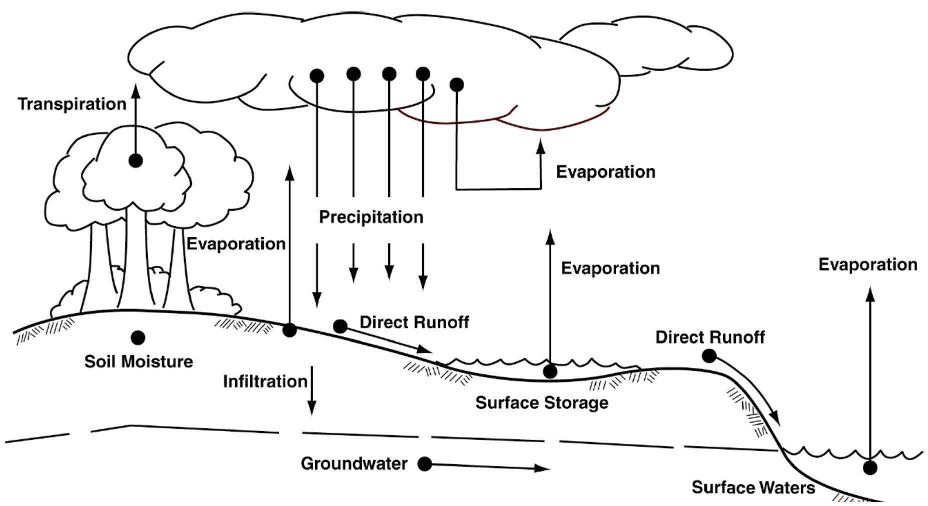
Computing Stormwater Runoff Rate and Volume



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Computing Stormwater Runoff Rates and Volumes

This chapter discusses the fundamentals of computing stormwater runoff rates and volumes from rainfall through the use of various mathematical methods. To do so effectively, the chapter also describes the fundamentals of the rainfall-runoff process that these methods attempt to simulate. Guidance is also provided in the use of the Natural Resources Conservation Service, Rational, and Modified Rational Methods that are specifically recommended and/or required by the NJDEP Stormwater Management Rules at N.J.A.C. 7:8. This guidance includes use of the methods to comply with the Rules' groundwater recharge, stormwater quality, and stormwater quantity requirements.

Fundamentals

The actual physical processes that convert rainfall to runoff are both complex and highly variable. As such, these processes cannot be replicated mathematically with exact certainty. However, through the use of simplifying assumptions and empirical data, there are several mathematical models and equations that can simulate these processes and predict resultant runoff volumes and rates with acceptable accuracy.

The selection of the appropriate model or equation depends upon a number of factors.

Desired Results

Some methods, such as the Rational Method, can be used to produce estimates of peak runoff rates, but cannot predict total runoff volumes. Other methods, conversely, can only produce estimates of total runoff volumes, while others, such as the Natural Resources Conservation Service (NRCS) methods, can accurately predict both total runoff volume and peak rate, and even entire runoff hydrographs.

Drainage Area Size

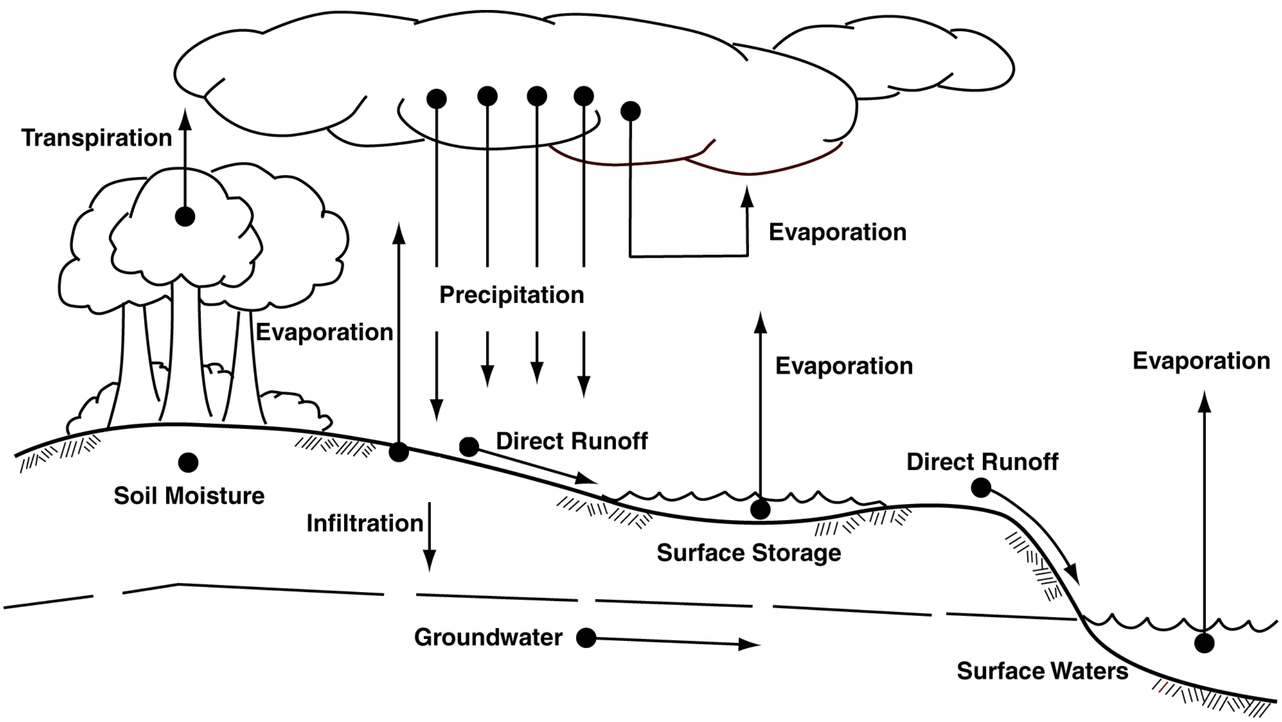
Due to their assumptions and/or theoretical basis, some methods can accurately predict runoff volumes or rates only for single drainage areas of 20 acres or less, while other methods can be applied to watersheds of 20 square miles or more with 100 or more subareas.

Data Availability

Simple methods, such as the Rational or Modified Rational Methods, require limited rainfall and drainage area data, while other, more sophisticated methods have extensive data needs, including long-term rainfall and temperature data as well as drainage area soils, subsoil, and ground cover information. In general, the more data-intensive models can produce more comprehensive runoff predictions.

In general, stormwater runoff can be described as a by-product of rainfall's interaction with the land. This interaction is one of several processes that the earth's water may go through as it continually cycles between the land and the atmosphere. In addition, stormwater runoff is only one of many forms water may take during one of these cycles, known scientifically as the hydrologic cycle. Shown in Figure 5-1 below, the hydrologic cycle depicts both the primary forms that water can take and the cyclical processes that produce them. In addition to runoff, these processes include precipitation, evaporation from surfaces or the atmosphere, evapotranspiration by plants, and infiltration into the soil or groundwater. As such, water that precipitates as rainfall can wind up or at least spend time on ground or plant surfaces, in the atmosphere, within the various soil layers, or in waterways and water bodies.

Figure 5-1: The Hydrologic Cycle



Source: Fundamentals of Urban Runoff Management.

In general, all runoff computation methods are, to some degree, mathematical expressions of the hydrologic cycle. However, most transform its cyclical character to a linear one, treating rainfall as an input and producing runoff as an output. During this transformation, each method uses mathematical approximations of the real rainfall-runoff processes to produce its estimates of runoff volume and/or rate. As described above, each method has its own complexity, data needs, accuracy, and range of results.

As the key input, rainfall is generally characterized by its size, intensity, and the frequency of its occurrence. The size of a rain storm is the total precipitation that occurs over a particular duration. How often this size of storm is likely to reoccur is called its recurrence interval. For instance, a rainfall of certain duration that occurs, on average, once every 25 years would have an average recurrence interval of 25 years or be called a 25-year storm.

Since storms have been shown to be mathematically random events, their recurrence can also be specified as an annual probability. The equation for converting between recurrence interval and annual probability is:

Annual probability (in percent) = 100/recurrence interval (in years)

For example, the 25-year storm noted above could also be described as having a probability of 4 percent (=100/25) or a 4 percent chance of being equaled or exceeded in any given year. Similarly, a 2-year storm has a 50 percent chance (=100/2), a 10-year storm has a 10 percent chance (=100/10), and a 100-year storm has a 1 percent chance (=100/100) of being equaled or exceeded in a given year. Resultant runoff peak rates and volumes events can also be described in such terms.

Runoff volumes are influenced primarily by the total amount of rainfall. However, runoff rates resulting from a given rainfall, including the peak rate or discharge, are influenced primarily by the rainfall's distribution, which is how the rainfall rate or intensity varies over a period of time. Studies of rainfall records show that actual storm distributions and durations can vary considerably from event to event. A rainfall may be evenly distributed over a time period or can vary widely within that same period. Its duration can also be long or very short. These different types of rain events can produce extremely different runoff volumes and peak discharges.

Runoff computation methods deal with this rainfall variability in one of two general ways. Many methods, including the Rational and NRCS methods, rely on a hypothetical rain event known as a design storm for their rainfall input. This single, hypothetical storm event is based on a compilation of local or regional rainfall data recorded over an extended time period. To use a design storm, the user must make some assumptions about the antecedent ground and waterway conditions that exist at its start. Most runoff computations are based on average antecedent conditions, although wetter or drier conditions can also be used depending upon the user's interests and concerns.

Instead of compiling long-term rainfall data into a single design storm, other runoff computation methods address the variability of real rain events by analyzing a long series of them, computing runoff rate and volume estimates for each. While such methods need only the exact antecedent conditions that existed prior to the first storm, they must mathematically account for changes in ground and waterway conditions during intervening dry periods. Therefore, such methods are generally more complex than design storm methods and, obviously, require extensive rainfall data for the drainage area or watershed under analysis. Their results, however, are based on the actual long-term rainfall history of the watershed instead of a single, hypothetical design storm.

In addition to rainfall and antecedent conditions, other factors that can significantly affect both runoff volume and peak discharge are the hydrologic characteristics of the soils in the watershed and the type of surface that covers those soils. This cover may vary from pervious surfaces such as woods and grass to impervious surfaces such as roofs, roadways, and parking lots. Another factor that can greatly influence the peak runoff rate or discharge is the time of concentration (Tc). This is a measure of how quickly or slowly a watershed will respond to rainfall input and is usually measured as the time required for runoff to travel from the hydraulically most distant point in the watershed to the point of analysis at the watershed's lower end. Factors such as surface roughness, irregularity, length, and slope generally affect a watershed's Tc.

In summary, runoff computation methods attempt to mathematically reproduce or simulate the hydrologic cycle. They treat rainfall as an input, converting it into estimates of resultant runoff volume and/or rate. There are certain characteristics of both the rainfall event and the area upon which it falls that can influence the resulting runoff. These include:

1. High intensity rainfall will generally produce a greater peak discharge than a rainfall that occurs over a longer time period.
2. Highly porous or permeable soils that can rapidly infiltrate rainfall generally produce less runoff volume than soils with more restrictive infiltration.
3. Dense vegetation such as woodland intercepts and help infiltrates rainfall, thereby reducing runoff volumes and rates.
4. Conversely, impervious areas such as roadways and rooftops prevent infiltration and increase runoff volumes and rates.
5. Drainage areas with shorter times of concentration will have higher peak runoff rates than those with a longer Tc.

Runoff Computation Methods

As described in the Stormwater Management Rules, the NJDEP has specified that one of two general runoff computation methods be used to compute runoff rates and volumes. These are the NRCS methodology, which consists of several components, and the Rational Method (and the associated Modified Rational Method), which are generally limited to drainage areas less than 20 acres. A general description of each method is provided below.

NRCS Methodology

The USDA Natural Resources Conservation Service (NRCS) methodology is perhaps the most widely used method for computing stormwater runoff rates, volumes, and hydrographs. It uses a hypothetical design storm and an empirical nonlinear runoff equation to compute runoff volumes and a dimensionless unit hydrograph to convert the volumes into runoff hydrographs. The methodology is particularly useful for comparing pre- and post-development peak rates, volumes, and hydrographs. The key component of the NRCS runoff equation is the NRCS Curve Number (CN), which is based on soil permeability, surface cover, hydrologic condition, and antecedent moisture. Watershed or drainage area time of concentration is the key component of the dimensionless unit hydrograph.

Several runoff computation methods use the overall NRCS methodology. The most commonly used are the June 1986 *Technical Release 55 – Urban Hydrology for Small Watersheds* (TR-55), the April 2002 *WinTR-55 – Small Watershed Hydrology* computer program, and *Technical Release 20 – Computer Program for Project Formulation: Hydrology* (TR-20) published by the NRCS. The computer programs *HEC-1 Flood Hydrograph Package* and *HEC-HMS Hydrologic Modeling System* published by the U.S. Army Corps of Engineers' Hydrologic Engineering Center also contain components of the NRCS methodology. A complete description of the NRCS methodology can be found in the NRCS *National Engineering Handbook Section 4 – Hydrology* (NEH-4).

Rational Method

The Rational Method uses an empirical linear equation to compute the peak runoff rate from a selected period of uniform rainfall intensity. Originally developed more than 100 years ago, it continues to be useful in estimating runoff from simple, relatively small drainage areas such as parking lots. Use of the Rational Method should be limited to drainage areas less than 20 acres with generally uniform surface cover and topography. It is important to note that the Rational Method can be used only to compute peak runoff rates. Since it is not based on a total storm duration, but rather a period of rain that produces the peak runoff rate, the method cannot compute runoff volumes unless the user assumes a total storm duration. Complete descriptions of the Rational Method can be found in many hydrology and drainage textbooks.

Modified Rational Method

The Modified Rational Method is a somewhat recent adaptation of the Rational Method that can be used to not only compute peak runoff rates, but also to estimate runoff volumes and hydrographs. This method uses the same input data and coefficients as the Rational Method along with the further assumption that, for the selected storm frequency, the duration of peak-producing rainfall is also the entire storm duration. Since, theoretically, there are an infinite number of rainfall intensities and associated durations with the same frequency or probability, the Modified Rational Method requires that several of these events be analyzed in the method to determine the most severe. Similar to the Rational Method, there are several urban hydrology and drainage publications that contain descriptions of the Modified Rational Method, including Appendix A-9 of the *Standards for Soil Erosion and Sediment Control in New Jersey* published by the New Jersey State Soil Conservation Committee. Use of the Modified Rational Method should also be limited to drainage areas less than 20 acres with generally uniform surface cover and topography.

Design Storms

To fully comply with the NJDEP Stormwater Management Rules, stormwater runoff must be computed for three types of rainfall or storm events. These storms are associated with the groundwater recharge, stormwater quality, and stormwater quantity requirements in the Rules. A description of each storm and the techniques used to model it in the NRCS, Rational and Modified Rational methods are presented below.

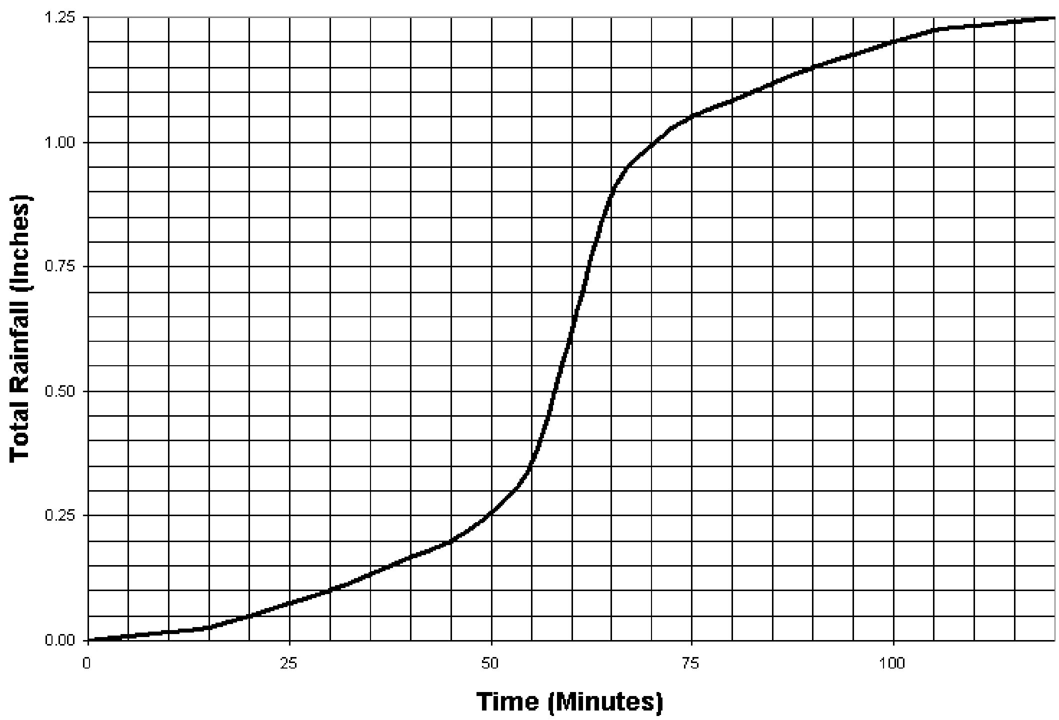
Groundwater Recharge Design Storm

As described in detail in *Chapter 6: Groundwater Recharge*, the NJDEP's groundwater recharge requirements are actually met through the analysis of a series of rainfall events derived from long-term New Jersey data. However, these events can also be expressed by an equivalent groundwater recharge design storm that represents the largest rainfall that must be controlled by a groundwater recharge facility. Due to the relatively small size of both the statistical rainfall series and the equivalent Design Storm, the NJDEP has developed specialized equations to compute the resultant runoff volume from each. The basis and use of these equations are described in detail in *Chapter 6: Groundwater Recharge*.

Stormwater Quality Design Storm

This is the rainfall event used to analyze and design structural and nonstructural stormwater quality measures (known as Best Management Practices or BMPs). As described in the Stormwater Management Rules, the NJDEP stormwater quality design storm has a total rainfall depth of 1.25 inches and a total duration of two hours. During its duration, the rain falls in a nonlinear pattern as depicted in Figure 5-2 below. This rainfall pattern or distribution is based on Trenton, New Jersey rainfall data collected between 1913 and 1975 and contains intermediate rainfall intensities that have the same probability or recurrence interval as the storm's total rainfall and duration. As such, for times of concentration up to two hours, the stormwater quality design storm can be used to compute runoff volumes, peak rates, and hydrographs of equal probability. This ensures that all stormwater quality BMPs, whether they are based on total runoff volume or peak runoff rate, will provide the same level of stormwater pollution control.

Figure 5-2: NJDEP 1.25-Inch/2-Hour Stormwater Quality Design Storm



The NJDEP stormwater quality design storm can be used to analyze and design stormwater quality BMPs based on the Rational, Modified Rational, or NRCS methods. Selection of the appropriate method will depend on the type of BMP selected and its required design data. BMPs that essentially store, treat, and slowly release the stormwater quality design storm runoff (such as extended detention basins, wet ponds, constructed stormwater wetlands, and sand filters) generally require a runoff volume at the very least and, ideally, an entire runoff hydrograph. This mandates the use of either the NRCS methodology or Modified Rational Method. However, BMPs that treat the stormwater quality design storm runoff as it is conveyed through them (such a filter strip, buffer or manufactured treatment device) generally require only a peak runoff rate. This can be computed using either the NRCS or Rational Methods. Further information on the use of these methods is presented below. When using either the Rational or Modified Rational Methods, it is important to remember their 20-acre drainage area limitations.

Table 5-1 was prepared for those using the NRCS methodology to compute stormwater quality design storm runoff peaks or hydrographs. It contains cumulative and incremental rainfall values for the stormwater quality design storm in five minute increments. These values can be used in computer programs such as TR-20, HEC-1, HEC-HMS, and other programs that both contain the NRCS methodology and allow user-specified rainfalls.

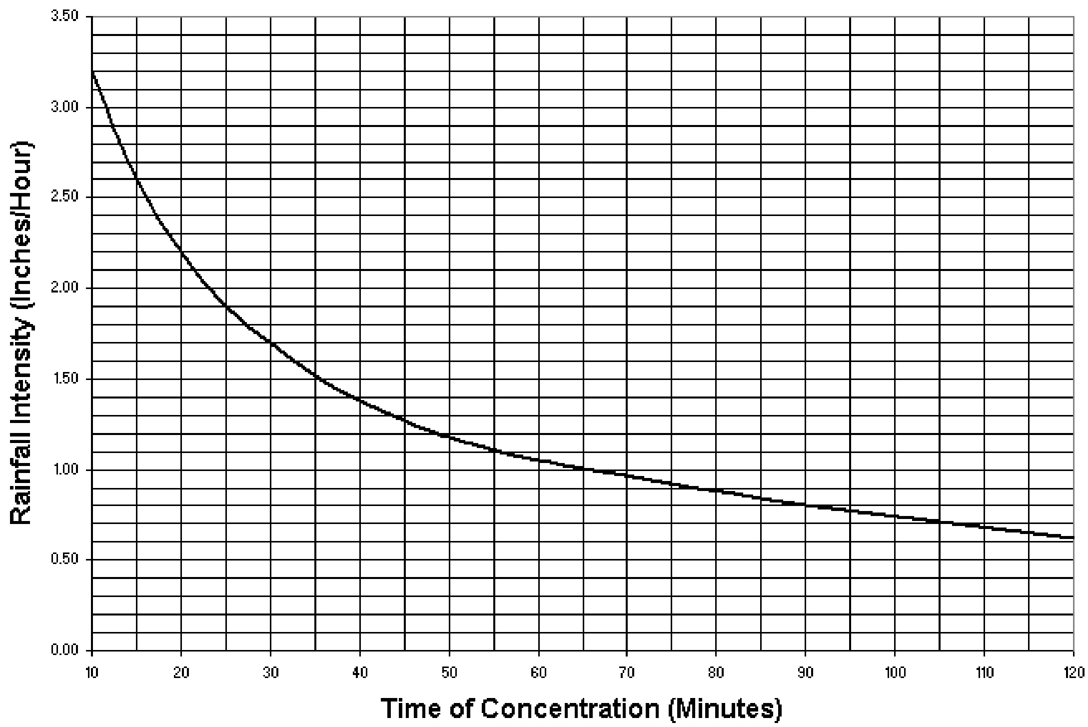
Table 5-1: NJDEP 1.25-Inch/2-Hour Stormwater Quality Design Storm
Cumulative and Incremental Rainfall Distributions

Time (minutes)	Cumulative Rainfall (inches)	Incremental Rainfall (inches)	Time (minutes)	Cumulative Rainfall (inches)	Incremental Rainfall (inches)
0	0.0000	0.0000	65	0.8917	0.2667
5	0.0083	0.0083	70	0.9917	0.1000
10	0.0166	0.0083	75	1.0500	0.0583
15	0.0250	0.0084	80	1.0840	0.0340
20	0.0500	0.0250	85	1.1170	0.0330
25	0.0750	0.0250	90	1.1500	0.0330
30	0.1000	0.0250	95	1.1750	0.0250
35	0.1330	0.0330	100	1.2000	0.0250
40	0.1660	0.0330	105	1.2250	0.0250
45	0.2000	0.0340	110	1.2334	0.0084
50	0.2583	0.0583	115	1.2417	0.0083
55	0.3583	0.1000	120	1.2500	0.0083
60	0.6250	0.2667			

Note: See Figure 5-1 for plot of cumulative rainfall distribution.

Figure 5-3 was prepared for those using the Rational Method to compute stormwater quality design storm runoff peaks. It presents the stormwater quality design storm as a rainfall intensity-duration curve that allows the user to determine the appropriate rainfall intensity for the selected time of concentration.

Figure 5-3: NJDEP 1.25-Inch/2-Hour Stormwater Quality Design Storm Rainfall Intensity-Duration Curve



Finally, when using the Modified Rational Method to compute a stormwater quality design storm hydrograph, the entire 2-hour storm duration at an average intensity of 0.625-inches/hour can be used. Example 5-1 below demonstrates this procedure.

Important Note: While the stormwater quality design storm actually falls in a variable pattern, use of the 2-hour average rate described above and demonstrated in Example 5-1 is consistent with the assumptions of the Modified Rational Method. In addition, analysis and experience has shown that the structural BMPs that store and slowly release the stormwater quality design storm hydrograph (such as extended detention basins, wet ponds, bioretention facilities, constructed wetlands, and sand filters) are not particularly sensitive to rainfall pattern. If such sensitivity does exist for a particular BMP, the designer should use the NRCS methodology, which allows for consideration of the stormwater quality design storm's variable rainfall pattern.

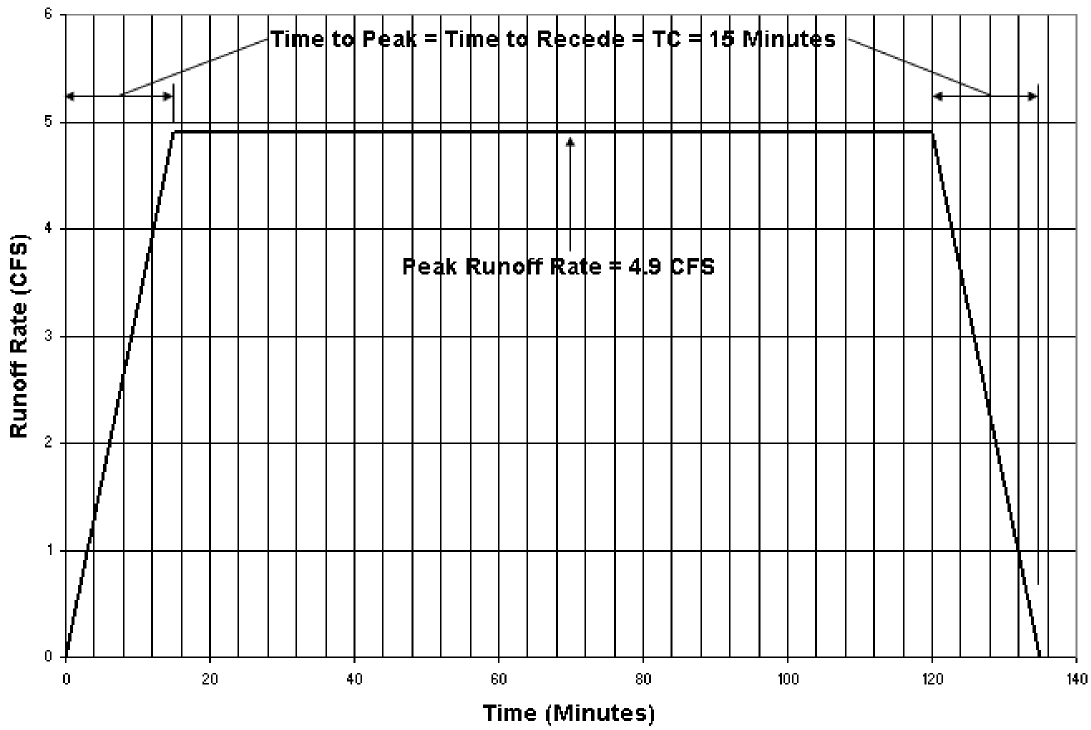
Example 5-1: NJDEP 1.25-Inch/2-Hour Stormwater Quality Design Storm Hydrograph Computation with Modified Rational Method

Description: A 10-acre development site has a Rational C value of 0.78 and a time of concentration of 15 minutes. Construct a runoff hydrograph from the site for the 1.25-inch/2-hour stormwater quality design storm using the Modified Rational Method.

C = 0.78 Average I = 1.25-inches/2-hours = 0.625 inches per hour
Area = 10 acres Tc = 15 minutes Storm duration = 2 hours

Q = runoff rate (cubic feet per second) = CIA
C = Rational Method runoff coefficient
I = rainfall intensity (inches per hour)
A = drainage area (acres)
D = storm duration (hours)
Q = (0.78) (0.625 inches per hour)(10 acres) = 4.9 CFS

In the Modified Rational Method, the runoff hydrograph is then constructed as shown here:



Finally, the total runoff volume is equal to the area under the hydrograph, which is equal to the peak runoff rate times the duration of the storm.

V = peak runoff rate x storm duration = Q x D

V = 4.9 cubic feet/second x 2 hours x 3600 seconds/hour

V = 35280 cubic feet = 0.81 acre-feet

Stormwater Quantity Storms

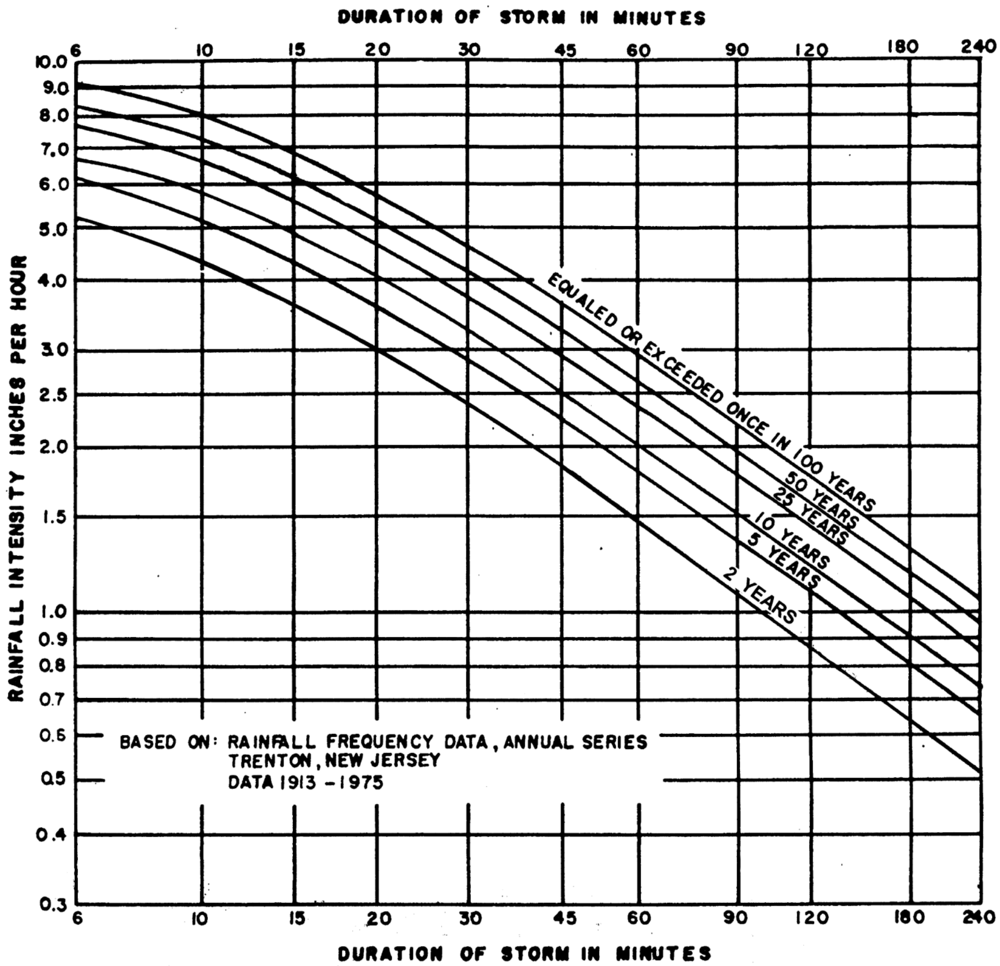
As described in the Stormwater Management Rules, the three storm frequencies of primary concern for stormwater quantity control are the 2, 10, and 100-year events. These storms are of such concern due to their potential to cause or aggravate downstream erosion and/or flooding. In certain instances, however, additional storm frequencies may need to be analyzed to ensure that downstream peak runoff rates and/or velocities are not increased by a land development or redevelopment project.

Selection of the appropriate stormwater quantity storm data will depend on the runoff estimation method being used. When using the NRCS methodology, the NRCS Type III Storm distribution should be selected. Details and data regarding this distribution can be found in the NRCS *Technical Release 55 – Urban Hydrology for Small Watersheds*. When using the Rational Method, the rainfall intensity-duration-frequency (IDF) curves shown in Figure 5-4 may be used. These curves were developed from Trenton area rainfall data between 1913 and 1975 and were adapted from Figure 2.1-2 in the *Technical Manual for Stream Encroachment Permits* prepared by the NJDEP Land Use Regulation Program. IDF curves based on rainfall data collected closer to an actual land development or redevelopment site may also be used if such data covers a sufficiently long time period and is analyzed by appropriate statistical methods.

Use of Long Term or Single Event Rainfall Data

As discussed in the *Fundamentals* section above, long term rainfall data for a watershed or development site may be used in certain runoff computations methods. Long term data can be used as input to the rainfall-runoff computations in place of a hypothetical, statistically-based design storm and, in certain instances, may be a more accurate or representative form of this input. In other instances, rainfall records from a significant historic storm in the watershed may also be used to test or verify a runoff computation or BMP design initially based on a hypothetical design storm. While the use of long term or single event rainfall data is not specifically required in the NJDEP Stormwater Management Rules, it is also not prohibited, since such uses may improve the effectiveness and/or reliability of a runoff computation or BMP design. Analysts and designers wishing to use such data should confer with the relevant review agencies prior to such use to ensure the suitability and acceptability of both the data and the computation method.

Figure 5-4: Rainfall Intensity-Duration-Frequency Curves



Note: Adapted from Figure 2.1-2 in the NJDEP *Technical Manual for Stream Encroachment Permits*.

Modeling Various Site Conditions

This section provides guidance for modeling various site conditions within a drainage area or watershed that may be encountered in the analysis and/or design of structural and nonstructural BMPs. This guidance is provided, where applicable, for the NRCS, Rational, and Modified Rational Methods and is intended to facilitate computation of required runoff volumes, peak rates, and hydrographs. A summary of the guidance for each computation method is presented at this end of this section in Table 5-2.

Pre-Developed Site Land Cover and Hydrologic Condition

As specified in the NJDEP Stormwater Management Rules, the predeveloped land cover at a development site must be assumed to be woods unless it can be verified that a different land cover has existed for at least five years prior to the analysis. Similarly, the predeveloped land cover must be assumed to be in good hydrologic condition for all land covers.

Sites With Pervious and Directly Connected Impervious Cover

It is virtually inevitable that a land development or redevelopment site will have a mixture of pervious and directly connected impervious surfaces, particularly under post-development conditions. As defined by the NRCS and others, impervious surfaces are directly connected when runoff from them can flow as shallow concentrated, channel, or pipe flow directly to the downstream drainage system. While such conditions pose no significant modeling problems for simple, linear methods such as the Rational and Modified Rational Methods, inaccuracies may occur for small rainfall depths when using more detailed, nonlinear methods such as the NRCS methodology. Analysis of such conditions using each method is presented here.

- **Rational and Modified Rational Methods:** Due to the linear character of the basic Rational Equation, a representative Rational Runoff Coefficient (C) can be computed for the entire site by standard area weighting techniques.
- **NRCS Methodology:** Due to the nonlinear character of the NRCS runoff equation and, primarily, the presence of the initial abstraction term Ia, inaccurate runoff estimates can result when the mixture of pervious and directly connected impervious surfaces within a drainage area or watershed are modeled with a weighted average NRCS Curve Number (CN). As discussed in the NRCS' TR-55, "the combination of impervious areas with pervious areas can imply a significant initial loss that may not take place." This problem will be particularly acute for small rainfalls less than an inch or two where the large (but incorrect) initial loss can be 50 percent or more of the total rainfall.

To avoid these errors, it is recommended that runoff volumes be computed separately from the pervious and directly connected impervious portions of the drainage area and then combined into a weighted average runoff volume. This volume averaging technique produces more accurate estimates of total runoff volume than the standard average Curve Number approach. At a minimum, it should generally be used for all rainfalls less than approximately 4 inches in depth. This would include the 1.25-inch/2-hour stormwater quality design storm and the 1-year and 2-year 24-hour storms. The technique can also be used for larger rainfall depths at the designer's discretion.

Example 5-2 below further illustrates this problem and the recommended volume averaging solution for the stormwater quality design storm.

Example 5-2: Site With Pervious and Directly Connected Impervious Cover

Runoff Volume Computation Using NRCS Methodology

Description: A 3-acre development site is comprised of 1 acre of impervious surface and 2 acres of lawn and woods with an NRCS Curve Number (CN) of 65. The entire impervious surface is directly connected to the site's drainage system. Compute the site's total runoff volume for the 1.25-inch stormwater quality design storm using the Weighted Average CN technique. Compare the results with the Weighted Average Volume technique.

Stormwater Quality Design Storm = P = 1.25 inches

Total drainage area = 3 acres

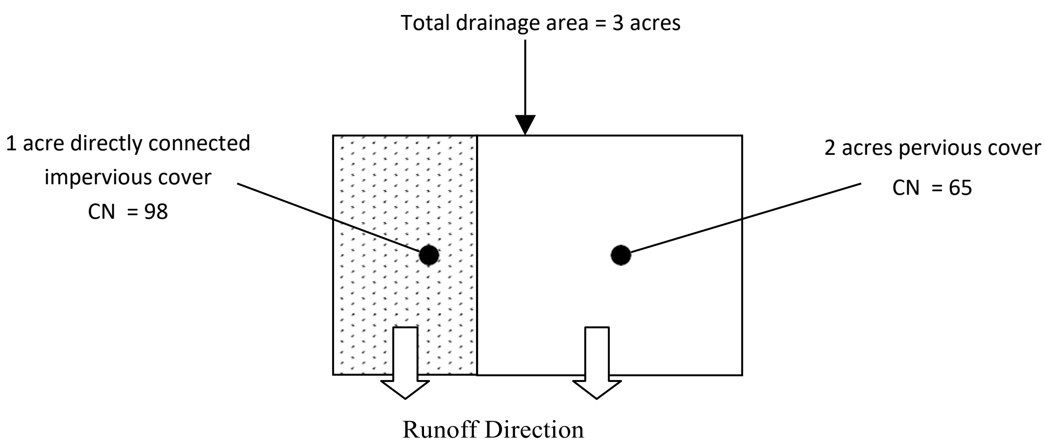
Impervious area = 1 acre (1/3 of total area)

Pervious area = 2 acres (2/3 of total area)

Pervious cover = mixture of lawn and woods   Pervious CN = 65

Impervious cover = asphalt   Impervious CN = 98

Note: All impervious cover is connected to the drainage system



1. Using Weighted Average Curve Number Technique

Weighted CN = (65)(2/3) + (98)(1/3) = 76

$$\text{Average } S = \frac{1000}{CN} - 10 = \frac{1000}{76} - 10 = 3.16 \text{ inches}$$

Average initial abstraction = Ia = 0.2S = (0.2)(3.16) = 0.63 inches

0.8S = (0.8)(3.16) = 2.53 inches

$$\text{Runoff volume} = Q = \frac{(P - 0.2\,S)^2}{P + 0.8\,S} = \frac{(1.25 - 0.63)^2}{1.25 + 2.53} = 0.10 \text{ inches}$$

Runoff volume = (0.10 inches/12 inches per foot)(3 acres)(43,560 sf per acre)

Total site runoff volume = 1089 cubic feet

2. Using Weighted Average Volume Technique

Impervious Area

$$\text{Impervious area } S = \frac{1000}{CN} - 10 = \frac{1000}{98} - 10 = 0.20 \text{ inches}$$

Impervious area initial abstraction = 0.2S = (0.2)(0.20) = 0.04 inches

0.8S = (0.8)(0.20) = 0.16 inches

$$\text{Impervious area runoff volume} = Q = \frac{(P - 0.2\,S)^2}{P + 0.8\,S} = \frac{(1.25 - 0.04)^2}{1.25 + 0.16} = 1.04 \text{ inches}$$

Runoff volume = (1.04 inches/12 inches per foot)(1 acre)(43,560 sf per acre)

Impervious area runoff volume = 3775 cubic feet

Pervious Area

$$\text{Pervious area } S = \frac{1000}{CN} - 10 = \frac{1000}{65} - 10 = 5.38 \text{ inches}$$

Pervious area initial abstraction = 0.2S = (0.2)(5.38) = 1.08 inches

0.8S = (0.8)(5.38) = 4.30 inches

$$\text{Pervious area runoff volume} = Q = \frac{(P - 0.2\,S)^2}{P + 0.8\,S} = \frac{(1.25 - 1.08)^2}{1.25 + 4.30} = 0.005 \text{ inches}$$

Runoff volume = (0.005 inches/12 inches per foot)(2 acres)(43,560 sf per acre)

Pervious area runoff volume = 36 cubic feet

Total site runoff volume = 3775 + 36 = 3811 cubic feet
(vs. 1089 cubic feet using weighted average CN)

As can be seen in Example 5-2 above, the weighted average CN technique produced an estimated stormwater quality design storm runoff volume that was less than 30 percent of the volume produced by the weighted average volume technique. Perhaps more significantly, the example also demonstrates how virtually the entire site runoff for the stormwater quality design storm comes from the impervious portion and that very little comes from the pervious portion (i.e., 3775 cubic feet vs. 36 cubic feet). The significant but erroneous initial loss that the NRCS cautions about in TR-55 can also be seen in the 0.63 inch initial abstraction for the entire site (including 1 acre of impervious surface) produced by the weighted average CN technique.

It is important to note that, in computing a weighted average runoff volume from the development site, Example 5-2 does not address the resultant peak discharge or hydrograph from the site. If both the pervious and directly connected impervious site areas will have the same time of concentration, the weighted runoff volume can then be used directly to compute the peak site discharge or hydrograph. However, if these areas will respond to rainfall with different times of concentration, separate hydrographs should be computed for each and then combined to produce the peak site discharge or hydrograph.

Sites with Unconnected Impervious Cover

As described in detail in *Chapter 2: Low Impact Development Techniques*, an important nonstructural BMP will be new impervious cover that is not directly connected to a site's drainage system. Instead, runoff from these impervious areas will sheet flow onto adjacent pervious areas, where a portion of the impervious area runoff will be given a second opportunity to infiltrate into the soil. Under certain conditions described below, this can help provide both groundwater recharge and stormwater quality treatment for small rainfalls as well as reduce the overall runoff volume that must be treated and/or controlled in a structural BMP downstream. Unconnected impervious areas may either by on-grade (e.g., a parking lot) or above-grade (e.g., a roof), while downstream pervious areas may either be constructed (e.g., lawn) or natural (e.g., woods or meadow).

In most circumstances, impervious areas can be considered unconnected under the following conditions:

1. All runoff from the unconnected impervious area must be sheet flow.
2. Upon entering the downstream pervious area, all runoff must remain as sheet flow.
3. Flow from the impervious surface must enter the downstream pervious area as sheet flow or, in the case of roofs, from downspouts equipped with splash pads, level spreaders, or dispersion trenches that reduce flow velocity and induce sheet flow in the downstream pervious area.
5. All discharges onto the downstream pervious surfaces must be stable and nonerosive.
6. The shape, slope, and vegetated cover in the downstream pervious area must be sufficient to maintain sheet flow throughout it length. Maximum slope of the downstream pervious area is 8 percent.
7. The maximum roof area that can be drained by a single downspout is 600 square feet.

To determine the hydrologic effects of unconnected impervious cover, the combined effects of the impervious area disconnection and the subsequent infiltration in downstream pervious areas must be quantified. Techniques to do so are presented below.

- **Rational and Modified Rational Methods:** Due to the character of the basic Rational Equation, there is currently no technique for addressing the effects of unconnected impervious cover. As such, neither the Rational nor Modified Rational Methods can be recommended at this time for use at sites with unconnected impervious areas.
- **Methodology Using NRCS Equations:** Computation of the resultant runoff from unconnected impervious areas can be performed using two different methods. The first method is described in the NRCS TR-55. The second method is a two-step technique using the NRCS runoff equation. Both methods are discussed in detail below. Additional discussion and computed examples of unconnected impervious cover are presented in *Chapter 2: Low Impact Development Techniques*.
  - **NRCS TR-55 Methodology:** This method is based on the procedures to compute runoff from unconnected impervious surfaces described in the NRCS TR-55. Complete details of these procedures are described in Chapter 2 of TR-55. It should be noted that the TR-55 procedures are applicable only to sites with less than 30 percent total impervious coverage. In addition, the size of the downstream pervious area must be at least twice as large as the unconnected impervious area.
  - **Two-Step Technique:** This method is a two-step technique using the NRCS runoff equation. First, the resultant runoff from the unconnected impervious area should be computed separately, using the NRCS runoff equation in a manner similar to the technique described above for impervious surfaces. However, once the runoff from the unconnected impervious area is computed, it should then be considered as additional rainfall on the downstream pervious area it sheet flows onto. As a result, these pervious areas will effectively be subject to

their own direct rainfall as well as the "rainfall" flowing from the upstream unconnected impervious areas. The resultant runoff from the downstream pervious areas in response to this combined rainfall can then be computed using the NRCS runoff equation again.

Example 5-3 illustrates this two-step runoff computation technique for unconnected impervious areas. In reviewing the example, it is important to note that the unconnected impervious area runoff depth must be converted to an equivalent uniform rainfall depth over the entire downstream pervious area based on the relative sizes of the unconnected impervious and downstream pervious areas.

Example 5-3: Site With Unconnected Impervious Cover
Runoff Volume Computation Using Two-Step Technique

Description: A 3-acre development site is comprised of 1 acre of impervious surface and 2 acres of lawn and woods with an NRCS Curve Number (CN) of 65. Runoff from the entire impervious surface sheet flows onto to the pervious portion of the site before entering the site's drainage system. Compute the total runoff volume for the 1.25-inch stormwater quality design storm using the NRCS methodology.

Stormwater Quality Design Storm = P = 1.25 inches

Total drainage area = 3 acres

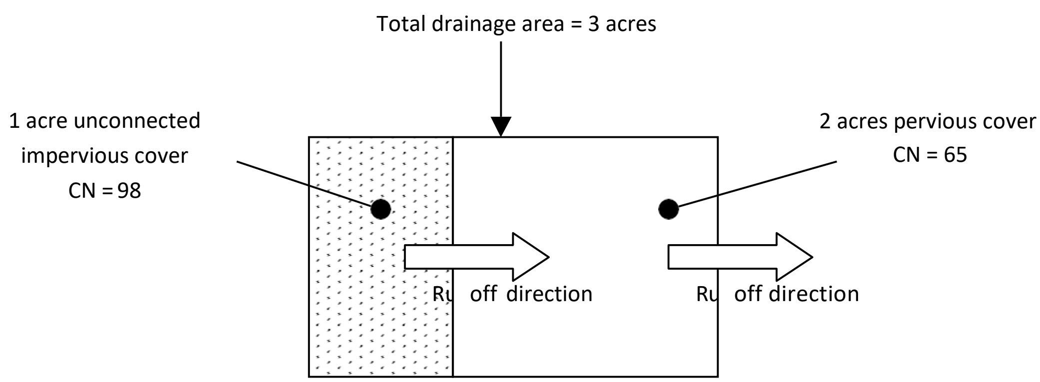
Impervious area = 1 acre (1/3 of total area)

Pervious area = 2 acres (2/3 of total area)

Pervious cover = mixture of lawn and woods pervious CN = 65

Impervious cover = asphalt impervious CN = 98

Note: All impervious area runoff sheet flows onto downstream pervious area



Impervious Area

$$\text{Impervious area } S = \frac{1000}{CN} - 10 = \frac{1000}{98} - 10 = 0.20 \text{ inches}$$

Impervious area initial abstraction = 0.2S = (0.2)(0.20) = 0.04 inches

0.8S = (0.8)(0.20) = 0.16 inches

$$\text{Impervious area runoff volume} = Q = \frac{(P - 0.2\,S)^2}{P + 0.8\,S} = \frac{(1.25 - 0.04)^2}{1.25 + 0.16} = 1.04 \text{ inches}$$

Runoff volume = (1.04 inches/12 inches per foot)(1 acre)(43,560 sf per acre)

Impervious area runoff volume = 3775 cubic feet

Equivalent rainfall depth on downstream pervious area =

(3775 cubic feet)/(2 acres)(43,560 sf per acre) = 0.043 feet = 0.52 inches

Pervious Area

Total effective rainfall = direct rainfall + unconnected impervious area runoff

= 1.25 inches + 0.52 inches = 1.77 inches total

$$\text{Pervious area } S = \frac{1000}{CN} - 10 = \frac{1000}{65} - 10 = 5.38 \text{ inches}$$

Pervious area initial abstraction = 0.2S = (0.2)(5.38) = 1.08 inches

0.8S = (0.8)(5.38) = 4.30 inches

$$\text{Pervious area runoff volume} = Q = \frac{(P - 0.2\,S)^2}{P + 0.8\,S} = \frac{(1.77 - 1.08)^2}{1.77 + 4.30} = 0.08 \text{ inches}$$

Runoff volume = (0.08 inches/12 inches per foot)(2 acres)(43,560 sf per acre)
= 581 cubic feet

Pervious area runoff volume = total runoff volume = 581 cubic feet

From the above example, it can be seen that a key parameter in the two-step runoff computation technique for unconnected impervious cover is the effective size of the downstream pervious area. The following three criteria, in conjunction with the seven requirements for all unconnected impervious areas shown above, should be used to determine the effective size of this downstream area:

1. The minimum sheet flow length across the downstream pervious area is 25 feet.
2. The maximum sheet flow length across the unconnected impervious area is 100 feet.
3. While the total flow length area may be greater, the maximum sheet flow length across the downstream pervious area that can be used to compute the total resultant runoff volume is 150 feet.

These criteria are illustrated below in Figures 5-5 and 5-6 for both on-grade and above-grade unconnected impervious areas, respectively. Additional criteria for determining the lower limits of the downstream pervious area are presented in Figure 5-7. When using Figure 5-6 with overlapping pervious areas downstream of roof downspouts, the overlapping areas should be counted only once in the computation of the total pervious area downstream of the roof.

Finally, when computing the peak runoff rate or hydrograph from an area with unconnected impervious cover, the time of concentration of the combined impervious and downstream pervious area should be based upon the Tc of the downstream pervious area only, with the Tc route beginning as sheet flow at the upper end of the pervious area.

Figure 5-5: Downstream Pervious Area Criteria for On-Grade Unconnected Impervious Area

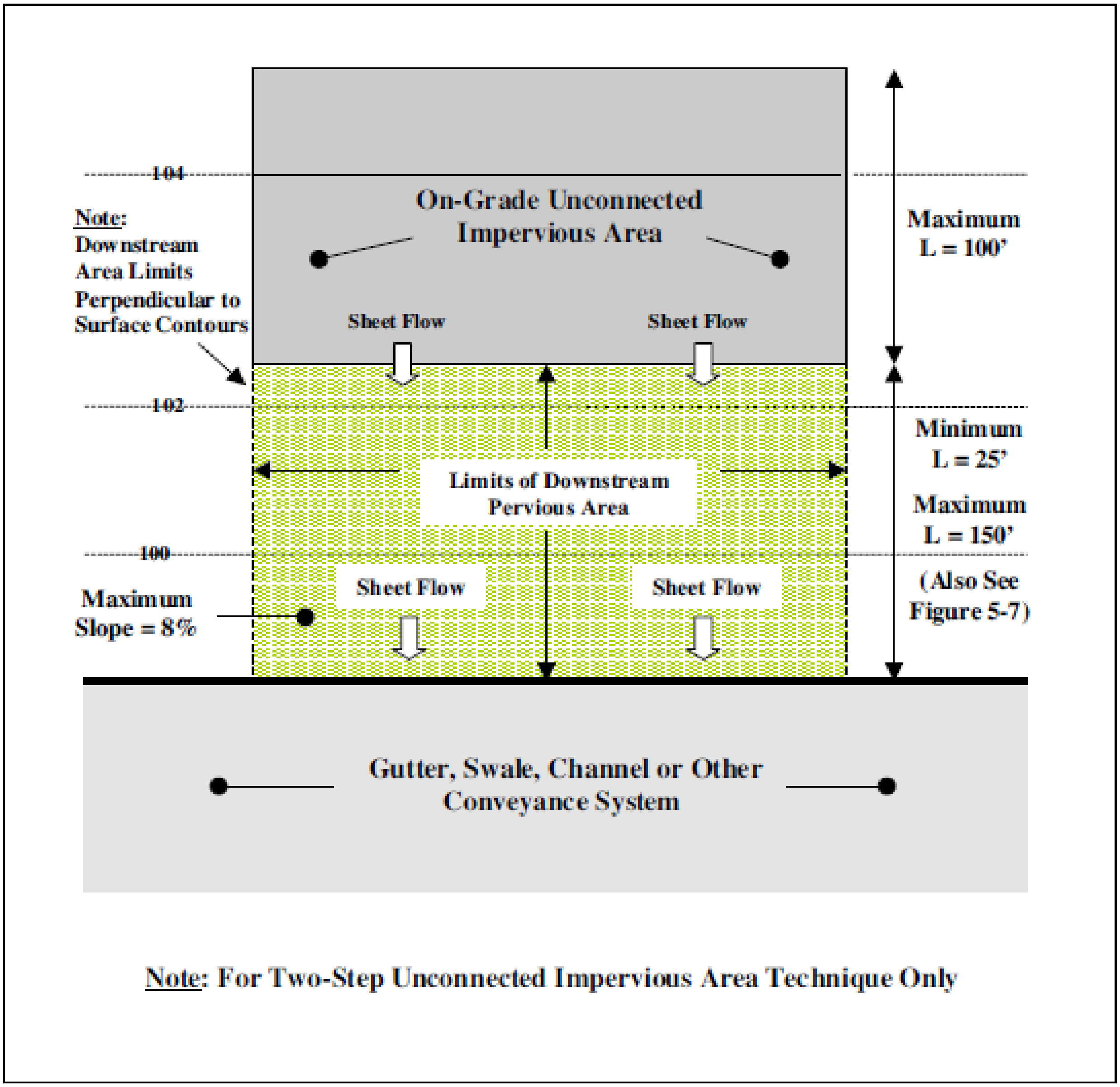


Figure 5-6: Downstream Pervious Area Criteria for Above-Grade Unconnected Impervious Area

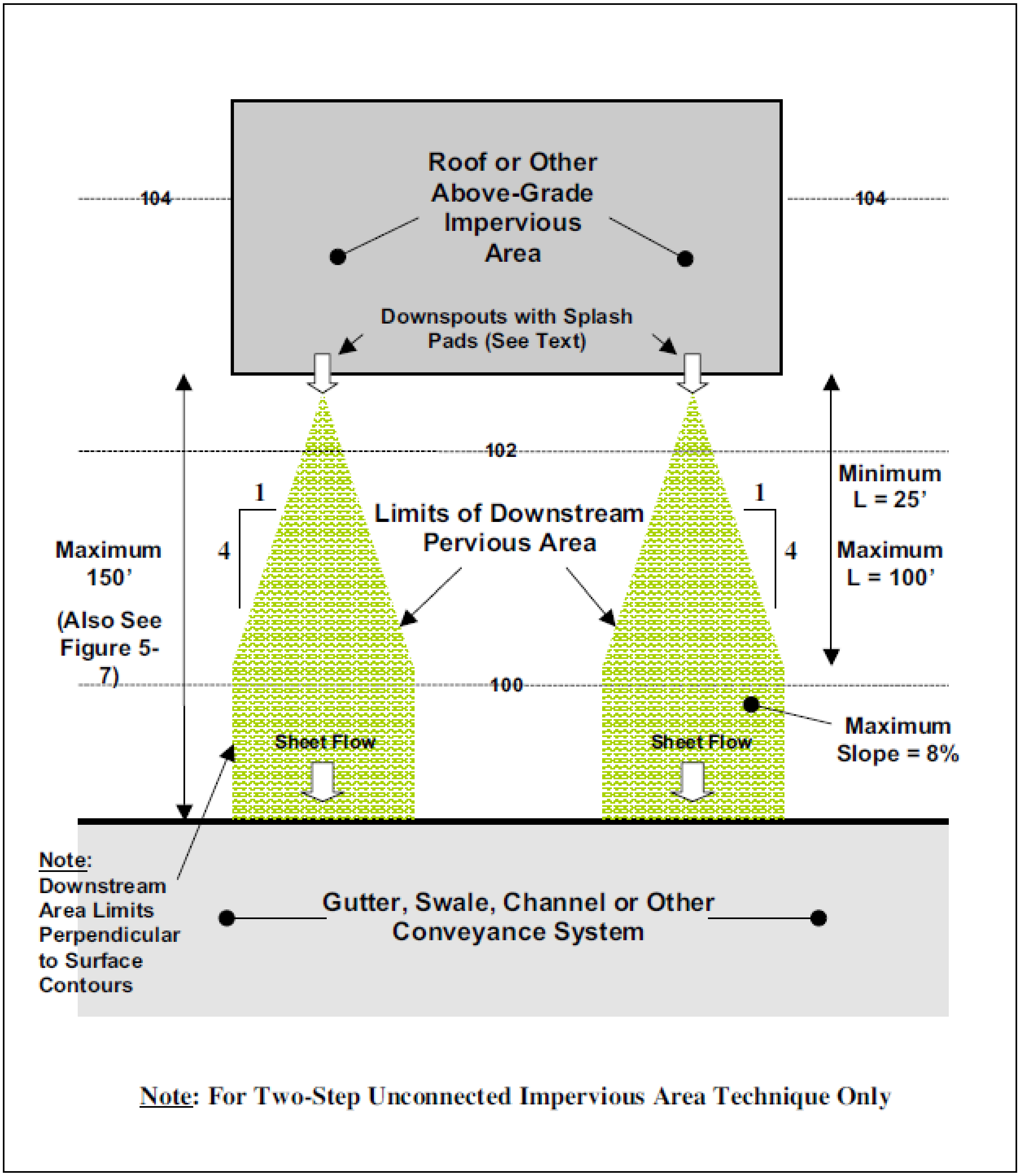
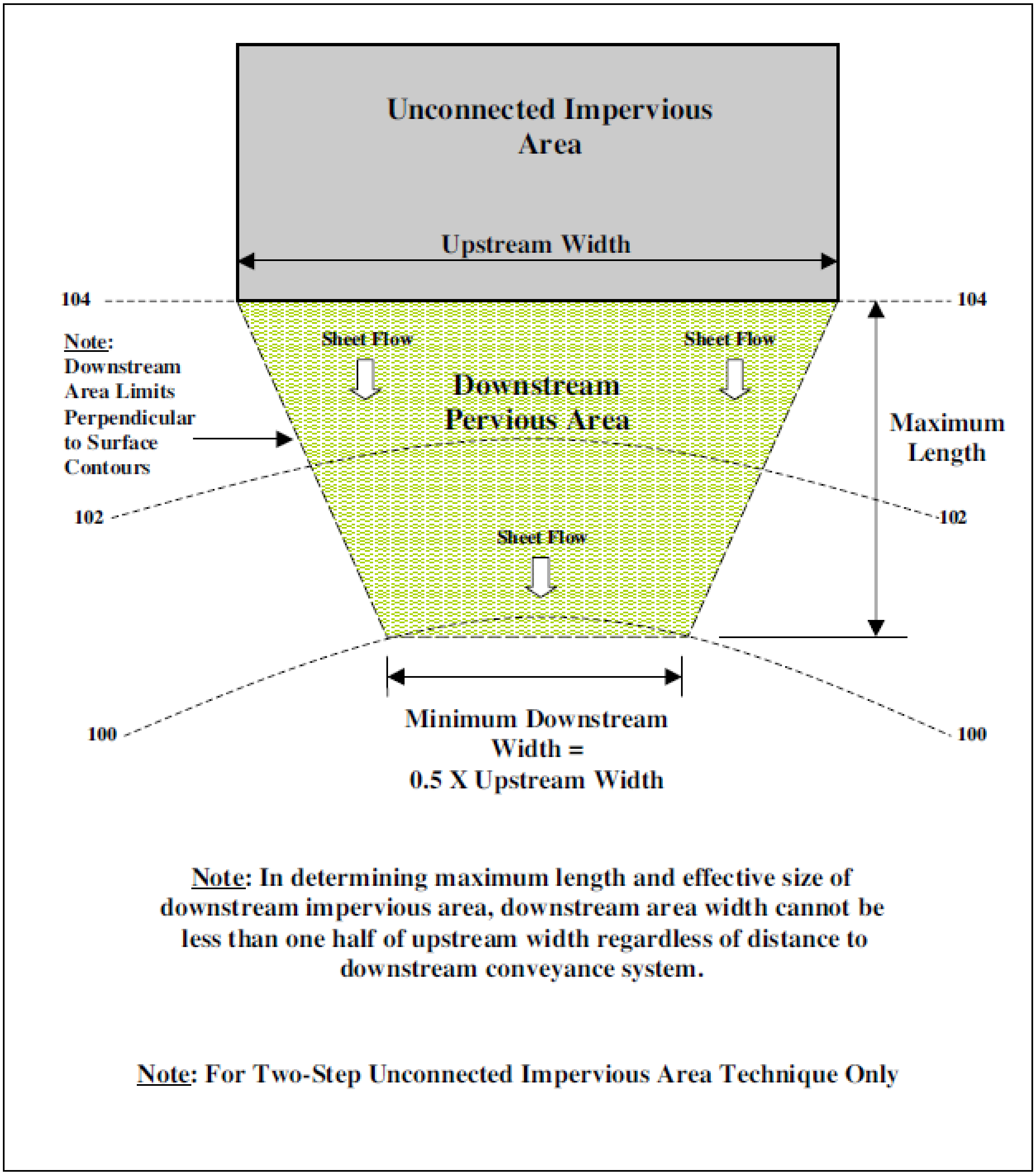


Figure 5-7: Additional Downstream Pervious Area Length and Effective Size Criteria



Sites With Groundwater Recharge

As required by the NJDEP Stormwater Management Rules and described in detail in *Chapter 6: Groundwater Recharge*, land development projects must maintain 100 percent of the site's annual pre-developed groundwater recharge. At most sites, this will require the design and construction of a groundwater recharge BMP that allows the runoff from the groundwater recharge design storm to infiltrate into the site's subsoil. This amount of infiltration can also be used by a designer to help meet the stormwater quality requirements of the Rules. Techniques to do so are presented below. However, to ensure downstream safety and channel stability, the amount of groundwater recharge provided at a development site *cannot* be considered when complying with the Rules' stormwater quantity requirements (i.e., control of the 2, 10, and 100-year storms).

Rational and Modified Rational Methods

When computing a peak runoff rate for the stormwater quality design storm using the Rational Method, the size of that portion of the site that contributes runoff to the groundwater recharge BMP can be reduced by the ratio of the total groundwater recharge design storm to the 1.25-inch stormwater quality design storm. Similar procedures can be used in most instances to construct a reduced inflow hydrograph for use in the Modified Rational Method. Examples 5-4 and 5-5 below demonstrate these techniques.

Example 5-4: Sites With Groundwater Recharge

Stormwater Quality Design Storm Peak Flow Computation Using Rational Method

Description: A 3-acre development site is comprised of 1 acre of impervious surface (Rational C = 0.99) and 2 acres of lawn and woods (Rational C = 0.40). The post-development time of concentration (Tc) is 20 minutes. All runoff from a 0.5-inch recharge design storm on the impervious surface is recharged. Runoff from larger storms on the impervious surface flows directly to the site's drainage system. Compute the site's total peak runoff rate for the 1.25-inch stormwater quality design storm using the Rational Method.

Recharge Design Storm = 0.5 inches on impervious cover only

Total Stormwater Quality Design Storm = 1.25 inches on entire site

Post-developed Tc = 20 minutes

Maximum Stormwater Quality Design Storm I = 2.2 inches (see Figure 5-3)

Total drainage area = 3 acres

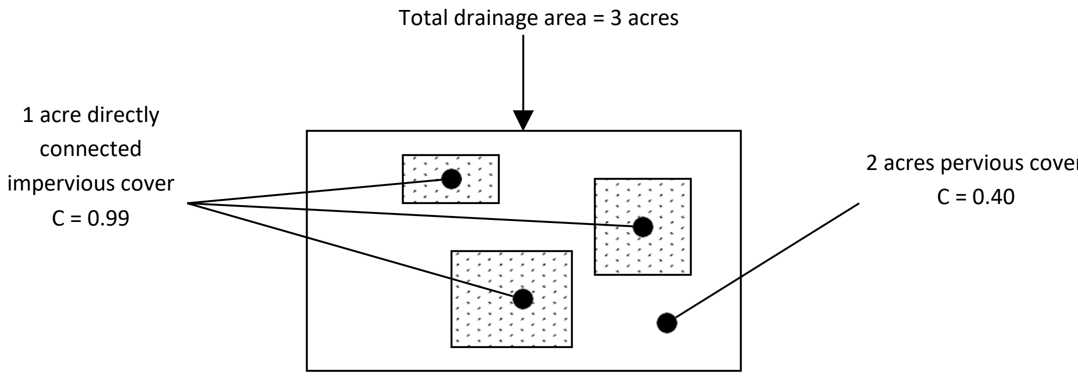
Impervious area = 1 acre (1/3 of total area)

Pervious area = 2 acres (2/3 of total area)

Pervious cover = mixture of lawn and woods pervious C = 0.40

Impervious cover = asphalt impervious C = 0.99

Note: All impervious cover is directly connected to the drainage system



Adjusted impervious area due to recharge =

$$\text{Total impervious area} \times \frac{(\text{Stormwater Quality Design Storm} - \text{Groundwater Recharge Design Storm})}{\text{Stormwater Quality Design Storm}}$$

$$= 1 \text{ acre} \times \frac{(1.25 \text{ inches} - 0.5 \text{ inches})}{1.25 \text{ inches}}$$

$$= 1 \text{ acre} \times \frac{0.75 \text{ inches}}{1.25 \text{ inches}} = 1 \text{ acre} \times 0.6 = 0.6 \text{ acres}$$

Adjusted total site area = 0.6 acres impervious + 2.0 acres pervious = 2.6 acres

$$\text{Composite site } C = \frac{(0.6 \text{ acres impervious} \times 0.99) + (2.0 \text{ acres pervious} \times 0.40)}{2.6 \text{ acres total}}$$

$$= \frac{0.59 + 0.8}{2.6} = \frac{1.39}{2.6} = 0.53$$

Peak Stormwater Quality Design Storm runoff rate = C I A
= 0.53 x 2.2 inches per hour x 2.6 acres = 3.0 CFS

Note: Without considering groundwater recharge credit, the peak rate would be:

Total area = 3.0 acres

$$C = \frac{(1.0 \times 0.99) + (2.0 \times 0.40)}{3.0} = \frac{1.79}{3.0} = 0.60$$

Peak stormwater quality runoff rate = 0.60 x 2.2 x 3.0 = 4.0 CFS

Example 5-5: Sites With Groundwater Recharge

Stormwater Quality Design Storm Hydrograph Using Modified Rational Method

Description: For land development site described in Example 5-4 above, compute runoff hydrograph for entire site using Modified Rational Method.

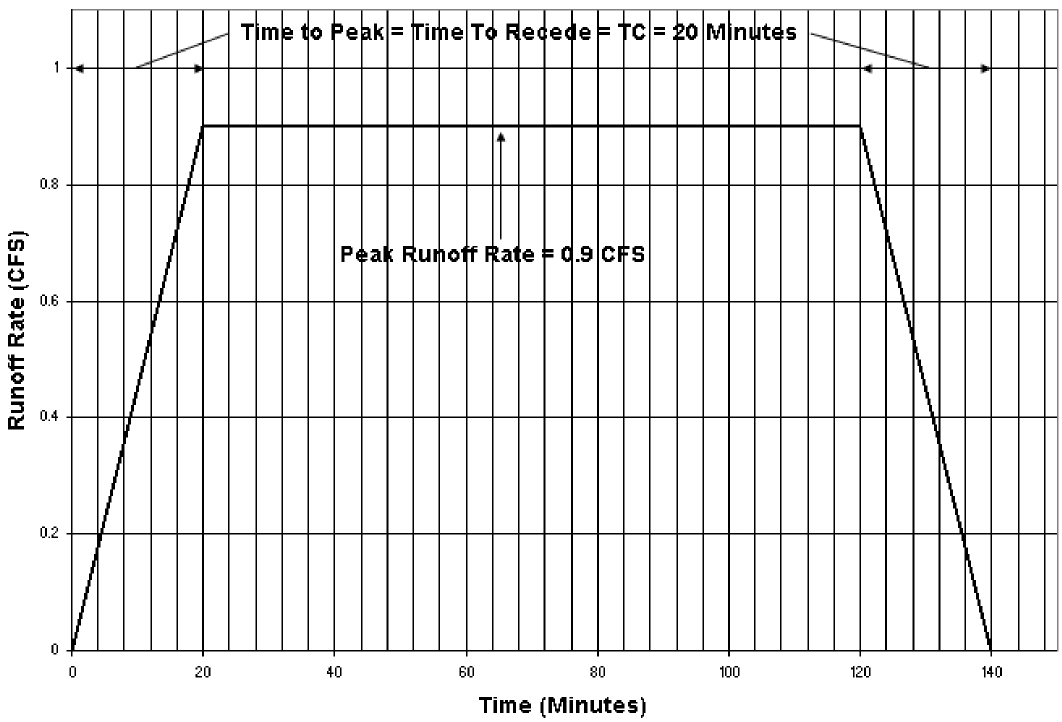
Adjusted total site area = 2.6 acres

Composite site C = 0.54

Average Stormwater Quality Design Storm I = 1.25-inches/2- hours = 0.625 inches per hour

Q = C I A = 0.54 x 0.625 x 2.6 Acres = 0.9 CFS

The Modified Rational Method runoff hydrograph is then constructed as shown below:



Note: See Example 5-1 for procedures to construct Modified Rational Method runoff hydrograph. Also see Important Note on page 5-8 regarding use of Modified Rational Method to compute a runoff hydrograph for the stormwater quality design storm.

It is important to note in Examples 5-4 and 5-5 that runoff from only a portion of the site was recharged during the 0.5-inch groundwater recharge design storm and that those areas were distributed throughout the site. This means that the remaining site areas would still be capable of generating runoff and that the overall site would produce runoff throughout the entire stormwater quality design storm. These conditions permitted the assumptions inherent in the Rational and Modified Rational Methods to be reasonably met when computing both the peak runoff rate and hydrograph from the larger, 1.25-inch stormwater quality design storm. Such site conditions are expected to be typical of most land developments.

However, in cases where the groundwater recharge design storm runoff from the entire drainage area is recharged, the assumptions of the Rational and Modified Rational Methods cannot be met. As such, neither method can be recommended for computing the peak site runoff if the recharge volume is to be considered. In such cases, the designer can either continue to use either method without considering the recharge volume or use the NRCS methodology with the actual, nonlinear stormwater quality design storm as shown in Figure 5-2 and Table 5-1.

NRCS Methodology

When using the NRCS methodology to compute the total stormwater quality design storm runoff volume from a development site where all or a portion of the site's groundwater recharge design storm runoff is recharged, the relative amount of recharged runoff volume can be deducted from the total stormwater quality design storm volume. However, due to the nonlinearity of the NRCS runoff equation, such a deduction must be based on the *volume* of groundwater recharge design storm runoff from the recharged area and not simply the size of the recharged areas. Example 5-6 below describes this technique. When computing the peak stormwater quality design storm runoff rate or hydrograph from such a site with the NRCS methodology, it will be necessary to route the stormwater quality design storm hydrograph through the recharge facility. Since the recharge facility will be designed to contain only the normally smaller groundwater recharge design storm, an accurate stage-discharge relationship for the facility's overflow must be included in the routing computations in order to obtain an accurate peak runoff rate or hydrograph.

Example 5-6: Sites With Groundwater Recharge
Stormwater Quality Design Storm Volume Using NRCS Methodology

Description: A 3-acre development site is comprised of 1 acre of impervious surface and 2 acres of lawn and woods with an NRCS Curve Number (CN) of 65. Runoff from the entire impervious surface is recharged during a 0.5-inch groundwater recharge design storm. Runoff from larger storms on the impervious surface flows directly to the site's drainage system. Compute the total stormwater quality design storm runoff volume from the site using the NRCS methodology.

Groundwater Recharge Design Storm = 0.5 inches on impervious cover only

Total Stormwater Quality Design Storm = 1.25 inches on entire site

Total drainage area = 3 acres

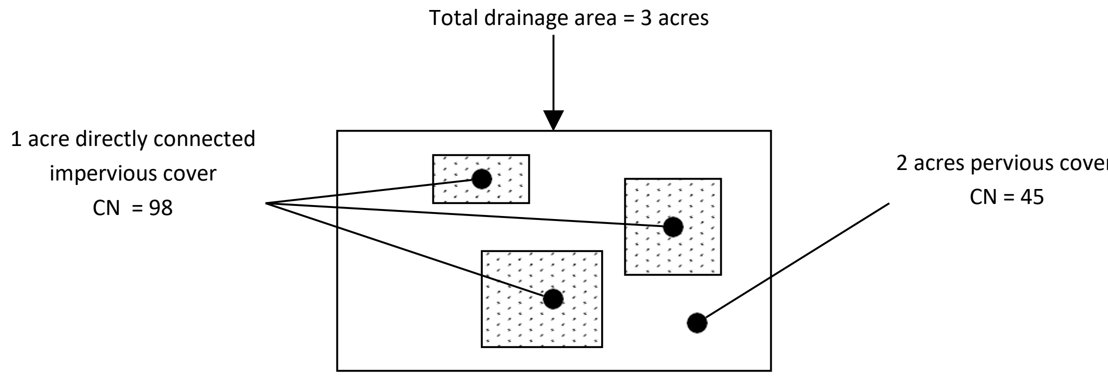
Impervious area = 1 acre (1/3 of total area)

Pervious area = 2 acres (2/3 of total area)

Pervious cover = mixture of lawn and woods pervious CN = 65

Impervious cover = asphalt impervious CN = 98

Note: All impervious cover is directly connected to the drainage system



Impervious Area

$$\text{Impervious area } S = \frac{1000}{CN} - 10 = \frac{1000}{98} \pm 10 = 0.20 \text{ inches}$$

Impervious area initial abstraction = 0.2S = (0.2)(0.20) = 0.04 inches

0.8S = (0.8)(0.20) = 0.16 inches

Groundwater Recharge Design Storm = 0.5 inches

$$\text{Recharged runoff volume for Groundwater Recharge Design Storm} = Q = \frac{(P - 0.2\,S)^2}{P + 0.8\,S}$$

$$= \frac{(0.50 - 0.04)^2}{0.50 + 0.16} = 0.32 \text{ inches}$$

Stormwater Quality Design Storm = 1.25 inches

$$\text{Runoff volume for Stormwater Quality Design Storm} = Q = \frac{(P - 0.2\,S)^2}{P + 0.8\,S}$$

$$= \frac{(1.25 - 0.04)^2}{1.25 + 0.16} = 1.04 \text{ inches}$$

Difference in runoff volumes = 1.04 inches - 0.32 inches = 0.72 inches

Net impervious area runoff volume =

(0.72 inches/12 inches per foot)(1 acre)(43,560 SF per acre)

= 2614 cubic feet

Pervious Area

$$\text{Pervious area } S = \frac{1000}{CN} - 10 = \frac{1000}{65} \pm 10 = 5.38 \text{ inches}$$

Pervious area initial abstraction = 0.2S = (0.2)(5.38) = 1.08 inches

0.8S = (0.8)(5.38) = 4.30 inches

$$\text{Pervious area runoff volume} = Q = \frac{(P - 0.2\,S)^2}{P + 0.8\,S} = \frac{(1.25 \pm 1.08)^2}{1.25 + 4.30} = 0.005 \text{ inches}$$

Runoff volume = (0.005 inches/12 inches per foot)(2 acres)(43,560 SF per acre)

Total pervious area runoff volume = 36 cubic feet

Total site runoff volume = 2614 + 36 = 2650 cubic feet

Note: in Example 5-2, where none of the impervious surface runoff was recharged, the same site produced 3811 cubic feet of runoff for the stormwater quality design storm.

Time of Concentration Considerations

Computation of a peak runoff rate or hydrograph will require an estimate of a drainage area's time of concentration (Tc). In performing Tc calculations, designers should consider the following factors.

- **Maximum sheet flow length:** When using the segmental Tc procedures contained in Chapter 3 of the NRCS *Technical Release 55 – Urban Hydrology for Small Watersheds* (TR-55), the maximum sheet flow length recommended by the NRCS is 150 feet. According to the NRCS, longer lengths may be used only in special cases, such as smooth, uniformly graded parking lots or athletic fields. In addition, it may be appropriate to use a longer sheet flow length in wooded areas with Hydrologic Soil Group A or B soils and ground slopes of 2 percent or flatter. In such areas, high infiltration rates, low sheet flow velocities, and the presence of surface irregularities that store and reinfiltrate runoff may limit the generation of runoff to such an extent that a larger than normal area (and therefore a longer than normal sheet flow length) is needed to produce sufficient runoff rates to exceed sheet flow depths and create shallow concentrated flow.
- **Maximum sheet flow roughness coefficient:** According to the NRCS, the maximum Manning's Roughness Coefficient (n) to be used in the Sheet Flow Equation in Chapter 3 of TR-55 is 0.040.
- **Tc routes:** Consideration must be given to the hydraulic conditions that exist along a selected Tc route, particularly in pre-developed drainage areas. Tc routes should not cross through significant flow constrictions and ponding areas without considering the peak flow and time attenuation effects of such areas. As noted in the NJDEP Stormwater Management Rules, such areas can occur at hedgerows, undersized culverts, fill areas, sinkholes, and isolated ponding areas. In general, a separate subarea tributary to such areas should be created and its runoff routed through the area before combining with downstream runoff.
- In certain areas with highly irregular topography, large surface storage volumes, high soil infiltration rates, and/or Karst topography, the segmental Tc method described in Chapter 3 of TR-55 may not be appropriate. In such areas, alternative Tc methods should be used.

Table 5-2: Summary of Modeling Guidance for Various Site Conditions

Rational, Modified Rational and NRCS Methods[1]

Site Condition or Parameter	Rational Method	Modified Rational Method	NRCS-Based Methods
Mixture of pervious and directly connected impervious surface	Use standard procedures	Use standard procedures	Use weighted average runoff volume
Unconnected impervious surface	Use not recommended	Use not recommended	TR-55 or Two-Step Technique
Groundwater recharge areas	Reduce effective size of recharge area[2]	Reduce effective size of recharge area[2]	Reduce runoff volume by recharge volume
Time of concentration	Maximum sheet flow length = 150 feet Maximum sheet flow n = 0.40 Include effects of storage and ponding areas		

Notes: Table presents summaries only. See text for complete descriptions for each computation method.

For sites with combination of recharge and non-recharge areas. Methods not recommended where entire area is recharged. See text for details.

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