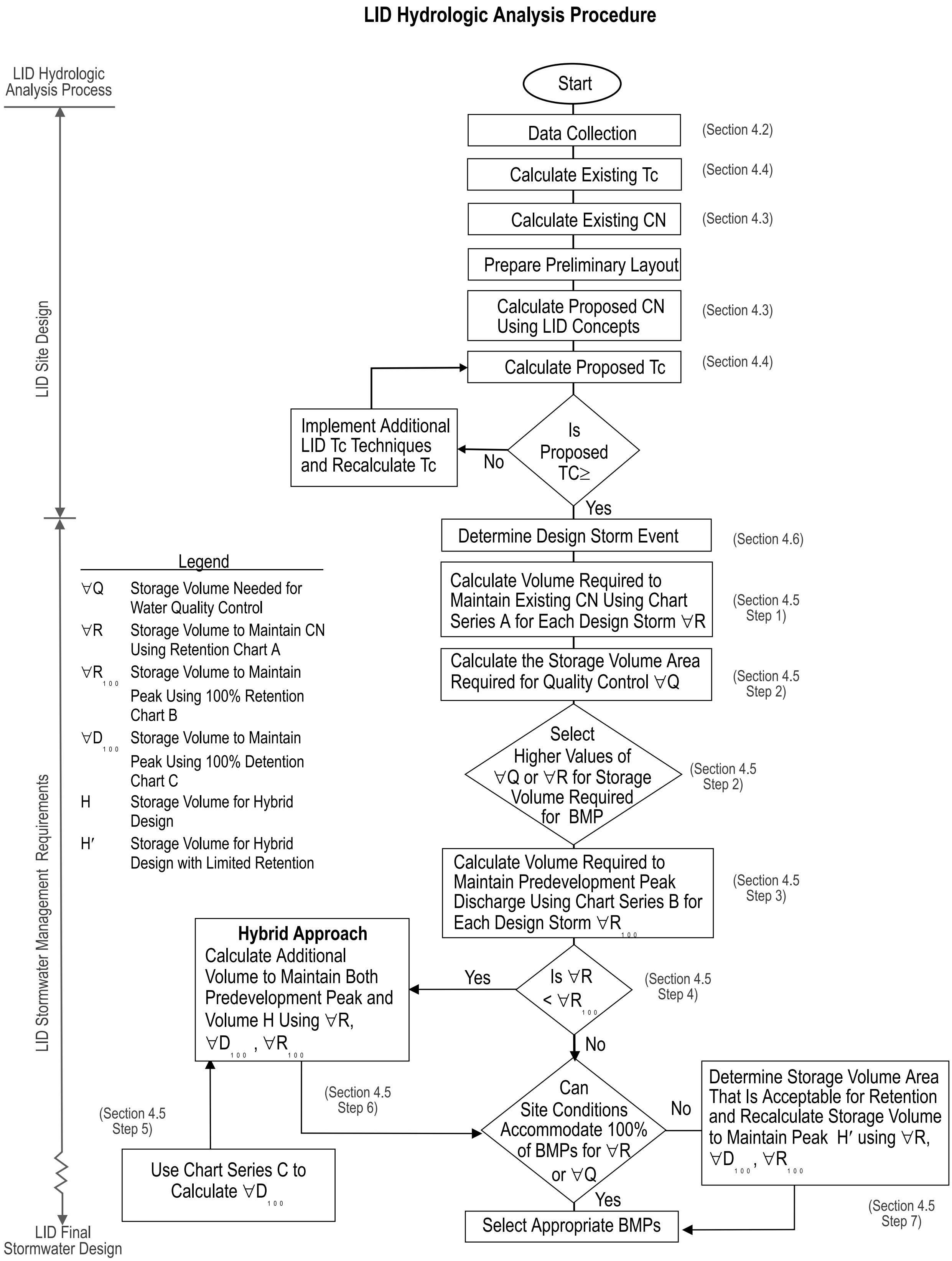

Figure 1.1. Low-impact development analysis procedure

There are numerous excellent texts and handbooks that describe the use of rainfall data to generate a "design storm" for the design of drainage systems (e.g., ASCE , 1994; Chow, 1964; SCS, 1985). For LID, a unique approach has been developed to determine the design storm based on the basic philosophy of LID. This approach is described in Section 4.6.

Storm events commonly used for evaluation of designs differ for the various climatic regions of the United States Summaries of typical storm event characteristics (i.e., amount/intensity, duration, and return period) are provided in national maps in Technical Paper 40 (Department of Commerce, 1963). In humid regions such as the Mid-Atlantic states, the 2-year storm is approximately 3 inches of rainfall and the 10-year storm is approximately 5 inches of rainfall. The 2-year storm has a 50 percent probability of occurring in any given year, while the 10-year storm has a 10 percent probability of occurring in any given year. In dry areas, such as portions of Colorado and New Mexico, the 2-year storm is approximately 1.5 inches of rainfall and the 5-year storm is approximately 2.0 inches of rainfall.

The rainfall time distributions vary throughout the geographic regions of the U.S. They are Type I, Type IA, Type II, and Type III. These differences in the distributions play a very important role in sizing the IMPs.

Rainfall Abstractions. Rainfall abstractions include the physical processes of interception of rainfall by vegetation, evaporation from land surfaces and the upper soil layers, transpiration by plants, infiltration of water into soil surfaces, and storage of water in surface depressions. Although these processes can be evaluated individually, simplified hydrologic modeling procedures typically consider the combined effect of the various components of rainfall abstraction.

The rainfall abstraction can be estimated as a depth of water (inches) over the total area of the site. This depth effectively represents the portion of rainfall that does not contribute to surface runoff. The portion of rainfall that is not abstracted by interception, infiltration, or depression storage is termed the excess rainfall or runoff.

The rainfall abstraction may change depending on the configuration of the site development plan. Of particular concern is the change in impervious cover. Impervious areas prevent infiltration of water into soil surfaces, effectively decreasing the rainfall abstraction and increasing the resulting runoff. Postdevelopment conditions, characterized by higher imperviousness, significantly decrease the overall rainfall abstraction, resulting not only in higher excess surface runoff volume but also a rapid accumulation of rainwater on land surfaces.

The LID approach attempts to match the predevelopment condition by compensating for losses of rainfall abstraction through maintenance of infiltration potential, evapotranspiration, and surface storage, as well as increased travel time to reduce rapid concentration of excess runoff. Several planning considerations combined with supplemental controls using LID integrated management practices can be used to compensate for rainfall abstraction losses and changes in runoff concentration due to site development.

Surface Runoff. The excess rainfall, or the portion of rainfall that is not abstracted by interception, infiltration, or depression storage, becomes surface runoff. Under natural and undeveloped conditions, surface runoff can range from 10 to 30 percent of the total annual precipitation (Figure 1.2). Depending on the level of development and the site planning methods used, the alteration of physical conditions can result in a significant increase of surface runoff to over 50 percent of the overall precipitation. In addition, enhancement of the site drainage to eliminate potential on-site flooding can also result in increases in surface runoff. Alteration in site runoff characteristics can cause an increase in the volume and frequency of runoff flows (discharge) and velocities that cause flooding, accelerated erosion, and reduced groundwater recharge and contribute to degradation of water quality and the ecological integrity of streams.

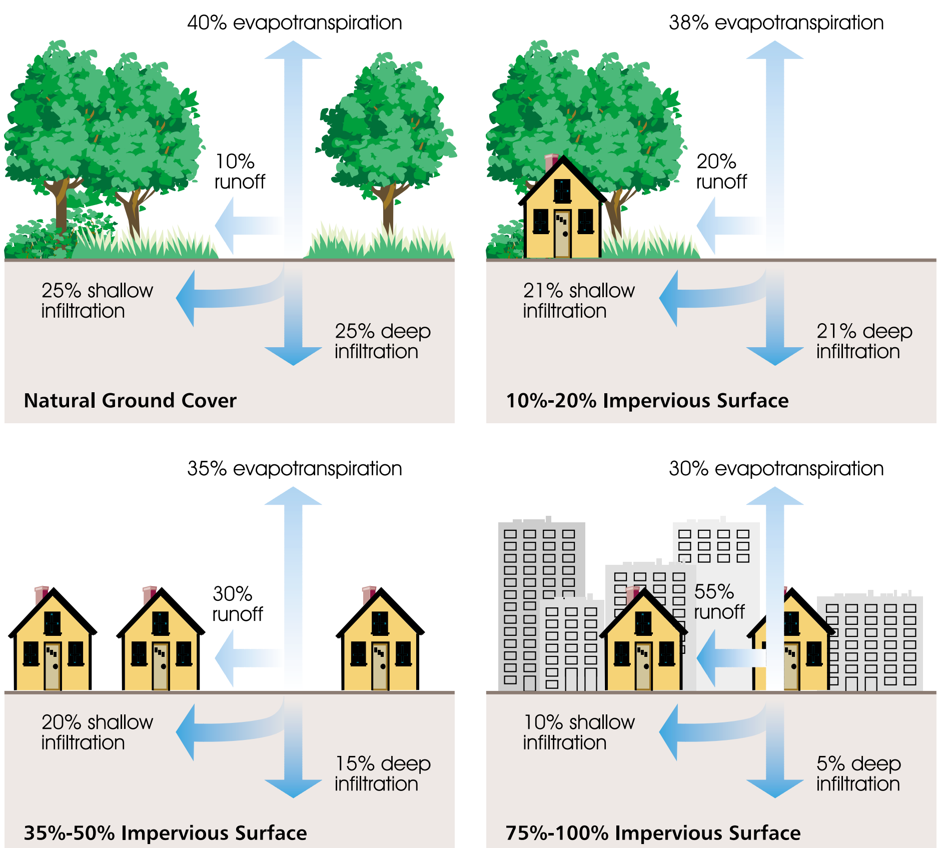

Figure 1.2. Runoff Variability with Increased Impervious Surfaces (FISRWG, 1998)

Groundwater Recharge. A considerable percentage of the rainfall abstraction infiltrates into the soil and contributes to the groundwater. Groundwater may be part of a local, intermediate, or regional water table, as illustrated in Figure 1.3. The local water table is often connected to nearby streams, providing seepage to streams during dry periods and maintaining base flow essential to the biological and habitat integrity of streams. A significant reduction or loss of groundwater recharge can lead to a lowering of the water table and a reduction of base flow in receiving streams during extended dry weather periods. Headwater streams, with small contributing drainage areas, are especially sensitive to localized changes in groundwater recharge and base flow.

1.3 HYDROLOGIC ALTERATIONS TO SITE DEVELOPMENT

Climate coupled with the geological and vegetative features of a watershed produce a unique hydrologic regime. Aquatic, wetland and riparian biota have evolved by adapting to this unique regime (Cairns, 1993). Urban development changes this regime, resulting in a new annual and seasonal hydrologic balance, causing frequency distribution changes of peak flows, magnitude and duration of high flows, and magnitude and duration of low flows.

Changes in the Existing Hydrologic Balance. Both the annual and seasonal water balance can change dramatically as a result of development practices. These changes include increases in surface runoff volume and decrease in evapotranspiration and groundwater recharge rates. For example, eastern hardwood forests typically have an annual water balance comprised of about 40% evapotranspiration, 50% subsurface flows and less than 10% surface runoff volume. Development, depending on its size and location in a watershed, alters the existing hydrologic balance by increasing surface flow volumes up to 43%, reducing subsurface flows to 32%, and reducing evapotranspiration rates to 25%. All this results in major changes to the local hydrology.

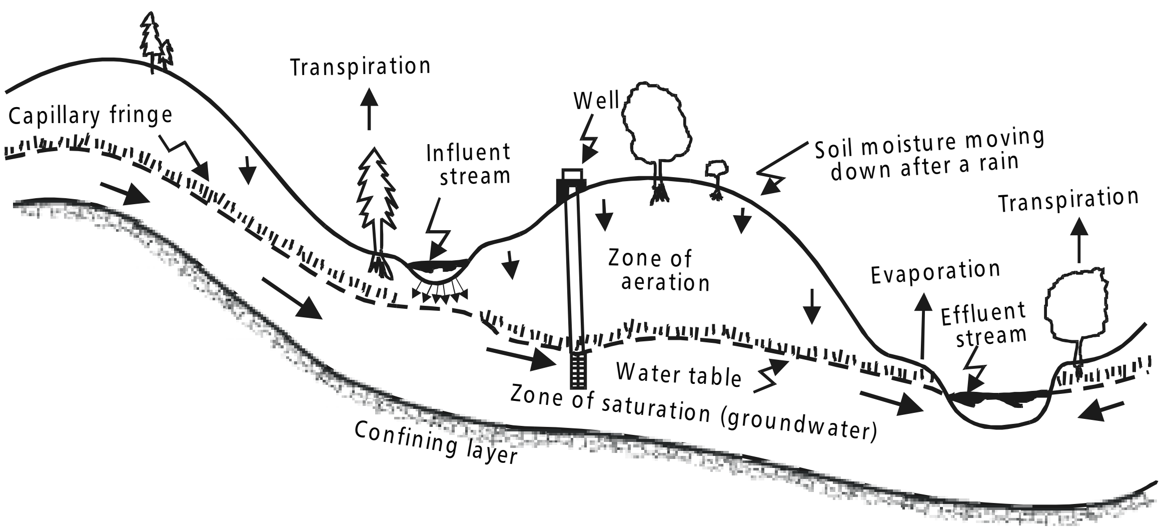

Figure 1.3. Groundwater in Local, Intermediate, or Regional Setting

Changes in Frequency Distribution of High Flows. Increased stream flows due to changes in surface topography result in more rapid drainage and increases in the amount of hydrologically active areas within a watershed. Hydrologically active areas are areas that produce runoff during precipitation events. These areas also increase in size, in comparison to their predevelopment size, due to reductions in depression storage capacity and in the retention capacity of the site's existing natural vegetation. Increases in impervious ground covers also contribute to increasing volumes of runoff. These changes coupled with shorter times of concentration result in sharp modifications to the shape of the resulting hydrograph.

A hydrograph represents diagramatically the changes in stream flow over time and during a storm event. As a site is developed, topography and land surfaces are modified, with the resulting hydrograph reflecting decreases in base flow, higher and more rapid peak discharge, and more runoff volume. As illustrated in Figure 1.4, development generally results in stream discharges which increase rapidly and recede at rates much greater than under natural conditions. Higher flow velocities also increase the runoff's potential to erode and transport sediment and pollutants. The frequency of that peak flow event also increases. In urbanized watersheds, extreme events, such as the frequency of the bankfull flows, might be expected to occur 2 to 8 times per year compared to less than once per year under natural condition.

Changes in Magnitude, Frequency, and Duration of Low Flows. Impervious surfaces such as roads, rooftops, driveways, and sidewalks reduce infiltration, filtration, and groundwater recharge. This can lower water tables, impacts flow to existing wetlands, and reduce the water available for stream base flow. Similarly, decreases in the time of concentration, or runoff travel time, reduces the time available for water to infiltrate. The problem may be further compounded by the installation of shallow ground water drainage systems to accommodate road or building construction. Lower recharge rates for

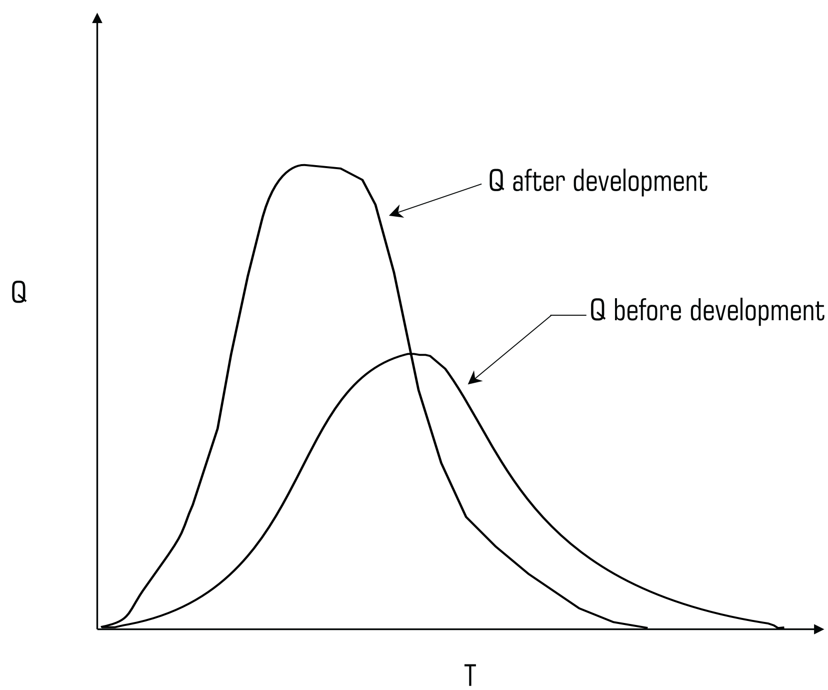

Figure 1.4. Hydrologic Alterations Due to Site Development

groundwater in a watershed are generally reflected in lower stream base flows. Low rates of recharge also extend low flow durations; particularly during prolonged droughts.

Conversely small storms which prior to development did not produce surface runoff now frequently do so.

Typical alterations to the hydrologic regime as a result of development include, but are not limited to, the following;

- Increased runoff volume
- Increased imperviousness
- Increased flow frequency, duration, and peak runoff rate

- Reduced infiltration (groundwater recharge)
- Modification of the flow pattern
- Faster time to peak, due to shorter Tc through storm drain systems
- Loss of storage

1.4 CONVENTIONAL STORMWATER MANAGEMENT

Traditionally, the response of watersheds to urban development has been measured in terms of changes in the flow regime, with management efforts focused on the prevention of property damage from flooding as previously described. Stormwater management efforts historically followed the design storm concept described earlier and focused almost exclusively on runoff collection systems such as curbs and gutters, and pipe conveyance systems which discharged directly to receiving water bodies. Stormwater quantity (peak discharge rate) management was incorporated as IMPs to address concerns about downstream flooding and stream bank erosion. Typically these IMPs, usually ponds or detention basins were located at the lowest point of the site and at the end of the network of inlets and pipes. This approach is often referred to as the "end of pipe" control approach.

Stormwater Quantity. Stormwater quantity controls are set by states or local government agencies to prevent site and downstream flooding and erosion. A typical design criteria requires that "the post development peak discharge for a 2- and 10- year frequency storm event be maintained at a level equal to or less than the respective 2-and 10-year predevelopment peak discharge rates, through the use of stormwater management structures that control the timing and rate of runoff." This requirement is based on the design storm concept described earlier under in this section.

The selection of the 2-year return frequency storm is based on a belief that the 1.5- to 2-year storm dictates the shape and form of natural channels (Leopold, et al., 1964, 1968). The selection of the 10-year storm is based on consideration of possible property damage due to local flooding and stream bank erosion

It is now becoming increasingly recognized that this type of approach is insufficient for a number of reasons:

- It does not address the loss of storage volume provided by rainfall abstractions, and consequently does not provide for groundwater recharge and maintenance of base flow during low flow periods.
- The 2 / 10 year storm policy does not adequately protect downstream channels form accelerated erosion.
- The inspection and maintenance costs of this approach are becoming an increasing burden for local governments

Stormwater Quality. The second stage in stormwater management was the recognition that runoff from urban areas was more polluted than runoff from undeveloped areas and was degrading the water quality of the receiving streams and other water bodies. For the most part this problem was addressed by modifying and improving the end of pipe approach to improve the pollutant removal effectiveness of these IMPs. Extended detention, forebays, wetlands, permanent pools and numerous other design improvements were introduced.

Also the concept of controlling the "first flush" was introduced. A "first flush" event is defined as the first half inch of runoff from an impervious surface, and is expected to carry with it most of the pollutant load associated with stormwater. In terms of a typical storm hydrograph, the "first flush" represents a small portion of a storm's total discharge, but a larger percentage of the total loading for a particular contaminant.

Designers and modelers discovered that the design storm approach used for peak discharge control was not appropriate foe water quality control issues, since water quality issues were related to the annual volume of runoff which consists of many small storms. For example, the rainfall frequency distribution at National Airport, Arlington, VA, for the period of 1908 to 1985 indicates that the average total annual precipitation is 38.40 inches and storms of 1 inch or less account for 70% of the total annual precipitation (Figure 1.5). In addition, if the first inch of the storm events greater than 1 inch are considered, the total annual volume of 1 inch or less is in the range of 80 to 85%. These relationships are not

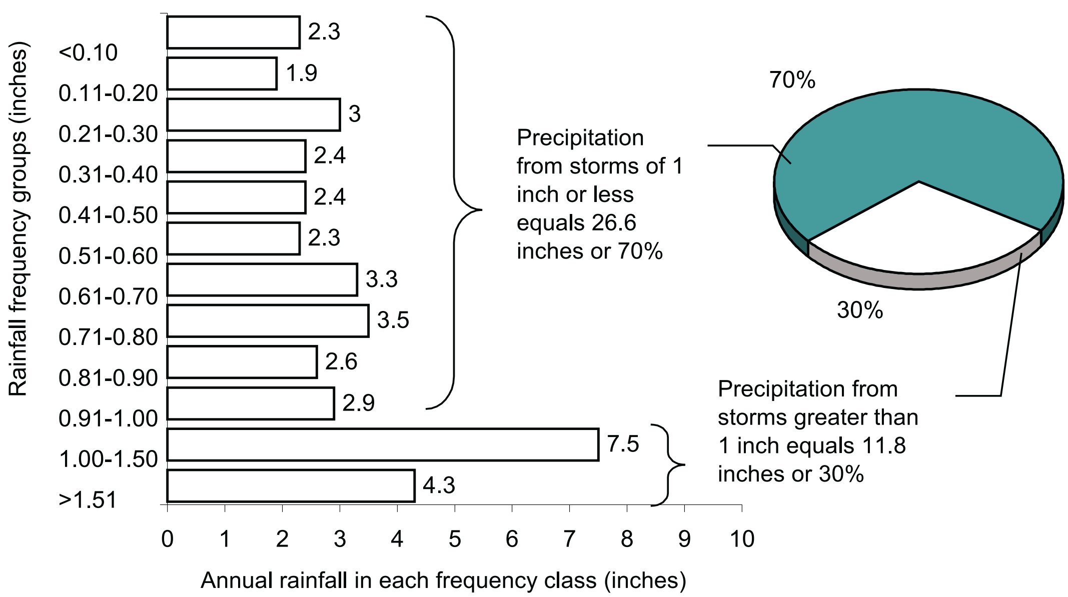

Figure 1.5. Rainfall Frequency Distribution at National Airport —1980 to 1985

considered in the traditional design storm concept because that approach is based on control of infrequent storms that are large enough to produce floods. However, this annual rainfall distribution pattern becomes an important consideration in the selection of appropriate rainfall conditions for low-impact development.

1.5. HYDROLOGIC COMPARISON BETWEEN CONVENTIONAL AND LOW-IMPACT DEVELOPMENT APPROACHES

Conventional stormwater conveyance systems are designed to collect, convey, and discharge runoff as efficiently as possible. Conventional stormwater management controls

(IMPs) are typically sited at the most downstream point of the entire site (end-of-pipe control). The stormwater management requirement is usually to maintain the peak runoff rates at predevelopment levels for a particular design storm event. Therefore, especially where a stormwater management pond is constructed, the peak flow will not be fully controlled for those storm events that are less severe than the design storm event. Low-impact development approaches, on the other hand, will fully control these storm events. This is a very important and significant difference between the two approaches. Figure 1.6 illustrates the hydrologic response of the runoff hydrograph to conventional IMPs.

- Hydrograph 1 represents the response to a given storm of a site in a predevelopment condition (i.e., woods, meadow). The hydrograph is defined by a gradual rise and fall of the peak discharge and volume.
- Hydrograph 2 represents a post development condition with conventional stormwater IMPs, such as a detention pond. Although the peak runoff rate is maintained at the predevelopment level, the hydrograph exhibits significant increases in the runoff volume and duration of runoff from the predevelopment condition.

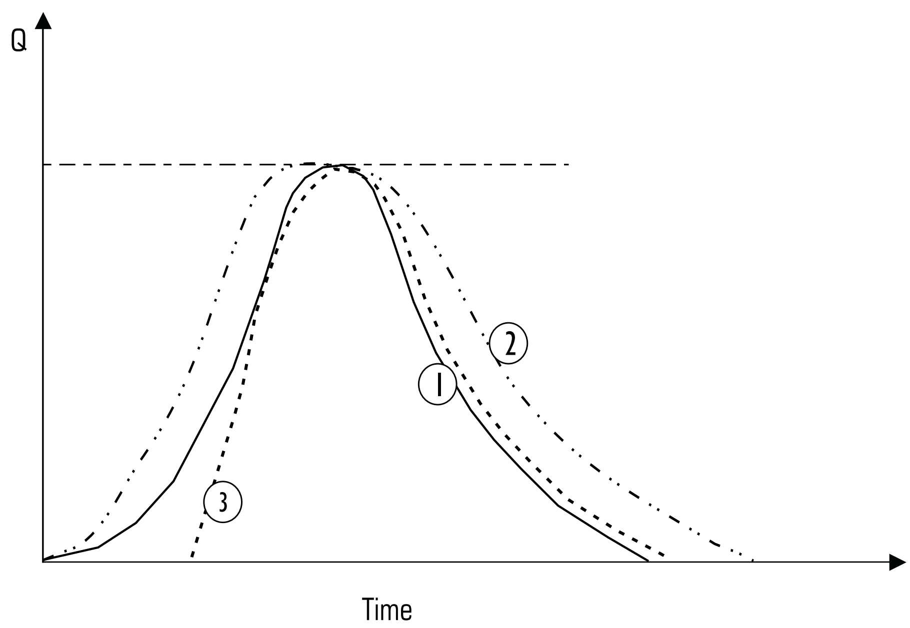

Figure 1.6. Comparison of the Hydrologic Response of Conventional and LID IMPs.

- Hydrograph 3 represents the response of post development condition that incorporates low-impact development stormwater management. Low-impact development uses undisturbed areas and on-lot and distributed retention storage to reduce to reduce runoff volume. The peak runoff rate and volume remain the same as the pre-development condition through the use of on-lot retention and/or detention. The frequency and duration of the runoff rate are also much closer to the existing condition than those typical of conventional IMPs.

The Distributed Control Approach. In comparison with conventional stormwater management, the objective of low-impact development hydrologic design is to retain the post development excess runoff volume is discrete units throughout the site to emulate the predevelopment hydrologic regime. This is called a distributed control approach. Management of both runoff volume and peak runoff rate is included in the design. The approach is to manage runoff at the source rather than at the end of pipe. Preserving the hydrologic regime of the predevelopment condition may require both structural and nonstructural techniques to compensate for the hydrologic alterations of development.

The Hydrologically Functional Landscape. In low-impact development, the design approach is to leave as many undisturbed areas as practical to reduce runoff volume and runoff rates by maximizing infiltration capacity. Integrated stormwater management controls or IMPs are then distributed throughout the site to compensate for the hydrologic alterations of development. The approach of maintaining areas of high infiltration and low runoff potential in combination with small, on-lot stormwater management facilities creates a “hydrologically functional landscape.” This functional landscape not only can help maintain the predevelopment hydrologic regime but also enhance the aesthetic and habitat value of the site.

Integrated Management Practices (IMPs). Low-impact development technology employs microscale and distributed management techniques, called integrated management practices (IMPs) to achieve desired post-development hydrologic conditions. LID IMPs are used to satisfy the storage volume requirements described in Section 3.3. They are the preferred method because they can maintain the predevelopment runoff volume and can be integrated into the site design. The design goal is to locate IMPs at the source or lot, ideally on level ground within individual lots of the development. Management practices that are suited to low-impact development include:

- bioretention facilities
- dry wells
- filter/buffer strips and other multifunctional landscape areas
- grassed swales, bioretention swales, and wet swales
- rain barrels
- cisterns
- infiltration trenches

More information on IMPs can be obtained in the publication titled, “Low-Impact Development Design Strategies: An Integrated Design Approach,” prepared by Prince George’s County, DM, May 1999.

CHAPTER 2. LID HYDROLOGIC ANALYSIS COMPONENTS

The low-impact development "functional landscape" emulates the predevelopment temporary storage (detention) and infiltration (retention) functions of the site. This functional landscape is designed to mimic the predevelopment hydrologic conditions through runoff volume control, peak runoff rate control, flow frequency/duration control, and water quality control.

Runoff Volume Control. The predevelopment volume is maintained by a combination of minimizing the site disturbance from the predevelopment condition and then providing distributed retention IMPs. Retention IMPs are structures that retain the runoff for the design storm event.

Peak Runoff Rate Control. Low-impact development is designed to maintain the predevelopment peak runoff discharge rate for the selected design storm events. This is done by maintaining the predevelopment Tc and then using retention and/or detention IMPs (e.g., rain gardens, open drainage systems, etc.) that are distributed throughout the site. The goal is to use retention practices to control runoff volume and, if these retention practices are not sufficient to control the peak runoff rate, to use additional detention practices to control the peak runoff rate. Detention is temporary storage that releases excess runoff at a controlled rate. The use of retention and detention to control the peak runoff rate is defined as the hybrid approach.

Flow Frequency/Duration Control. Since low-impact development is designed to emulate the predevelopment hydrologic regime through both volume and peak runoff rate controls, the flow frequency and duration for the post development conditions will be almost identical to those for the predevelopment conditions (see Figure 1.3.). The impacts on the sediment and erosion and stream habitat potential at downstream reaches can then be minimized.

Water Quality Control. Low-impact development is designed to provide water quality treatment control for the first ½ inch of runoff from impervious areas using retention practices. Low-impact development also provides pollution prevention by modifying human activities to reduce the introduction of pollutants into the environment.

The low-impact analysis and design approach focuses on the following hydrologic analysis and design components:

- **Runoff Curve Number (CN).** Minimizing change in post development hydrology by reducing impervious areas and preserving more trees and meadows to reduce the storage requirements to maintain the pre development runoff volume.
- **Time of Concentration (Tc).** Maintaining the predevelopment Tc in order to minimize the increase of the peak runoff rate after development by lengthening flow paths and reducing the length of the runoff conveyance systems.
- **Retention.** Providing retention storage for volume and peak control, as well as water quality control, to maintain the same storage volume as the predevelopment condition.

- **Detention.** Providing additional detention storage, if required, to maintain the same peak runoff rate and/or prevent flooding.

Table 2.1 provides a summary of low-impact techniques that affect these components.

Table 2.1. Low-Impact Development Techniques and Hydrologic Design and Analysis Components

	Low-Impact Development Technique															
Low-Impact Hydrologic Design and Analysis Components	Flatten slope	Increase flow path	Increase sheet flow	Increase roughness	Minimize disturbance	Flatten slopes on swales	Infiltration swales	Vegetative filter strips	Constricted Pipes	Disconnected impervious areas	Reduce curb and gutter	Rain barrels	Rooftop storage	Bioretention	Revegetation	Vegetation preservation
Lower Postdevelopment CN					✔		✔	✔		✔	✔			✔	✔	✔
Increase Tc	✔	✔	✔	✔		✔		✔	✔	✔	✔	✔	✔	✔	✔	✔
Retention							✔	✔				✔	✔	✔	✔	✔
Detention						✔			✔			✔	✔			

CHAPTER 3. HYDROLOGIC EVALUATION

The purpose of the hydrologic evaluation is to determine stormwater management requirements for low-impact development sites. The evaluation method is used to determine the amount of retention and/or detention to control the runoff volume and peak discharge rate. Appropriate detention and/or retention techniques are then selected to meet these requirements.

3.1 LOW-IMPACT DEVELOPMENT RUNOFF POTENTIAL

Calculation of the low-impact development runoff potential is based on a detailed evaluation of the existing and proposed land cover so that an accurate representation of the potential for runoff can be obtained. This calculation requires the engineer to investigate several key parameters associated with a low-impact development:

- Land cover type
- Percentage of and connectivity of impervious areas
- Soils type and texture
- Antecedent soil moisture conditions

A comparison of conventional and low-impact development runoff potential using the SCS Curve Number (CN) approach is presented. The CN for conventional development are based on the land cover assumptions and parameters shown in Table 2.2a of TR-55 (SCS, 1986). The low-impact development CN are based on a detailed evaluation of the land cover and parameters listed above. As illustrated in Figure 3.1, customizing the CN for a low-impact development site allows the developer/engineer to take advantage of and get credit for such low-impact development site planning practices as the following:

- Narrower driveways and roads (minimizing impervious areas)
- Maximizing tree preservation or aforestation (tree planting)
- Site fingerprinting (minimal disturbance)
- Open drainage swales
- Preservation of soils with high infiltration rates to reduce CN
- Location of IMPs on high infiltration soils.

Table 3.1 illustrates a comparison of low-impact development CN land covers with those of a conventional development CN, as found in Table 2.2a of TR-55 (SCS, 1986) for a typical 1-acre lot. Figure 3.1 illustrates a comparison of conventional land covers, based on the land covers in Table 2.2a of TR-55, with a low-impact development customized CN for a 1-acre lot.

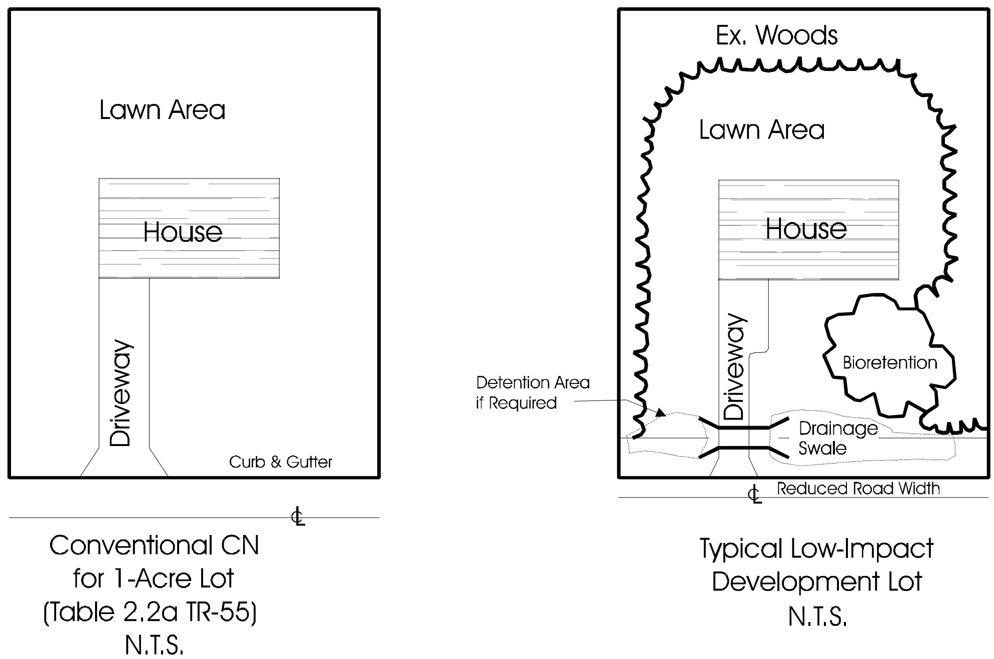

Figure 3.1. Comparison of Land Covers Between Conventional and LID CNs

Table 3.1. Comparison of Conventional and LID Land Covers

Conventional Land Covers (TR-55 Assumptions)	**LID Land Covers**
20% impervious 80% grass	15% imperviousness 25% woods 60% grass

Table 3.2 provides a list of low-impact development site planning practices and their relationship to the components of the low-impact development CN. Key low-impact techniques that will reduce the post development CN, and corresponding runoff volumes, are as follows:

Table 3.2. Low-Impact Development Planning Techniques to Reduce the Postdevelopment Low-Impact Development CN

Suggested Options Affecting Curve Number	Limit use of sidewalks	Reduce road length and width	Reduce driveway length and width	Conserve natural resources areas	Minimize disturbance	Preserve infiltratable soils	Preserve natural depression areas	Use transition zones	Use vegetated swales	Preserve Vegetation
Land Cover Type				✔	✔			✔	✔	✔
Percent of Imperviousness	✔	✔	✔					✔		
Hydrologic Soils Group				✔		✔				
Hydrologic Condition				✔	✔	✔				
Disconnectivity of Impervious Area	✔	✔	✔							
Storage and Infiltration							✔			✔

Preservation of Infiltratable Soils: This approach includes site planning techniques such as minimizing disturbance of soils, particularly vegetated areas, with high infiltration rates (sandy and loamy soils), and placement of infrastructure and impervious areas such as houses, roads, and buildings on more impermeable soils (silty and clayey soils). Care must be taken when determining the suitability of soils for proposed construction practices. Adequate geotechnical information is required for planning practices.

Preservation of Existing Natural Vegetation. Woods and other vegetated areas provide many opportunities for storage and infiltration of runoff. By maintaining the surface coverage to the greatest extent possible, the amount of compensatory storage for IMPs is minimized. Vegetated areas can also be used to provide surface roughness, thereby increasing the Tc. In addition, they function to filter out and uptake pollutants.

Minimization of Site Imperviousness. Reducing the amount of imperviousness on the site will have a significant impact on the amount of compensatory IMP storage required since there is almost a one-to-one corresponding relationship between rainfall and runoff for impervious areas.

Disconnection of Site Imperviousness. Impervious areas are considered disconnected if they do not connect to a storm drain system or other impervious areas through direct or shallow concentrated flow. Directing impervious areas to sheet flow onto vegetated or bioretention areas to allow infiltration results in a direct reduction in runoff and corresponding storage volume requirements.

Creation of Transition Zones and Bioretention: Transition zones are vegetated areas that can be used to store and infiltrate runoff from impervious areas before they discharge from the site. These areas are located at the sheet or discharge points from graded and impervious areas. These areas affect the land cover type calculations of the LID CN.

The use of these techniques will provide incentives in cost savings to the overall site development and infrastructure. It will also reduce costs for stormwater permit fees, inspection, and maintenance of the infrastructure as well as project based costs.

Figure 3.2. illustrates the hydrologic response using LID techniques to reduce the impervious areas and increase the storage volume.

- For hydrograph 1, refer to Figure 1.3 for description.
- Hydrograph 2 represents the response of a post development condition with no stormwater management IMPs. This hydrograph definition reflects a shorter time of concentration (Tc), and an increase in total site imperviousness than that of the predevelopment condition. The resultant hydrograph shows a decrease in the time to reach the peak runoff rate, a significant increase in the peak runoff and discharge rate and volume, and increased duration of the discharge volume.
- Hydrograph 3 represents the resulting post development hydrograph using the low-impact techniques to reduce impervious area and increase storage volume. There is a reduction in both post development peak rate and volume.

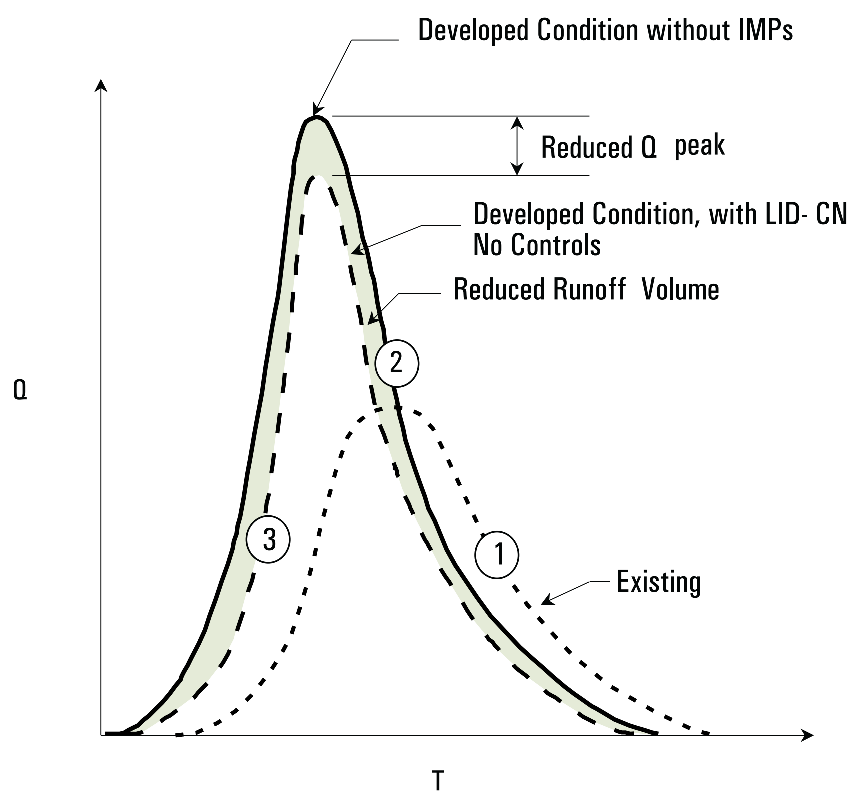

Figure 3.2. Effect of Low-Impact Development CN on the Postdevelopment Hydrograph without Stormwater IMPs

3.2. MAINTAINING THE PREDEVELOPMENT TIME OF CONCENTRATION

The low-impact development hydrologic evaluation requires that the post development time of concentration (Tc) be maintained close to the predevelopment Tc. The travel time (Tt) throughout individual lots and areas should be approximately the same so that the Tc is representative of the drainage. This is critical because low-impact development is based on a homogeneous land cover and distributed IMPs. To maintain the Tc, low-impact developments use the following site planning techniques:

- Maintaining predevelopment flow path length by dispersing and redirecting flows, generally, through open swales and natural drainage patterns
- Increasing surface roughness (e.g., reserving woodlands, using vegetated swales).
- Detaining flows(e.g. open swales, rain gardens).
- Minimize disturbance(minimizing compaction and changes to existing vegetation).
- Flattening grades in impacted areas.
- Disconnecting impervious areas (e.g., eliminating curb/gutter and redirecting downspouts).
- Connecting pervious and vegetated areas (e.g., reforestation, aforestation, tree planting).

To maintain predevelopment Tc, an iterative process that analyzes different combinations of the above appropriate techniques may be required. These site planning techniques are incorporated into the hydrologic analysis computations for post development Tc to demonstrate an increase in post development Tc above conventional techniques and a corresponding reduction in peak discharge rates.

Figure 3.3 illustrates the hydrologic response to maintaining equal predevelopment and post-development Tc.

- For hydrograph 1 refer to Figure 1.3.
- For hydrograph 3 refer to Figure 3.2.
- Hydrograph 4 represents the effects of the low-impact development techniques to maintain the Tc. This effectively shifts the post peak runoff time to that of the predevelopment condition and lowers the peak runoff rate.

The greatest gains for increasing the Tc in a small watershed can be accomplished by increasing the Manning's roughness "n" for the initial surface flow at the top of the watershed and increasing the flow path length for the most hydraulically distant point in the drainage area. After the transition to shallow concentrated flow, additional gains in Tc can be accomplished by:

- Decreasing the slope
- Increasing the flow length
- Directing flow over pervious areas.

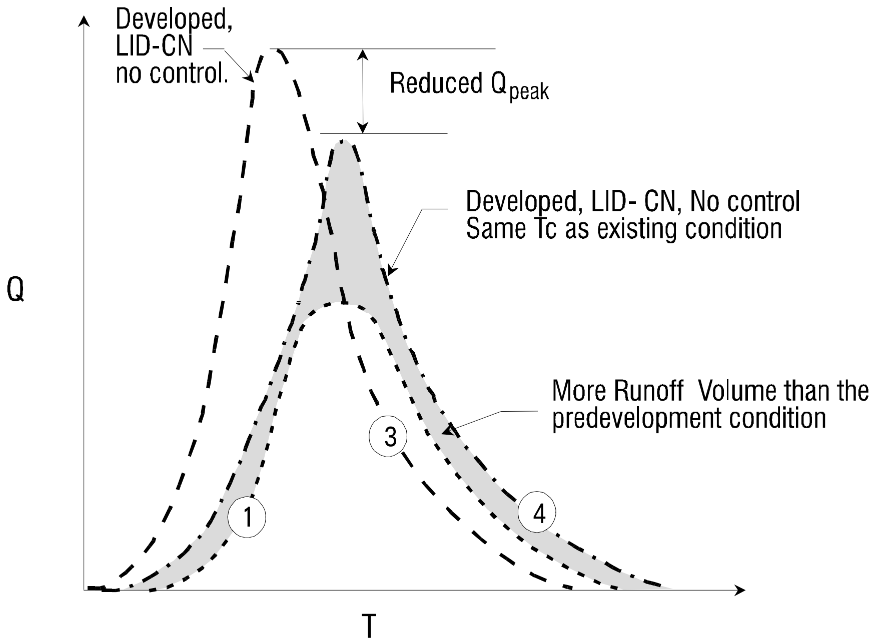

Figure 3.3. Low-Impact Development Hydrograph That Has a Reduced CN and Maintains the Tc Without Stormwater IMPs

In low-impact development sites, the amount of flow in closed channels (pipes) should be minimized to the greatest extent possible. Swales and open channels should be designed with the following features:

- Increase surface roughness to retard velocity
- Maximize sheet flow conditions
- Use a network of wider and flatter channels to avoid fast-moving channel flow
- Increase channel flow path
- Reduce channel gradients to decrease velocity (minimum slope is 2-percent; 1 percent may be considered on a case by case basis).
- The channel should flow over pervious soils whenever possible to increase infiltration so that there is a reduction of runoff to maximize infiltration capacity

Table 3.3 identifies low-impact development techniques and volumes objectives to maintain the predevelopment Tc.

3.3 MAINTAINING THE PREDEVELOPMENT RUNOFF VOLUME

After all the available and feasible options to reduce the runoff potential of a site described have been deployed, and after all the available techniques to maintain the Tc as close as possible to predevelopment levels have been used, any additional reductions in runoff volume must be accomplished through distributed on-site stormwater management techniques. The goal is to select the appropriate combination of management techniques that emulate the hydrologic functions of the predevelopment condition to maintain the

Table 3.3. Low-Impact Development Techniques to Maintain the Predevelopment Time of Concentration

	Low Impact Development Technique									
Low-Impact Development Objective	On-lot bioretention	Wider and flatter swales	Maintain sheet flow	Clusters of trees and shrubs in flow path	Provide tree conservation/ transition zones	Minimize storm drain pipes	Disconnect impervious areas	Save trees	Preserve existing topography	LID drainage and infiltration zones
Minimize disturbance	✔		✔	✔	✔	✔	✔	✔	✔	
Flatten grades		✔	✔			✔			✔	✔
Reduce height of slopes						✔			✔	✔
Increase flow path (divert and redirect)		✔	✔	✔		✔	✔	✔		
Increase roughness "n"	✔		✔	✔	✔	✔	✔	✔		✔

existing runoff curve numbers and corresponding runoff volume. Low-impact development sites use retention to accomplish this goal. These facilities must be sited on individual lots throughout the site to provide volume controls at the source.

Retention storage allows for a reduction in the post development volume and the peak runoff rate. The increased storage and infiltration capacity of IMPs allows the predevelopment volume to be maintained. IMPs that maintain the predevelopment storage volume include, but are not limited to the following:

- Bioretention (rain garden)
- Infiltration trenches
- Vegetative Filter/Buffer
- Rain barrels

As the retention storage volume of the low-impact development IMPs is increased, there is a corresponding decrease in the peak runoff rate in addition to runoff volume reduction. If sufficient amount of runoff is stored, the peak runoff rate may be reduced to a level at or below the predevelopment runoff rate (see Figure 3.4). This storage may be all that is necessary to control the peak runoff rate when there is a small change in runoff curve number (CN) and storage volume. However, when there is a large change in CN, it may be less practical to achieve flow control using volume control only.

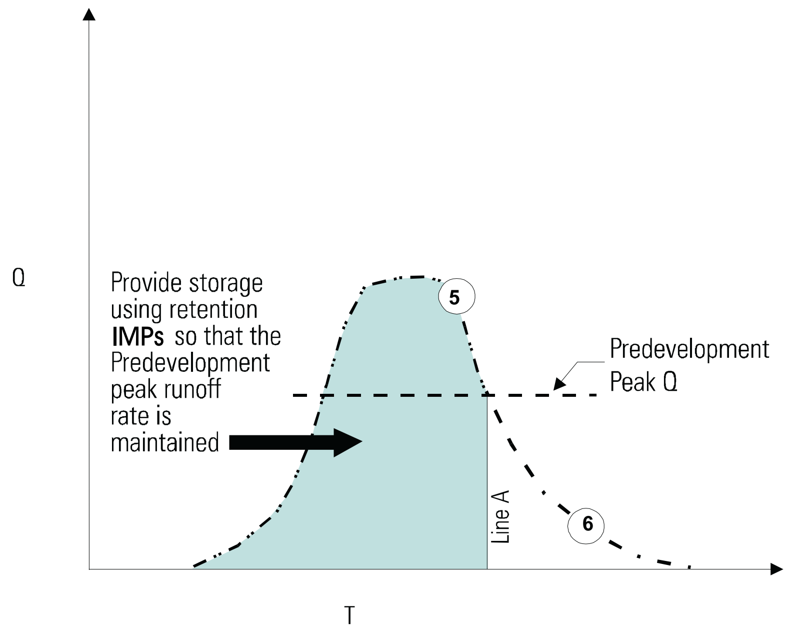

Figure 3.4. Retention Storage Required to Maintain Peak Development Runoff Rate

In Figure 3.4., Hydrograph 5 represents the IMP inflow hydrograph for the post-development condition for a site using low-impact development IMPs. Because of the IMP retention storage, runoff is not released until the maximum retention storage volume is exceeded. Line A represents the limit of retention storage. Hydrograph 6 is the outflow hydrograph from the low-impact development retention IMP. The release begins at the limit of retention storage, represented by line A. The storage maintains the predevelopment volume and controls the peak runoff rate. For this situation, the falling limb of the hydrograph represents a condition where the inflow (hydrograph 5) equals the outflow (hydrograph 6).

3.4 POTENTIAL REQUIREMENT FOR ADDITIONAL DETENTION STORAGE

Even though the post-development Tc and CN are maintained at the predevelopment level, in some cases additional detention storage is needed to maintain the predevelopment peak runoff rate due to the spatial distribution of the retention storage provided (i.e., storage areas are not *uniformly* distributed throughout the site).

The amount of storage that maintains the predevelopment runoff volume might not be sufficient to also maintain the predevelopment peak runoff rate. Therefore, additional on-lot storage is required in the form of ***detention storage.*** Low-impact development stormwater management techniques for providing detention storage include, but are not limited to the following:

- Swales with check dams, restricted drainage pipe, and inlet entrances
- Wider swales
- Rain barrels
- Rooftop storage
- Diversion structures

The effect of this additional detention storage is illustrated in Figure 3.5.

- For hydrograph 1, refer to Figure 1.3.
- Hydrograph 7 represents the response of a post-development condition that incorporates low-impact development retention practices. The amount of retention storage provided is not large enough to maintain the predevelopment peak runoff discharge rate. Additional detention storage is required.
- Hydrograph 8 illustrates the effect of providing additional detention storage to reduce the post-development peak discharge rate to predevelopment conditions.

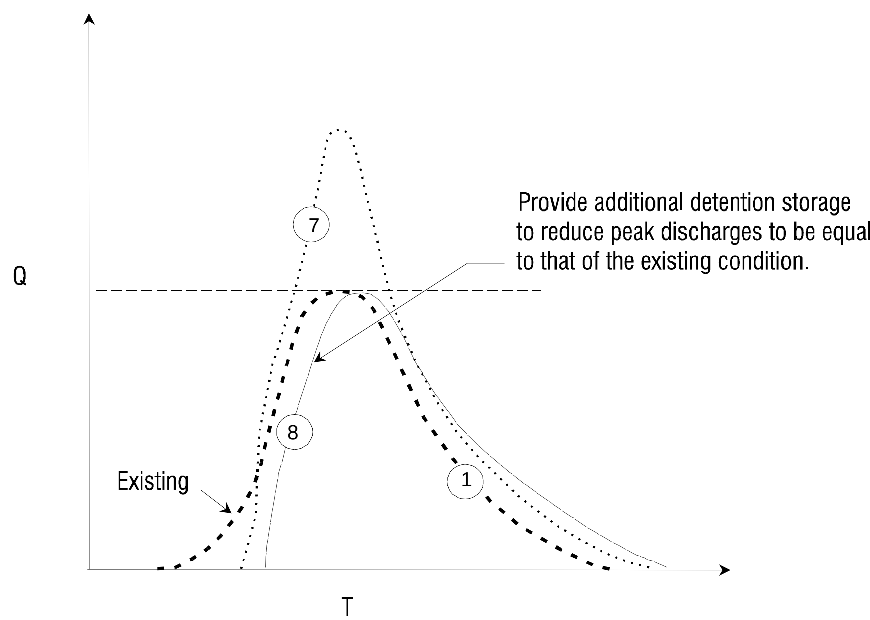

Figure 3.5. Effect of Additional Detention Storage on LID Retention Practices

CHAPTER 4. PROCESS AND COMPUTATIONAL PROCEDURE

4.1 INTRODUCTION

The hydrologic analysis of low-impact development is a sequential decision making process that can be illustrated by the flow chart shown in Figure 1.1. Several iterations may occur within each step until the appropriate approach to reduce stormwater impacts is determined. The procedures for each step are given in the following section. Design charts have been developed to determine the amount of storage required to maintain the existing volume and peak runoff rates to satisfy county storm water management requirements (Appendices A, B, and C).

4.2 DATA COLLECTION

The basic information used to develop the low-impact development site plan and used to determine the Runoff Curve Number (CN) and Time of Concentration (Tc) for the pre- and post-development condition is the same as conventional site plan and stormwater management approaches.

4.3 DETERMINING THE LID RUNOFF CURVE NUMBER

The determination of the low-impact development CN requires a detailed evaluation of each land cover within the development site. This will allow the designer to take full advantage of the storage and infiltration characteristics of low-impact development site planning to maintain the CN. This approach encourages the conservation of more woodlands and the reduction of impervious area to minimize the needs of IMPs.

The steps for determining the low-impact development CN are as follows:

Step 1: Determine Percentage of Each Land Use/Cover.

In conventional site development, the engineer would refer to Figure 2.2.a of TR-55 (SCS, 1986) to select the CN that represents the proposed land use of the overall development (i.e., residential, commercial) without checking the actual percentages of impervious area, grass areas, etc. Because low-impact design emphasizes minimal site disturbance (tree preservation, site fingerprinting, etc.), it is possible to retain much of the pre-development land cover and CN.

Therefore, it is appropriate to analyze the site as discrete units to determine the CN. Table 4.1 lists representative land cover CNs used to calculate the composite "custom" low-impact development CN.

Step 2: Calculate Composite Custom CN.

The initial composite CN is calculated using a weighted approach based on individual land covers *without* considering disconnectivity of the site imperviousness. This is done using Equation 4.1. This weighted approach is illustrated in Example 4.1.

TABLE 4.1. REPRESENTATIVE LID CURVE NUMBERS

Land Use/Cover	Curve Number for Hydrologic Soils Groups[1]			
	A	**B**	**C**	**D**
Impervious Area	98	98	98	98
Grass	39	61	74	80
Woods (fair condition)	36	60	73	79
Woods (good condition)	30	55	70	77

[1]Figure 2.2a, TR-55 (SCS, 1986).

$$CN_c = \frac{CN_1 A_1 + CN_2 A_2 ... + CN_j A_j}{A_1 + A_2 ... + A_j} \qquad \text{Eq. 4.1}$$

Where:

CNc = composite curve number;

A_j = area of each land cover; and

CN_j = curve number for each land cover.

Overlays of SCS Hydrologic Soil Group (HSG) boundaries onto homogeneous land cover areas are used to develop the low-impact development CN. What is unique about the low-impact development custom-made CN technique is the way this overlaid information is analyzed as small discrete units that represent the hydrologic condition, rather than a conventional TR-55 approach that is based on a representative national average. This is appropriate because of the emphasis on minimal disturbance and retaining site areas that have potential for high storage and infiltration.

This approach provides an incentive to save more trees and maximize the use of HSG A and B soils for recharge. Careful planning can result in significant reductions in post-development runoff volume and corresponding stormwater management costs.

Step 3: Calculate low-impact development CN based on the connectivity of site impervious area.

When the impervious areas are less than 30 percent of the site, the percentage of the unconnected impervious areas within the watershed influences the calculation of the CN (SCS, 1986). Disconnected impervious areas are impervious areas without any direct connection to a drainage system or other impervious surface. For example, roof drains from houses could be directed onto lawn areas where sheet flow occurs, instead of to a swale or driveway. By increasing the ratio of disconnected impervious areas to pervious areas on the site, the CN and resultant runoff volume can be reduced. Equation 4.2 is used to calculate the CN for sites with less than 30 percent impervious area.

Example 4.1: Detailed CN Calculation

Given:

One-acre residential lot

Conventional CN: 68 (From TR-55 Table 2.2a-Runoff curve numbers for urban areas (SCS, 1986) Table 2.2a assumes HSG B, 20% imperviousness with a CN of 98 and 80% open space in good condition.

Custom-made LID CN: CN for individual land covers based on Table 2.2a. Assume 25% of the site will be used for reforestation/landscaping (see Figure 3.1) HSG B.

Procedure:

Step 1: Determine percentage of each land cover occurring on site and the CN associated with each land cover.

Land Use	HSG (1)	CN (2)	% of Site (3)	Land Coverage (ft^2) (4)
Impervious (Directly Connected)	B	98	5	2,178
Impervious (Unconnected)	B	98	10	4,356
Open Space (Good Condition, Graded)	B	61	60	26,136
Woods (Fair Condition)	B	55	25	10,890

Step 2: Calculate composite custom CN (using Equation 4.1).

$$CN_c = \frac{98 \times 4{,}356 + 98 \times 2{,}178 + 61 \times 26{,}136 + 55 \times 10{,}890}{43{,}560}$$

$$CN_c = 65$$

Step 3: Calculate low-impact development CN based on the connectivity of the site imperviousness (using Equation 4.2).

$$CN_p = \frac{61 \times 26{,}136 + 55 \times 10{,}890}{37{,}026}$$

$$CN_p = 59.2$$

$$R = \frac{10}{15}$$

$$R = 0.67$$

$$CN_c = CN_p + \left(\frac{P_{imp}}{100}\right) \times (98 - CN_p) \times (1 - 0.5 \times R)$$

$$CN_c = 59.2 + \left(\frac{15}{100}\right) \times (98 - 59.2) \times (1 - 0.5 \times 0.67)$$

$$CN_c = 63.1\,(\text{use } 63)$$

LID custom CN of 63 is less than conventional CN of 68 (predevelopment CN is 55).

$$CN_c = CN_p + \left(\frac{P_{imp}}{100}\right) \times (98 - CN_p) \times (1 - 0.5R) \qquad \text{Eq. 4.2}$$

where:

R = ratio of unconnected impervious area to total impervious area;

CN_c = composite CN;

CN_p = composite pervious CN; and

P_{imp} = percent of impervious site area.

Example 4.1 uses steps 1 through 3 to compare the calculation of the curve number using conventional and low-impact development techniques using the percentages of land cover for a typical 1-acre residential lot from Figure 3.1.

4.4 DEVELOPMENT OF THE TIME OF CONCENTRATION (TC)

The pre- and post-development calculation of the Tc for low-impact development is exactly the same as that described in the TR-55 (SCS, 1986) and NEH-4 (SCS, 1985) manuals.

4.5 LOW-IMPACT DEVELOPMENT STORMWATER MANAGEMENT REQUIREMENTS

Once the CN and Tc are determined for the pre- and post-development conditions, the stormwater management storage volume requirements can be calculated. The low-impact development objective is to maintain all the pre-development volume, pre-development peak runoff rate, and frequency. The required storage volume is calculated using the design charts in Appendices A, B, and C for different geographic regions in the nation.

As stated previously, the required storage volume is heavily dependent on the intensity of rainfall (rainfall distribution). Since the intensity of rainfall varies considerably over geographic regions in the nation, the National Resource Conservation Service (NRCS) developed four synthetic 24-hour rainfall distributions (I, IA, II, and III) from available National Weather Service (NWS) duration-frequency data and local storm data. Type IA is the least intense and type II the most intense short duration rainfall. Figure 4.1. shows approximate geographic boundaries for these four distributions.

The remaining low-impact development hydrologic analysis techniques are based on the premise that the post-development Tc is the same as the pre-development condition. If the post-development Tc does not equal the pre-development Tc, additional low-impact development site design techniques must be implemented to maintain the Tc.

Three series of design charts are needed to determine the storage volume required to control the increase in runoff volume and peak runoff rate using retention and detention practices. The required storages shown in these design charts are presented as a depth in hundredths of an inch (over the development site). Equation 4.3 is used to determine the volume required for IMPs.

Volume = (depth obtained from the chart) x (development size) / 100 Eq. 4.3

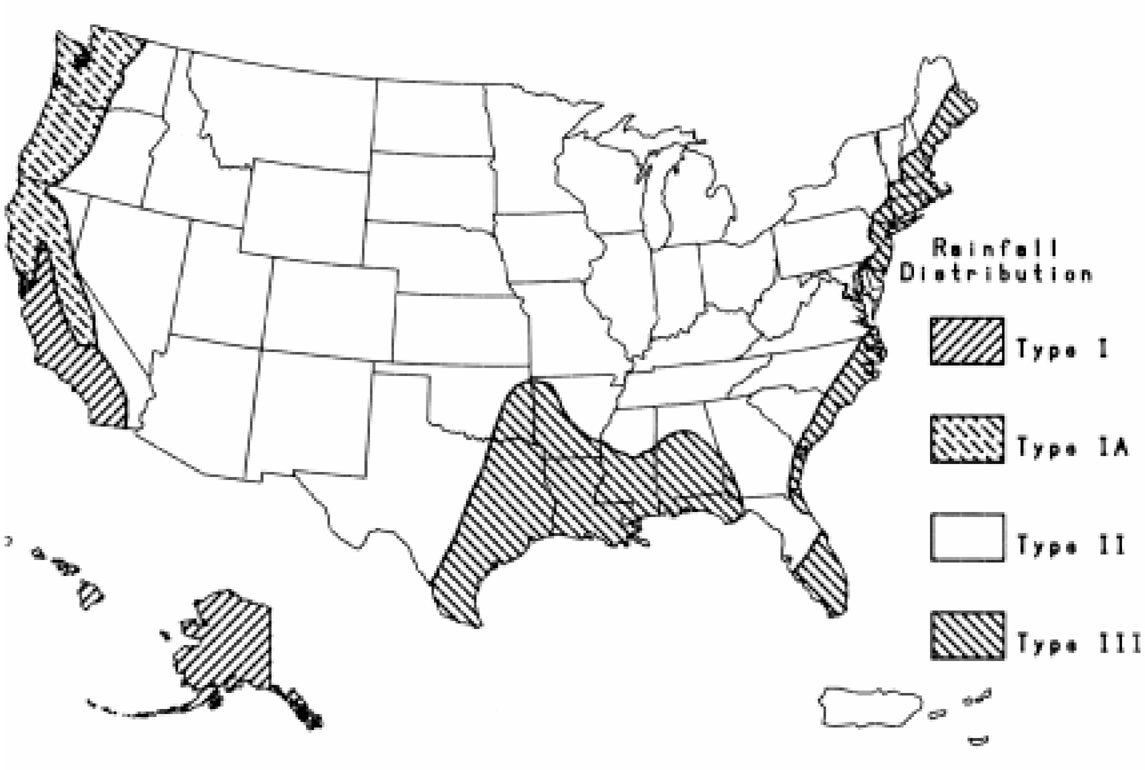

Figure 4.1. Approximate Geographic Boundaries for NRCS Rainfall Distributions.

It is recommended that 6-inch depth be the maximum depth for bioretention basins used in low-impact development.

The amount, or depth, of exfiltration of the runoff by infiltration or by the process of evapotranspiration is not included in the design charts. Reducing surface area requirements through the consideration of these factors can be determined by using Equation 4.4.

$$\text{Volume of site area for IMPs} = (\text{initial volume}) \times (100 - x) / 100 \qquad \text{Eq. 4.4}$$

where: x = % of the storage volume infiltrated and/or reduced by evaporation or transpiration. x% should be minimal (less than 10% is considered).

Stormwater management is accomplished by selecting the appropriate IMP, or combination of IMPs, to satisfy the surface area and volume requirements calculated from using the design charts. The design charts to be used to evaluate these requirements are:

- Chart Series A: Storage Volume Required to Maintain the Predevelopment Runoff Volume Using Retention Storage (Appendix A).
- Chart Series B: Storage Volume Required to Maintain the Predevelopment Peak Runoff Rate Using 100% Retention (Appendix B).
- Chart Series C: Storage Volume Required to Maintain the Predevelopment Peak Runoff Rate Using 100% Detention (Appendix C).

These charts are based on the following general conditions:

- The land uses for the development are relatively homogeneous throughout the site.
- The stormwater management measures are to be distributed evenly across the development, to the greatest extent possible.
- The design storm is based on 1-inch increments. Use linear interpolation for determining intermediate values.

The procedure to determine the IMP requirements is outlined in Figure 4.2 and described in the following sections.

Step 1: Determine storage volume required to maintain predevelopment volume or CN using retention storage.

The post-development runoff volume generated as a result of the post-development custom-made CN is compared to the predevelopment runoff volume to determine the surface area required for volume control. Use Chart Series A: Storage Volume Required to Maintain the Predevelopment Runoff Volume using Retention Storage. The procedure for calculating the site area required for maintaining runoff volume is provided in Example 4.2. It should be noted that the practical and reasonable use of the site must be considered. The IMPs must not restrict the use of the site.

The storage area, expressed is for runoff volume control only; additional storage may be required for water quality control. The procedure to account for the first ½-inch of runoff from impervious areas, which is the current water quality requirement, is found in Step 2.

Step 2: Determine storage volume required for water quality control.

The surface area, expressed as a percentage of the site, is then compared to the percentage of site area required for water quality control. The volume requirement for stormwater management quality control is based on the requirement to treat the first ½-inch of runoff (approximately 1,800 cubic feet per acre) from impervious areas. This volume is translated to a percent of the site area by assuming a storage depth of 6 inches. The procedure for calculating the site area required for quality control is provided in Example 4.3. The greater number, or percent, is used as the required storage volume to maintain the CN.

From the *results* of Example 4.3, 0.1" of storage is required for water quality using retention; from Example 4.2, 0.35" of storage is required to maintain the runoff volume using retention. Since the volume required to maintain the runoff volume is larger, in this case 0.35" of storage over the site should be reserved for retention IMPs.

Step 1:

Determine storage volume required to maintain runoff volume or CN. Use Chart Series A: Storage Volume Required to Maintain the Predevelopment Runoff Volume Using Retention Storage (Example 4.2)

Step 2:

Determine storage volume for water quality volume requirements. Determine storage volume required for quality control IMPs. Use larger of volumes to maintain CN (Step 1, Example 4.2) or water quality volume (Example 4.3).

Step 3:

Determine storage volume required to maintain predevelopment peak runoff rate using 100% retention. Use Chart Series B: Storage Volume Required to Maintain the Predevelopment Peak Runoff Rate Using 100% Retention.

Step 4:

Determine whether additional detention storage is required to maintain predevelopment peak runoff rate. Compare the results of Steps 1 and 2 to the results of Step 3. If the storage volume in Steps 1 and 2 is determined to be greater than that in Step 3, the storage volume required to maintain the predevelopment CN also controls the peak runoff rate. No additional detention storage is needed. If the storage volume in Step 1 is less than that in Step 3, additional detention storage is required to maintain the pak runoff rate (Example 4.4).

Step 5 (use if additional detention storage is required):

Determine storage volume required to maintain predevelopment peak runoff rate using 100% detention. Use Chart Series C: Storage Volume Required to Maintain the Predevelopment Peak Runoff Rate Using 100% Detention. This is used in conjunction with Chart Series A and B to determine the hybrid volume in Step 6.

Step 6 (use if additional detention storage is required):

Hybrid approach. Use results from Chart Series A, B, and C to determine storage volume to maintain both the predevelopment peak runoff rate and runoff volume. Refer to Equations 4.5 and 4.6 as found in Example 4.4.

Step 7 (use if additional detention storage is required):

Determine appropriate storage volume available for retention practices. If the storage volume available for retention practices is less than the storage determined in Step 3, recalculate the amount of IMP area required to maintain the peak runoff rate while attenuating some volume using the procedure in Example 4.6 using Equations 4.7 and 4.8.

Figure 4.2. Procedure to Determine Storage Volume Required for IMPs to Maintain Predevelopment Runoff Volume and Peak Runoff Rate.

Example 4.2: Determine Site Area Required to Maintain Volume (CN) Using Chart Series A: Storage Volume Required to Maintain the Predevelopment Runoff Volume Using Retention Storage

Given:

Site Area is 18 acres

Existing CN is 60

Proposed CN is 65

Design storm is 5 inches

Design depth of IMP is 6 inches

Solution: Use Chart Series A: Storage Volume Required to Maintain Runoff Volume or CN.

0.35" of storage over the site is required to maintain the runoff volume.

Therefore: if 6" design depth is used, 1.1 acres (18 acres x 0.35 / 6) of IMPs distributed evenly throughout the site are required to maintain the runoff volume, or CN.

Additional Considerations:

1) Account for depths other than 6 inches:

Site of IMP Area = 1.1 acres, if 6" depth is used

Depth of IMPs = 4"

Site of IMP Area = 1.1 x 6"/4"

Site of IMP Area = 1.65 acres

2) Account for infiltration and/or evapotranspiration (using Equation 4.4)

If 10% of the storage volume is infiltrated and/or reduced by evaporation and transpiration.

Site of IMP Area = (storage volume) x (100 - X) / 100

Site of IMP Area =1.1 x (100-10)/100

Area for IMP Storage = 1.0 acre

Example 4.3: Calculation of Volume, or Site Area, for Water Quality Control

Given:

Site area is 18 acres

Impervious area is 3.6 acres (20%)

Depth of IMP is 6 inches

Solution:

Water quality requirement is for the first ½ inch of runoff from impervious areas

(18 acres x 20%) x 0.5" / 18 acres = 0.1" storage for water quality

0.1" is less than 0.35" (from example 4.2). Therefore, use storage for runoff volume control to meet water quality requirement.

Step 3: Determine storage volume required to maintain peak stormwater runoff rate using 100 percent retention.

The percentage of site area or amount of storage required to maintain the predevelopment peak runoff rate is based on *Chart Series B: Percentage of Site Area Required to Maintain Predevelopment Peak Runoff Rate Using 100% Retention (Appendix B).* This chart is based on the relationship between storage volume, $\forall_s / \forall_r$, and discharge, Q_o / Q_i , to maintain the predevelopment peak runoff rate.

Where: *Vs* = volume of storage to maintain the predevelopment peak runoff rate using 100% retention;

Vr = post development peak runoff volume;

Qo = peak outflow discharge rate; and

Qi = peak inflow discharge rate.

The relationship for retention storage to control the peak runoff rate is similar to the relationship for detention storage. Figure 4.3 is an illustration of the comparison of the storage volume/discharge relationship for retention and detention. Curve A is the relationship of storage volume to discharge to maintain the predevelopment peak runoff rate using the detention relationship from Figure 6-1 of the TR-55 manual (SCS, 1986) for a Type II 24-hour storm event. Curve B is the ratio of storage volume to discharge to maintain the predevelopment peak runoff rate using 100 percent retention. Note that the volume required to maintain the peak runoff rate using detention is less than the requirement for retention. This is graphically demonstrated in Figure 4.4.

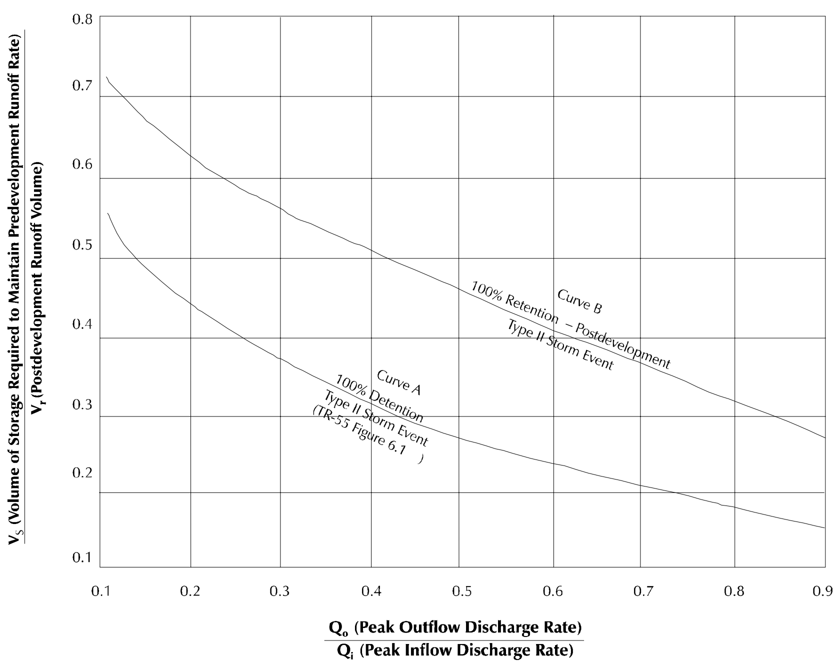

Figure 4.3. Comparison of Retention of Storage Volumes Required to Maintain Peak Runoff Rate Using Retention and Detention.

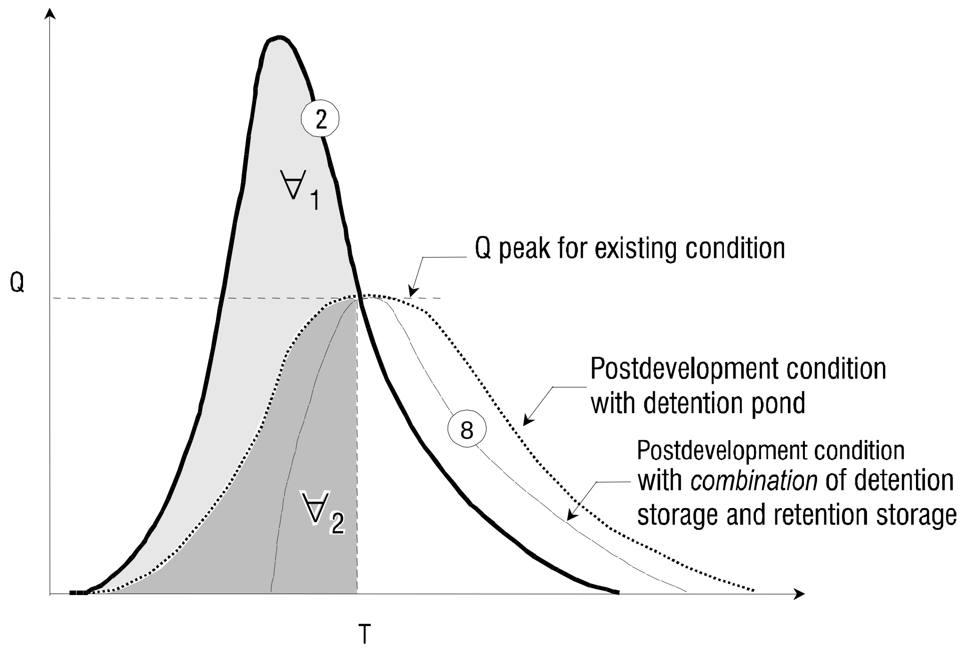

Figure 4.4. Storage Volume Required to Maintain Peak Runoff Rate

- For hydrograph 2, refer to Figure 3.2 for description.
- For hydrograph 8, refer to Figure 3.5 for description.

$\forall_1$ is the storage volume required to maintain the predevelopment peak discharge ratio using 100% detention storage. The combination of $\forall_1$ and $\forall_2$ is the storage volume required to maintain the predevelopment peak discharge rate using 100% retention storage.

The following calculations apply to Design Chart Series B:

- The Tc for the post-development condition is equal to the Tc for the predevelopment condition. This equality can be achieved by techniques such as maintaining sheet flow lengths, increasing surface roughness, decreasing the amount and size of storm drain pipes, and decreasing open channel slopes. Section 3.2 provides more details on these techniques.
- IMPs are to be distributed evenly across the development cite.

If the Tc is equal for the predevelopment and post-development conditions, the peak runoff rate is independent of Tc for retention and detention practices. The difference in volume required to maintain the predevelopment peak runoff rate is practically the same if the Tcs for the predevelopment and post-development conditions are the same. These concepts are illustrated in Figure 4.5. In Figure 4.5, the difference in the required IMP area between a Tc of 0.5 and a Tc of 2.0 is minimal if the predevelopment and post-development Tcs are maintained.

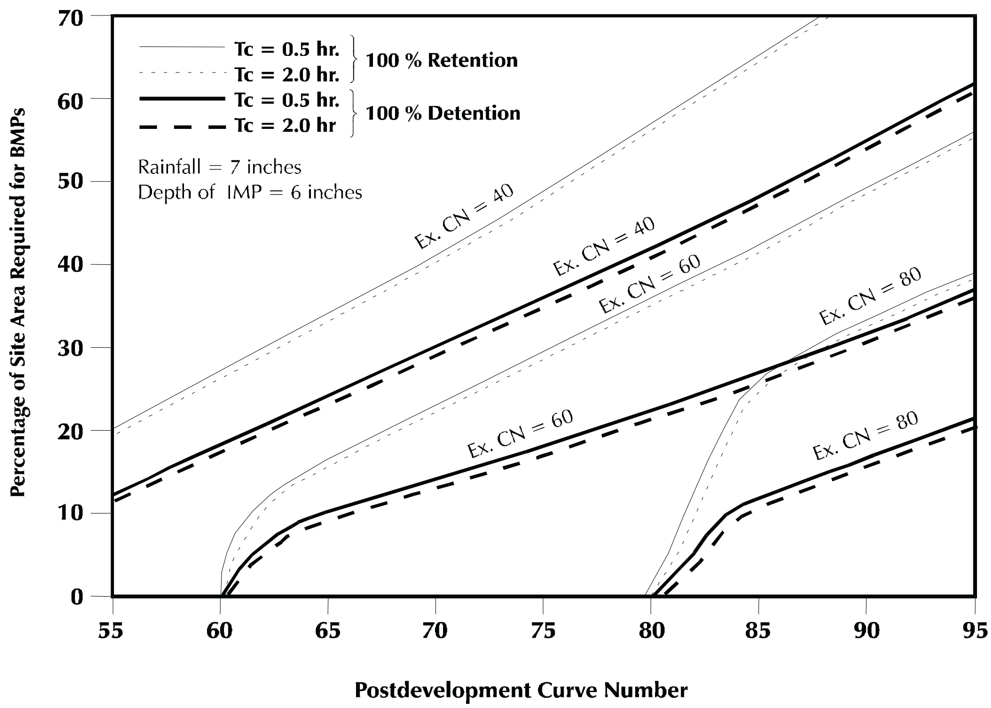

Figure 4.5. Comparison of Storage Volumes for Various Tcs.

Step 4: Determine whether additional detention storage is required to maintain the predevelopment peak runoff rate.

The storage volume required to maintain the predevelopment runoff volume using retention, as calculated in Step 1, might or might not be adequate to maintain both the predevelopment volume and peak runoff rate. As the CNs diverge, the storage requirement to maintain the volume is much greater than the storage volume required to maintain the peak runoff rate. As the CNs converge, however, the storage required to maintain the peak runoff rate is greater than that required to maintain the volume. Additional detention storage will be required if the storage volume required to maintain the runoff volume (determined in Step 1) is less than the storage volume required to maintain the predevelopment peak runoff rate using 100 percent retention (determined in Step 3).

The combination of retention and detention practices is defined as a hybrid approach. The procedure for determining the storage volume required for the hybrid approach is described in Step 5.

Table 4.2 illustrates the percentage of site area required for volume and peak control for representative curve numbers. Using a 5-inch type II 24-hour storm event and 6" design depth, with a predevelopment CN of 60, the following relationships exist:

- For a post-development CN of 65, 5.9 percent of the site area (column 4) is required for retention practices to maintain the predevelopment volume. To maintain the predevelopment peak runoff rate (column 5), 9.5 percent of the site is required. Therefore, additional detention storage or a hybrid approach (calculated in column 7) is required.

Table 4.2. Representative Percentages of Site Required for Volume and Peak Control

Type of 24-Hour Storm Event (1)	Runoff Curve No. Existing (2)	Runoff Curve No. Proposed (3)	% of Area Needed for IMP: Volume Control Using 100% Retention Chart Series A (4)	Peak Control Using 100% Retention Chart Series B (5)	Peak Control Using 100% Detention Chart Series C (6)	Hybrid Design (Eq. 4.6) (7)	Percent of Volume Retention for Hybrid Design (Eq. 4.5) (8)
3"	50	55	1.7	1.6	0.9	1.7	100
		60	4.0	3.4	2.4	4.0	100
		65	6.9	6.2	4.5	6.9	100
		70	10.4	9.3	7.3	10.4	100
		80	19.3	18.0	15.8	19.3	100
	60	65	2.9	3.9	2.3	3.6	80
		70	6.3	6.7	4.4	6.6	96
		75	10.5	10.0	7.1	10.5	100
		90	27.5	24.9	18.7	27.5	100
	70	75	4.1	5.9	3.4	5.3	77
		80	8.9	9.7	5.8	9.5	94
		85	14.6	13.9	8.8	14.6	100
		90	21.2	18.7	12.6	21.2	100
	75	80	4.8	7.5	4.2	6.6	73
		85	10.5	11.8	7.0	11.4	91
		90	17.1	16.6	10.2	17.1	100
5"	50	55	4.8	6.9	4.0	6.3	77
		60	10.1	11.1	6.9	10.9	93
		65	16.0	15.6	10.4	16.0	100
		70	22.4	20.6	14.5	22.4	100
		80	36.7	32.8	23.9	36.7	100
	60	65	5.9	9.5	5.3	8.3	71
		70	12.3	14.6	8.4	13.9	88
		75	19.1	19.8	12.0	19.6	97
		90	42.9	37.2	25.3	42.9	100
	70	75	6.9	13.2	7.2	10.9	63
		80	14.3	18.9	10.7	17.4	82
		85	22.2	24.5	14.3	23.8	93
		90	30.7	30.5	18.2	30.7	100
	75	80	7.4	15.0	8.1	12.3	60
		85	15.3	20.6	11.6	18.9	81
		90	23.8	26.7	15.2	25.7	92
7"	50	55	7.6	12.3	6.8	10.7	71
		60	15.6	18.6	10.7	17.7	88
		65	23.9	25.0	15.1	24.7	97
		70	32.5	31.4	19.6	32.5	100
		80	50.5	44.5	30.0	50.5	100
	60	65	8.3	16.6	9.0	13.6	61
		70	16.9	23.2	13.2	21.2	80
		75	25.8	29.9	17.3	28.7	90
		90	53.7	49.7	30.7	53.7	100
	70	75	8.9	20.4	10.9	16.1	55
		80	17.9	26.8	14.7	23.8	75
		85	27.2	33.4	18.9	31.5	87
		90	36.7	42.3	23.0	39.2	94
	75	80	9.1	22.1	11.5	17.1	53
		85	18.4	28.6	15.6	25.1	73
		90	27.9	35.3	19.8	32.9	85

- For a post-development CN of 90, 42.9 percent of the site area (column 4) is required for retention practices to maintain the predevelopment volume. To maintain the predevelopment peak runoff rate (column 5) 37.2 percent of the site is required. Therefore, the storage required to maintain the runoff volume is also adequate to maintain the peak runoff rate. However, 42.9 percent of the site for IMPs is not a practical and reasonable use of the site. Refer to Step 7, hybrid approach, for a more reasonable combination of retention and detention storage.

Step 5: Determine storage required to maintain predevelopment peak runoff rate using 100 percent detention. (This step is required if additional detention storage is needed.)

Chart Series C: Storage Volume Required to Maintain the Predevelopment Peak Runoff Rate Using 100% Detention is used to determine the amount of site area to maintain the peak runoff rate only. This information is needed to determine the amount of detention storage required for hybrid design, or where site limitations prevent the use of retention storage to maintain runoff volume. This includes sites that have severely limited soils for infiltration or retention practices. The procedure to determine the site area is the same as that of Step 3. Using Chart Series C, the following assumptions apply:

- The Tc for the post-development condition is equal to the Tc for the predevelopment condition.
- The storage volume, expressed as a depth in hundredths of an inch (over the development site), is for peak flow control.

These charts are based on the relationship and calculations from Figure 6.1 (Approximate Detention Basin Routing for Rainfall Types I, IA, II and III) in TR-55 (SCS, 1986).

Step 6: Use hybrid facility design (required for additional detention storage).

When the percentage of site area for peak control exceeds that for volume control as determined in Step 3, a hybrid approach must be used. For example, a dry swale (infiltration and retention) may incorporate additional detention storage. Equation 2.5 is used to determine the ratio of retention to total storage. Equation 2.6 is then used to determine the additional amount of site area, above the percentage of site required for volume control, needed to maintain the predevelopment peak runoff rate.

$$x = \frac{50}{(\forall_{R100} - \forall_{D100})} \times \left(-\forall_{D100} + \sqrt{\forall^2_{D100} + 4 \times (\forall_{R100} - \forall_{D100}) \times \forall R}\right) \qquad \text{Eq. 4.5}$$

where

$\forall R$ = Storage Volume required to maintain predevelopment runoff volume (Chart Series A)

$\forall_{R_{100}}$ = Storage Volume required to maintain predevelopment peak runoff rate using 100% retention (Chart Series B)

$\forall_{D_{100}}$ = Storage Volume required to maintain predevelopment peak runoff rate using 100% detention (Chart Series C)

x = Area ratio of retention storage to total storage and the hybrid storage can be determined as:

$$H = \forall R \times (100 \div x) \qquad \text{Eq. 4.6}$$

Equations 4.5 and 4.6 are based on the following assumptions:

- *x*% of the total storage volume is the retention storage required to maintain the predevelopment CN calculated from Chart Series A: Storage Volume Required to Maintain Predevelopment Volume using Retention Storage.
- There is a linear relationship between the storage volume required to maintain the peak predevelopment runoff rate using 100% retention and 100% detention (Chart Series B and C)

The procedure for calculating hybrid facilities size is shown in Example 4.4.

Example 4.4: Calculation of Additional Storage Above Volume Required to Maintain CN and Maintain Predevelopment Peak Runoff Rate Using Hybrid Approach

Given:

- 5-inch Storm Event with Rainfall Distribution Type II
- Existing CN = 60
- Proposed CN = 65
- Storage volume required to maintain volume (CN) using retention storage = 0.35" (from Chart Series A)
- Storage volume required to maintain peak runoff rate using 100% retention = 0.62" (from Chart Series B)
- Storage volume required to maintain peak runoff rate using 100% detention = 0.31" (from Chart Series C)

Step 1: Solve for *x* (ratio of retention to total storage) using Equation 4.5:

$$\chi = \frac{50}{(.62 - .31)} \times \left(-.31 + \sqrt{.31^2 + 4 \times (.62 - .31) \times .35}\right)$$

$$\chi = 68$$

Therefore: 0.35" of storage needed for runoff volume control is 68% of the total volume needed to maintain both the predevelopment volume and peak runoff rates.

Step 2: Solve for the total area to maintain both the peak runoff rate and volume using Equation 4.6.

$$H = .35 \times \frac{100}{68}$$

$$H = 0.51''$$

Therefore , the difference between 0.35" and 0.51" is the additional detention area needed to maintain peak discharge.

Step 7: Determine hybrid amount of IMP site area required to maintain peak runoff rate with partial volume attenuation using hybrid design (required when retention area is limited).

Site conditions, such as high percentage of site needed for retention storage, poor soil infiltration rates, or physical constraints, can limit the amount of site area that can be used for retention practices. For poor soil infiltration rates, bioretention is still an acceptable alternative, but an underdrain system must be installed. In this case, the bioretention basin is considered detention storage.

When this occurs, the site area available for retention IMPs is less than that required to maintain the runoff volume, or CN. A variation of the hybrid approach is used to maintain the peak runoff rate while attenuating as much of the increased runoff volume as possible. First, the appropriate storage volume that is available for runoff volume control ($\forall R'$) is determined by the designer by analyzing the site constraints. Equation 4.7 is used to determine the ratio of retention to total storage. Equation 4.8 is then used to determine the total site IMP area in which the storage volume available for retention practices ($\forall R'$) substitutes the storage volume required to maintain the runoff volume.

$$X' = \frac{50}{(\forall_{R100} - \forall_{D100})} \times \left(-\forall_{D100} + \sqrt{\forall^2_{D100} + 4 \times (\forall_{R100} - \forall_{D100}) \times \forall R'}\right) \qquad \text{Eq. 4.7}$$

Where $\forall R'$ = storage volume acceptable for retention IMPs. The total storage with limited retention storage is:

$$H' = \forall R' \times (100 \div \chi') \qquad \text{Eq. 4.8}$$

where H' is hybrid area with a limited storage volume available for retention IMPs.

Example 4.5 illustrates this approach.

4.6 DETERMINATION OF DESIGN STORM EVENT

Conventional stormwater management runoff quantity control is generally based on not exceeding the predevelopment peak runoff rate for the 2-year and 10-year 24-hour Type II storm events. The amount of rainfall used to determine the runoff for the site is derived from Technical Paper 40 (Department of Commerce, 1963). For Prince George's County, these amounts are 3.3 and 5.3 inches, respectively. The 2-year storm event was selected to protect receiving channels from sedimentation and erosion. The 10-year event was selected for adequate flow conveyance considerations. In situations where there is potential for flooding, the 100-year event is used.

The criteria used to select the design storm for low-impact development are based on the goal of maintaining the predevelopment hydrologic conditions for the site. The determination of the design storm begins with an evaluation of the predevelopment condition. The hydrologic approach of low-impact development is to retain the same

Example 4.5: Calculation of Percentage of Site Area Required to Maintain the Peak Runoff Rate Using the Hybrid Approach of Retention and Detention

Given:

- 5-inch storm event with rainfall distribution Type II
- Existing CN = 60
- Proposed CN = 65
- Storage volume required to maintain volume (CN) = 0.35" (From Chart Series A)
- Storage volume required to maintain peak runoff rate using 100% retention = 0.62" (from Chart Series B)
- Storage volume required to maintain peak runoff rate using 100% detention = 0.31" (from Chart Series C)
- Only half of the required site area is suitable for retention practices, remainder must incorporate detention. ($\forall R'$ = 0.35 x 0.50 = 0.18")

Step 1: Determine appropriate amount of overall IMP area suitable for retention practices.

Half of area is appropriate (given above). Use Equation 2.7:

$$\chi' = \frac{50}{(.62 - .31)} \times \left(-.31 + \sqrt{.31^2 + 4 \times (.62 - .31) \times .18}\right)$$

$$\chi' = 41.2\%$$

Therefore, 0.18" of storage available for runoff volume control is 41.2% of the total volume needed for maintaining the predevelopment peak runoff rate.

Step 2: Solve for the total area required to maintain the peak runoff rate using Equation 4.8.

Solve for H′

$$H' = 0.18 \times \frac{100}{41.2}$$

$$H' = 0.43''$$

Therefore, totally 0.43" of the site is required to maintain the predevelopment peak runoff rate but not the runoff volume. Of the 0.43" storage, 0.18" of the storage is required for retention volume.

amount of rainfall within the development site as that retained by woods, in good condition, and then to gradually release the excess runoff as woodlands would release it. By doing so, we can emulate, to the greatest extent practical, the predevelopment hydrologic regime to protect watershed and natural habitats. Therefore, the predevelopment condition of the low-impact development site is required to be *woods in good condition*. This requirement is identical to the State of Maryland's definition of the predevelopment condition. The CN for the predevelopment condition is to be determined based on the land cover being woods in good condition and the existing HSG. The design storm is to be the greater of the rainfall at which direct runoff begins from a woods in good condition, with a modifying factor, or the 1-year 24-hour storm event. The rainfall at which direct runoff begins is determined using Equation 4.9. The initial rainfall amount at which direct runoff begins from a woodland is modified by multiplying this amount by a factor of 1.5 account for the slower runoff release rate under the wooded predevelopment condition.

$$P = 0.2 \times \left(\frac{1000}{CN_c} - 10 \right) \qquad \text{Eq. 4.9}$$

where P is rainfall at which direct runoff begins.

A three-step process, illustrated in Example 4.6, is used to determine the design storm event.

Step 1: Determine the predevelopment CN.

Use an existing land cover of woods in good condition overlaid over the hydrologic soils group (HSG) to determine the composite site CN.

Step 2: Determine the amount of rainfall needed to initiate direct runoff.

Use Equation 4.9 to determine the amount of rainfall (P) needed to initiate direct runoff.

Step 3: Account for variation in land cover.

Multiply the amount of rainfall (P) determined in Step 2 by a factor of 1.5.

Example 4.6 demonstrates this approach.

Example 4.6: Determination of Design Storm

Step 1: Determine the predevelopment CN based on woods (good condition) and HSG.

Given: Site condition of 90% HSG soil type B and 10% HSG soil type C,

$CN_c = 0.9\ (55) + 0.1 \times (70)$

$CN_c \geq 56.5 \approx 57$ use 57

Step 2: Determine the amount of rainfall to initiate direct runoff using Equation 4.9.

$$P = 0.2 \times \left(\frac{1000}{57} - 10 \right)$$

P = 1.5 inches

Step 3: Multiply the amount of rainfall by a factor of 1.5.

Design rainfall = P x 1.5

Design rainfall = 1.5 inches x 1.5

Design rainfall = 2.25 inches

References

American Society of Civil Engineers (ASCE). 1994. *Design and Construction of Urban Stormwater Management Systems.* ASCE Manuals and Reports of Engineering Practice, No.77. Prepared by the Urban Water Resources Research Council of the American Society of Civil Engineers and the Water Environment Federation, Reston, VA.

Cairns, J. 1993. Ecological Restoration: Replenishing our National Global Ecological Capital. Nature Conservation 3: Reconstruction of Fragmented Ecosystems: Ed. By D.A. Saunders, R.J. Hobbs, and P.E. Eherlich. Surrey Beatty & Sons.

Chow, V.T. 1964. *Handbook of Applied Hydrology*. McGraw-Hill, Inc., New York.

Department of Commerce. 1963. *Rainfall Frequency Atlas of the United States for* Durations *from 30 minutes to 24 hours and Return Periods from 1 to 100 Years.* Technical Paper 40. U.S. Department of Commerce, Washington, D.C.

Federal Interagency Stream Restoration Working Group (FISRWG). 1998. Stream Corridor Restoration: Principles, processes, and Practices. PB98-158348LUW.

Leopold , L.B. 1968. *Hydrology for Urban Land Planning: A Guidebook on the Hydrologic Effects of Land Use*. U.S. Geological Survey Circular 554.

Leopold, L.B., M.G. Wolman, and J.P. Miller. 1964. *Fluvial Processes in Geomorphology*. Dover Publications, Inc., Mineola, New York.

Maidment, D.R. 1993. *Handbook of Hydrology*. McGraw-Hill, Inc. New York.

Maryland Department of the Environment (MDE). 1998. *Maryland Stormwater*

Prince George's County, Maryland. 1997. *Low-Impact Development Design Manual*, Department of Environmental Resources, Prince George's County, Maryland.

SCS. 1986. *Urban Hydrology for Small Watersheds*. Technical Release 55, US Department of Agriculture, Soil Conservation Service, Engineering Division, Washington, DC.

SCS. 1985. *National Engineering Handbook*. Section 4, Hydrology (NEH-4). Soil Conservation Service, US Department of Agriculture, Washington, DC.

APPENDIX A

STORAGE VOLUME REQUIRED TO MAINTAIN THE PRE-DEVELOPMENT RUNOFF VOLUME USING RETENTION STORAGE

APPENDIX B

STORAGE VOLUME REQUIRED TO MAINTAIN
THE PRE-DEVELOPMENT
PEAK RUNOFF RATE USING 100% RETENTION STORAGE

APPENDIX C

STORAGE VOLUME REQUIRED TO MAINTAIN THE PRE-DEVELOPMENT PEAK RUNOFF RATE USING 100% DETENTION STORAGE