A. Introduction

This section presents a brief summary of low-impact development (LID) hydrologic analysis and computational procedures used to determine low-impact development stormwater management requirements. The hydrologic analysis used for the initial development of these procedures is based on the Natural Resources Conservation Service (NRCS) TR-55 hydrologic model (NRCS, 1986). As described in Chapter 3 - Section 5 NRCS TR-55 Methodology, TR-55 was updated to WinTR-55 in 2004. WinTR-55 now uses the TR-20 computation for rainfall analysis and hydrograph routing. However, the basic underlying hydrology concepts of CN, time of concentration, peak flow estimation, and determination of runoff volume and storage remain part of the program (albeit under a different user interface). The material presented here is a summary of the LID hydrologic analysis principles. The US EPA has published a two-volume manual for low-impact development which is available at http://www.epa.gov/nps/lid_hydr.pdf. Additional information is also available from the Low-Impact Development Center at http://www.lowimpactdevelopment.org/. Additional discussion of the LID design approach is included in Chapter 1 and Chapter 4 of this manual.

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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. These hydrologic principles were discussed in detail in Chapter 3 - Section 2 Rainfall and Runoff Analysis through Chapter 3 - Section 6 Small Storm Hydrology. 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.

B. Hydrologic comparison: conventional vs. low-impact development

Conventional stormwater conveyance systems have traditionally been designed to collect, convey, and discharge runoff as efficiently as possible. Conventional stormwater management controls 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 (typically the Q_5 predevelopment runoff in most Iowa jurisdictions). This level of control is called overbank flooding in the unified sizing criteria (see Chapter 2). 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. The smaller storms associated with the WQv and Cpv are not retained in the traditional management approach.

Low-impact development approaches on the other hand, will fully control these storm events, and there is significant difference between the two approaches. Application of the unified sizing criteria in Chapter 2 can be considered a LID approach with respect to the size and frequency of storm events captured. Figure C3-S8-1 illustrates the hydrologic response of the runoff hydrograph to conventional integrated management practices.

- 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 BMPs, such as a standard dry 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 re-development condition.
- Hydrograph 3 represents the response of post-development condition that incorporates low-impact development stormwater management. Low-impact development uses undisturbed areas and onsite and distributed retention storage to reduce to reduce runoff volume. The peak runoff rate and volume remain the same as the predevelopment condition through the use of onsite 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 BMPs.

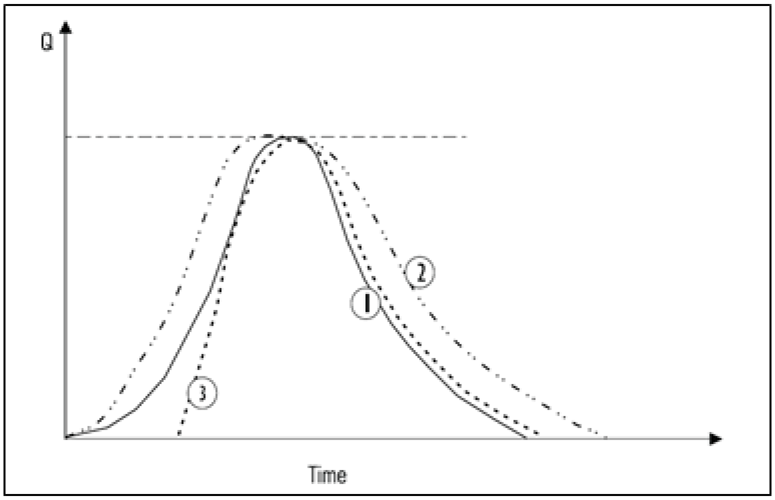

Figure C3-S8-1: Comparison of the hydrologic response of conventional and LID practices
Source: Prince George's County Maryland, 1999

1. **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 non-structural techniques to compensate for the hydrologic alterations of development.
2. **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 are 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 can not only help maintain the predevelopment hydrologic regime, but also enhance the aesthetic and habitat value of the site.
3. **Integrated management practices (IMPs).** Low-impact development technology employs micro-scale and distributed management techniques, called integrated management practices, to achieve desired post-development hydrologic conditions. LID IMPs are used to satisfy the storage volume requirements described later in this section. 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.

   Best management practices (BMPs) suited to low-impact development include:
   - Bioretention facilities Chapter 5, section 4)
   - Filter/buffer strips and other multifunctional landscape areas (Chapter 5, section 6 and Chapter 9)
   - Grassed swales, dry (enhanced) swales, and wet swales (Chapter 9)
   - Infiltration trenches (Chapter 5, section 2)

C. 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.

1. **Runoff volume control.** The predevelopment volume is maintained by a combination of minimizing the site disturbance from the predevelopment condition and providing distributed BMPs to capture and retain rainfall on the landscape. These BMPs are structures that capture and retain the WQv, and perhaps the Cpv runoff for the design storm event.

2. **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 T_c and then using retention and/or detention BMPs (e.g., rain gardens, bioretention, 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.
3. **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. The impacts on the sediment and erosion and stream habitat potential at downstream reaches can then be minimized.
4. **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. This is equivalent to the WQv criteria in Chapter 2 where the WQv design storm is 1.25 inches. For a development site with 40% impervious area, the Rv would be 0.41 and the runoff volume captured as the WQv would be 0.51 inches.

   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 predevelopment runoff volume.
   - **Time of concentration (T_c).** Maintaining the predevelopment T_c 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 for storm recurrence intervals ≥5-10 years.

The LID design objectives listed above are carried out through application of basic hydrologic principles related to rainfall and runoff analysis. The current capabilities in WinTR-55 allow for the user development and user input of Custom CN's based on a careful analysis of the site conditions. Development and design practices for implementing the hydrologic controls above are summarized in Table C3-S8-1.

Table C3-S8-1: Low-impact development techniques and hydrologic design and analysis techniques

Low Impact Hydrologic Design and Analysis Components	**Low-Impact Development Technique**															
	Flatten slope	**Increase flow path**	**Increase sheet flow**	**Increase roughness**	**Minimize disturbance**	**Flatten slopes on swales**	**Infiltration swales**	**Vegetative filter strips**	**Constructed pipes**	**Disconnected impervious areas**	**Reduce curb and gutter**	**Rain barrels**	**Rooftop storage**	**Bioretention**	**Revegetation**	**Vegetation preservation**
Lower Post-development CN					✓		✓	✓		✓	✓			✓	✓	✓
Increase T_c	✓	✓	✓	✓		✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
Retention							✓	✓				✓	✓	✓	✓	✓
Detention						✓			✓			✓	✓			

Source: Prince George's County Maryland, 1999

D. Process and computational procedure

The hydrologic analysis of low-impact development is a sequential decision-making process, and is illustrated in Figure C3-S8-2. Several iterations may occur within each step until the appropriate approach to reduce stormwater impacts is determined. The procedures for each step are summarized below. A set of design charts have been developed to determine the amount of storage required to maintain the existing volume and peak runoff rates to satisfy jurisdictional requirements for stormwater management requirements. The full set of charts is not included in this manual, but examples of each of the three types of charts (Figure C3-S8-3, Figure C3-S8-4, and Figure C3-S8-5) are provided so the design process can be illustrated. The full set of manuals, including “Low-Impact Development Design Strategies: An Integrated Design Approach” (EPA 841-B-00-003) and “Low-Impact Development Hydrologic Analysis” (EPA 841-B-00-002) are available at http://www.lowimpactdevelopment.org/publications.htm. The full set of design charts is available from the Prince George’s County Maryland DER.

The procedure is summarized below and the sequence is portrayed graphically in Figure C3-S8-2.

1. **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 (T_c) for the pre- and post-development condition is the same as conventional site plan and stormwater management approaches discussed earlier in the section.
2. **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. The goal is to take full advantage of the storage and infiltration characteristics of low-impact development site planning to maintain the CN. The LID approach encourages the conservation and creation of more open grassland and wooded areas, and the reduction of impervious area to minimize the need for extensive piped drainage. The steps for determining the low-impact development CN are as follows:

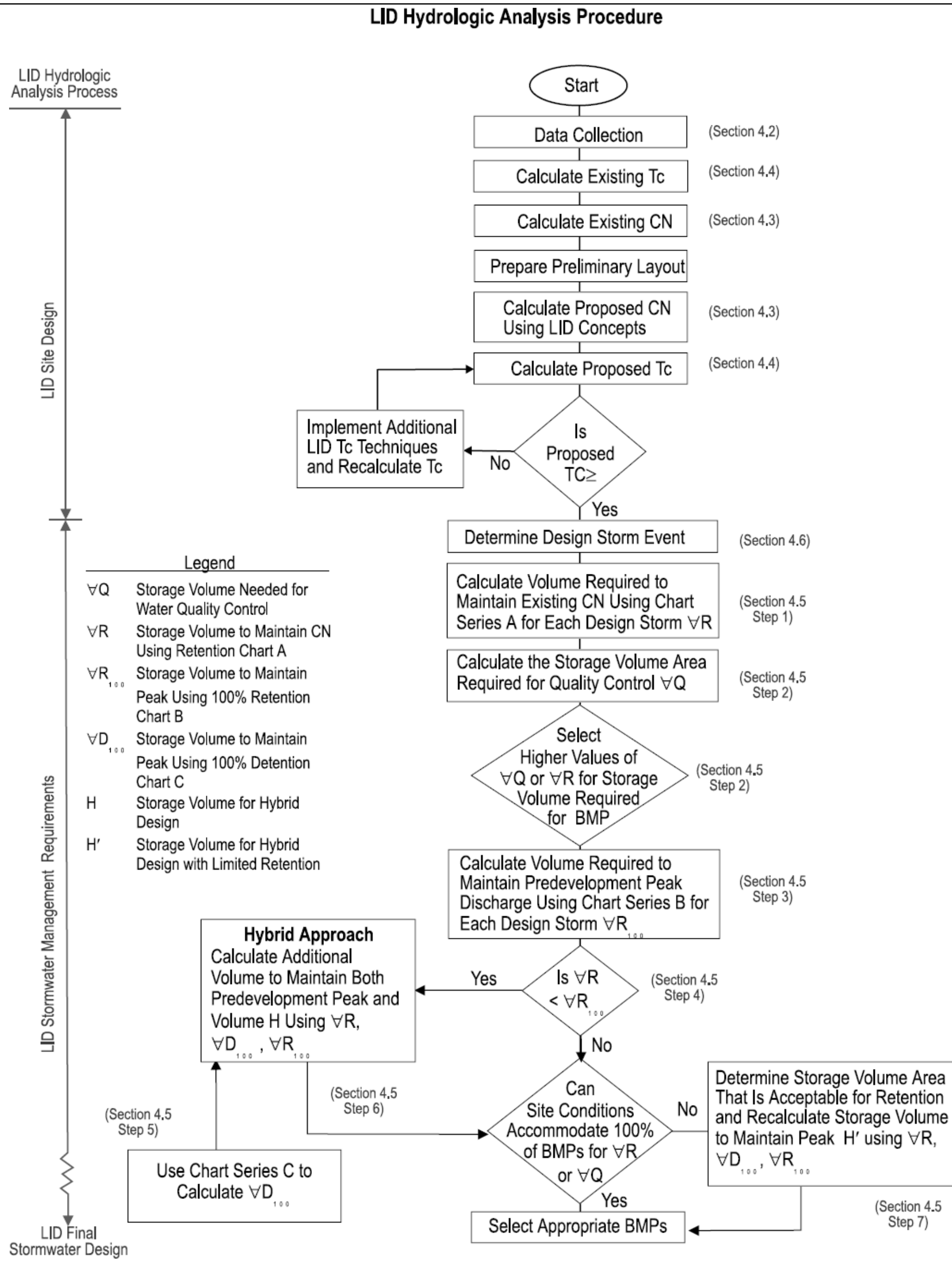

Figure C3-S8-2: Low-impact development analysis procedure
Source: PGC, Maryland 1999

a. **Determine percentage of each land use/cover.** In conventional site development, the designer would use the default values in WinTR-55 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. Since low-impact design emphasizes minimal site disturbance (tree preservation, site fingerprinting, etc.), the approach is to retain much of the predevelopment land cover and CN. Therefore, the site is analyzed as discrete units to determine the CN. Table C3-S8-2 lists representative land cover types used to calculate a composite custom low-impact development CN. In the land use menu in WinTR-55, there is an option to develop a custom CN for the subarea definition.

Land Use Cover	CN for Hydrologic Soil Groups[1]			
	A	B	C	D
Impervious area	98	98	98	98
Grass	39	61	74	80
Meadow (good condition)	30	58	71	78
Woods (fair condition)	36	60	73	79
Woods (good condition)	30	55	70	77

[1]From Chapter 3 - Section 5 NRCS TR-55 Methodology

b. **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. A manual method for considering the configuration of impervious area is presented in Chapter 3 - Section 5 NRCS TR-55 Methodology, and can also be completed in the WinTR-55 land use menu. The application of custom-made CN's for a development site is an LID technique to represent the development site as a composite of discrete units that represent the hydrologic condition, rather than using the conventional (default) values used in WinTR-55, which are 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.

A factor that must be considered when using this approach is the soil disturbance and compaction that will occur during the grading for the site construction. It would be appropriate to identify the sub-areas on the site where BMPs are located as part of the final site plan, and designate as off-limits for grading and other disturbance. If extensive site grading must be done, the designer may want to consider applying soil quality restoration as described in Chapter 5, section 5, and including native plants (Chapter 5, section 6) in the final landscaping for the site. These practices are intended for increasing the infiltration capacity of disturbed soils.

c. **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 (NRCS, 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 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. A method for applying the impervious area connectivity is described in Chapter 3 - Section 5 NRCS TR-55 Methodology. The calculation is also included in the WinTR-55 custom CN menu.

The computation is completed using Equation C3-S8-1.

Equation C3-S8-1

$$CN_c = CN_p + (P_{imp}/100)(98 - CN_p)(1 - 0.5R)$$

Where:
R = ratio of unconnected impervious area to total impervious area
CN_c = composite CN
CN_p = composite pervious CN
P_{imp} = percent of impervious site area

3. **Development of the time of concentration (T_c).** The pre- and post-development calculation of the T_c for low-impact development is exactly the same as that described in the NEH-4 (NRCS, 1985), as described in Chapter 3 - Section 3 Time of Concentration, and computed with WinTR-55.
4. **Low-impact development stormwater management requirements.** Once the CN and T_c 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 create enough runoff retention capacity onsite to maintain all the predevelopment volume, predevelopment peak runoff rate, and frequency. In the LID procedure, the required runoff retention capacity is termed "storage," even though this includes all of processes that abstract rainfall after a rainfall event. In traditional terms, the storage is equal to the term "S" in the NRCS rainfall-runoff equation (Chapter 3 - Section 5 NRCS TR-55 Methodology) and includes infiltration. This may be accomplished through application of a series of non-structural and structural BMPs, including detention practices. By adding onsite practices to increase infiltration, the site storage value for "S" in the rainfall-runoff relationship is increased. The required storage volume is calculated using the design charts in Figure C3-S8-3, Figure C3-S8-4, and Figure C3-S8-5. The required storage volume is heavily dependent on the rainfall intensity (rainfall distribution). Rainfall intensity varies considerably over geographic regions in the US, and the standard NRCS Type II distribution is used in Iowa (Chapter 3 - Section 1 General Information for Stormwater Hydrology). The remaining low- impact development hydrologic analysis techniques are based on the premise that the post-development T_c is the same as the predevelopment condition. If the post-development T_c does not equal the predevelopment T_c, additional low-impact development site design techniques must be implemented to maintain the T_c. However, the final site hydrologic design after the application of all recommended BMPs should be based on the actual T_c achieved.

   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 C3-S8-2 is used to determine the volume required for IMPs.

   Equation C3-S8-2

$$Volume(in) = (depth\ from\ design\ chart - in) \times \frac{development\ size - ac}{100}$$

   A 6-inch depth is the recommended 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 C3-S8-3.

   Equation C3-S8-3

$$Volume\ of\ site\ area\ for\ IMPs = (initial\ volumen) \times \frac{100 - x}{100}$$

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

   Stormwater management is accomplished by selecting the appropriate BMP, or combination of BMPs, 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 for maintaining the predevelopment runoff volume using retention storage (Figure C3-S8-4 and Figure C3-S8-5).
   - Chart Series B: Storage volume required for maintaining the predevelopment peak runoff rate using 100% retention (Figure C3-S8-4).
   - Chart Series C: Storage volume required for maintaining the predevelopment peak runoff rate using 100%

detention (Figure C3-S8-5).

The 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.

E. Determination of design storm event

As discussed previously in Chapter 1, Chapter 2, and Chapter 3 - Section 6 Small Storm Hydrology, conventional stormwater management runoff quantity control is generally based on not exceeding the predevelopment peak runoff rate for the 2-year/5-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 the Midwest Rainfall Atlas (Bulletin 71) rainfalls provided in **Error! Reference source not found.** and **Error! Reference source not found.**. As an example, the 2-year and 10- year, 24-hour storm events for Climate District 5 (Central Iowa) are 2.91 and 4.27 inches, respectively. In the unified sizing criteria (Chapter 2), the design storm for the WQv is established at 1.25 inches, and the design storm for Cpv is the 1-year, 24-hour duration rainfall. The WQv design rainfall is considered to be a statewide value. The 1-year, 24-hour rainfall for central Iowa is 2.38 inches. The 5-year and 10-year events are typically used for sizing of stormwater conveyance inlets and piping.

For low-impact development, the design storm is 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 amount of rainfall within the development site as that which is retained by meadow in good condition, and then to gradually release the excess runoff as a grassland meadow would release it. The predominant landscape condition in Iowa before development was native prairie, and a meadow in good condition would be the best land condition comparison. By using this approach, the final design will 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 meadow in good condition. Note that a predevelopment condition of row-crop agriculture is not undeveloped in a hydrologic sense. In some cases, residential development on a pre-existing site with row-crop land use can actually show a decrease in CN from the predevelopment condition. This is consistent with the predevelopment condition described in Chapter 2. The design storm will be the greater of the rainfall at which direct runoff begins from a meadow 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 C3-S8-4.

Equation C3-S8-4

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

P is the rainfall at which direct runoff begins. This is the same relationship used in the NRCS runoff equation to compute the runoff in inches from a given rainfall depth and watershed CN.

- **Step 1: Determine the predevelopment CN.** Use an existing land cover of meadow 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 C3-S8-4 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:

- A site is 70% HSG-B and 30% HSG-C soils. The CN's for meadow in good condition for HSG-B and HSG-C soils are 58 and 71, respectively (Chapter 3 - Section 5 NRCS TR-55 Methodology).
- CN_c = (0,70)(58) + (0.30)(71) = 61.9 → Use 62

- Determine the rainfall amount to initiate runoff: P = 0.2 (1000/62-10) = 1.22 inches
- Multiply by rainfall amount by a factor of 1.5: Design rainfall = 1,22 in x 1.5 = 1.83 inches

The procedure to determine the BMP requirements is outlined in Figure C3-S8-3. A summary description is described below.

1. **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 1. It should be noted that the practical and reasonable use of the site must be considered. The BMPs 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 water quality volume in the current water quality requirement is found in Step 2.

   Example 1
   Given:
   Site area = 28 acres
   Existing CN = 62
   Proposed CN = 68
   Design storm is 1.83 inches (round up to 2 inches to use charts)
   Design depth of BMP will be 6 inches

   Solution: Use Chart Series A: Storage volume required to maintain runoff volume or CN.

   From Chart A:
   0.11 inch (from Chart A for 2-inch rainfall and CN's of 62/68) of storage over the site is required to maintain the runoff volume. Therefore, if 6-inch design depth is used: 0.51 acres (28 acres x 0.11 in/6 in) of BMPs distributed evenly throughout the site are required to maintain the runoff volume, or CN.

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 peak runoff rate (Example 4.4).

Step 5:

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:

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:

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 C3-S8-3: Procedure to determine storage volume required for BMPs to maintain predevelopment runoff volume and peak runoff rate

Source: PGC, Maryland, 1999

Additional considerations:

- Account for depths other than 6 inches:
  Site BMP area = 1.1 acres, if 6-inch depth is used
  Depth of BMPs = 4 inches
  Site of BMP area = 0.51 ac x 6 in/4 in
  Site of IMP area = 0.76 ac

- Account for infiltration and/or evapotranspiration (using Equation C3-S8-3):
  If 10% of the storage volume is infiltrated and/or reduced by evaporation and transpiration:

$$Site\ of\ IMP\ area = (storage\ volume) \times \frac{100 - X}{100}$$

$$Site\ of\ IMP\ area = 0.51ac \times \frac{100 - 10}{100} Area\ for\ IMP\ storage = 0.46ac$$

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 a design rainfall of 1.25 inches,

and the Rv coefficient for the site based on percent impervious area and the drainage area. 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 2. The greater number or percent is used as the required storage volume to maintain the CN.

Example 2
Given:
Site area is 28 acres
Impervious area is 7.84 ac (28%)
Depth of BMP is 6 inches

Solution:
Compute WQv requirement for the site (Chapter 2 and Chapter 3 - Section 6 Small Storm Hydrology)
WQv design storm is 1.25 inches

$$Rv = 0.05 + 0.009(28\%) = 0.30$$

From Chapter 2:

$$WQv = \frac{(Rv)(P)(A)}{12}$$

Runoff volume from site: 0.30 × 1.25 $iinn$ = 0.375 $iinnccheess$

Under the scenario where the entire WQv is captured, treated, and stored within the 28-acre development, then the WQv requirement is greater than the LID requirement computed above for the 2-inch LID design rainfall.

If a 4-inch rainfall depth is used for the LID design, then the LID requirement from Step 1 would be 0.34 in (Figure C3-S8-5) and CN's of 62/68.

The recharge volume (Rev) for this site, considered part of the WQv, is calculated as described in Chapter 2. Rev = (S)(Rv)

where:
S = site specific recharge factor (inches)

S is a function of the soils HSG on the site. From Table C2-S1-4 in Chapter 2, the values for S for HSG-B and HSG-C soils are 0.34 and 0.17, respectively. A composite value of S for this site would be:

$$S_c - inches = (0.70)(0.34in) + (0.30)(17in) = 0.289in$$

The recharge volume, Rev is the volume of water to be infiltrated onsite through a number of practices. It is considered that part of the total WQv to be retained completely within the site drainage area. For this example scenario, the computed Rev (0.09 in) is less than the computed LID volume (0.11 in) to maintain predevelopment runoff volume for the 2-inch design storm.

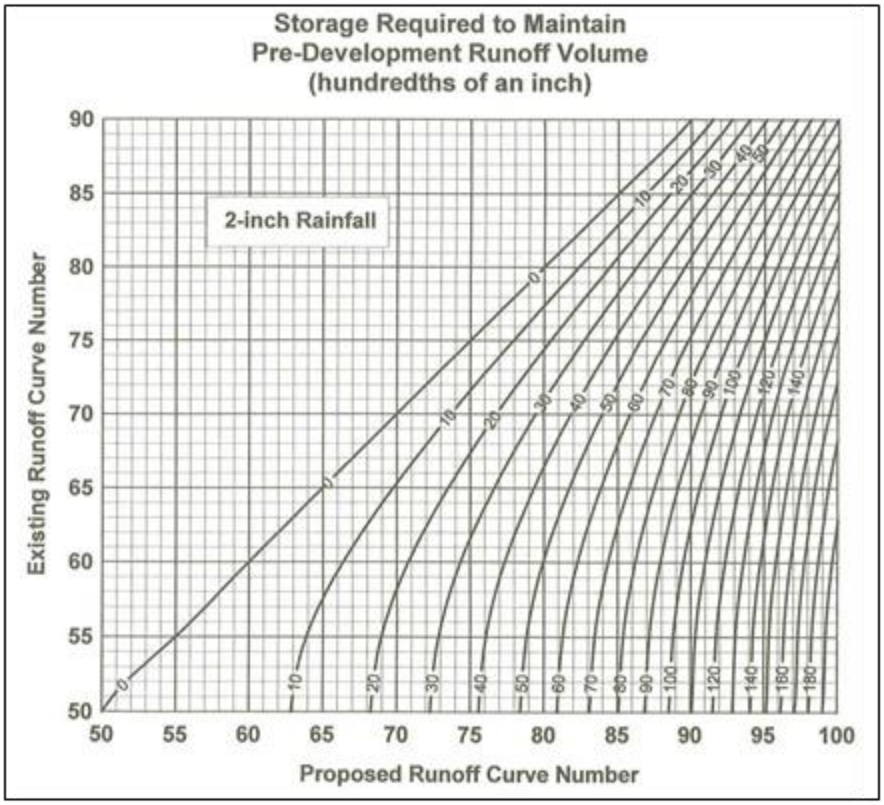

Figure C3-S8-4: Chart A for 2-inch design rainfall
Source: PGC, Maryland, 1999

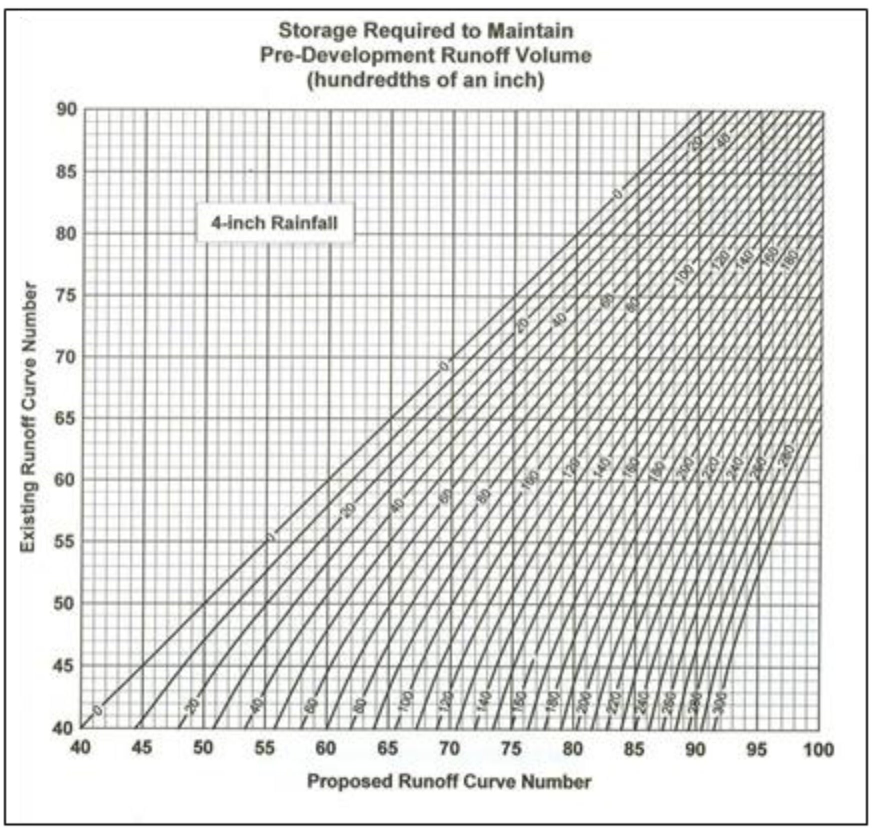

Figure C3-S8-5: Chart A for 4-inch design rainfall
Source: PGC, Maryland, 1999

Summary for Step 2: From the results of Example 2, the WQv requirement is 0.37 inches. Of the total WQv requirement for the site, the recharge volume, Rev, of 0.09 inches would be retained onsite. The remainder of the WQv could substantially be released after treatment in a BMP. Using the LID volume of 0.11 inches (for a 2-inch design storm) would meet the requirement to maintain the predevelopment runoff volume.

3. **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. This chart is based on the relationship between storage volume ratio (V_s/V_r) and discharge (q_0/q_i) to maintain the predevelopment peak runoff rate.

   Where:
   V_s = volume of storage required to maintain the predevelopment peak runoff rate using 100% retention
   V_r = post-development runoff volume
   q_0 = peak outflow discharge rate (i.e., the peak discharge for the predevelopment condition)
   q_i = peak inflow rate (the peak discharge rate for the post-development condition)

   The relationship for retention storage to control the peak runoff rate is similar to the relationship for detention storage. Figure C3-S8-6 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. This is the same relationship provided in Chapter 3 - Section 6 Small Storm Hydrology, and is the same principle used in Chapter 3 - Section 9 Detention Storage Design for making preliminary estimates of detention volume for peak rate control. The relationship is based on data prepared for the NRCS TR-55, and is included in Chapter 6 of the 1986 user's manual for TR-55. 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 C3-S8-6. The retention value is larger since the runoff volume is permanently retained onsite while the detention value is captured and then ultimately released over a set period of time.

   The values for V_r, q_0, and q_i are determined from the WinTR-55 analysis of the predevelopment and post-development scenarios for the site. In this case, the design storm for LID analysis would be manually entered in the rainfall menu in the program. Using the predevelopment and post-development CN and T_c values determined in Step 2 and Step 3 of the LID procedure, the WinTR-55 analysis is then run for both the predevelopment and post-development scenarios. In WinTR-55, the peak discharge rate and runoff values are accessed in the TR-20 reports menu.

   In Figure C3-S8-6:

   - Hydrograph 2 represents the runoff response for a post-development condition with no BMPs used on the site. As discussed in earlier this manual, the post-development hydrograph will generally reflect a shorter time of concentration, T_c, and the increase in total site imperviousness compared to the predevelopment condition. The hydrograph shows a decrease in the time to peak, T_p, and an increase in peak runoff rate and total runoff volume, as well as an increased discharge duration.
   - Hydrograph 8 illustrates the effect of providing additional detention storage to reduce the post-development peak discharge rate to predevelopment conditions.
   - V_1 is the storage volume required to maintain the predevelopment peak discharge ratio using 100% detention storage (Chapter 3 - Section 9 Detention Storage Design). The combination of V_1 and V_2 is the storage volume required to maintain the predevelopment peak rate using 100% retention storage.

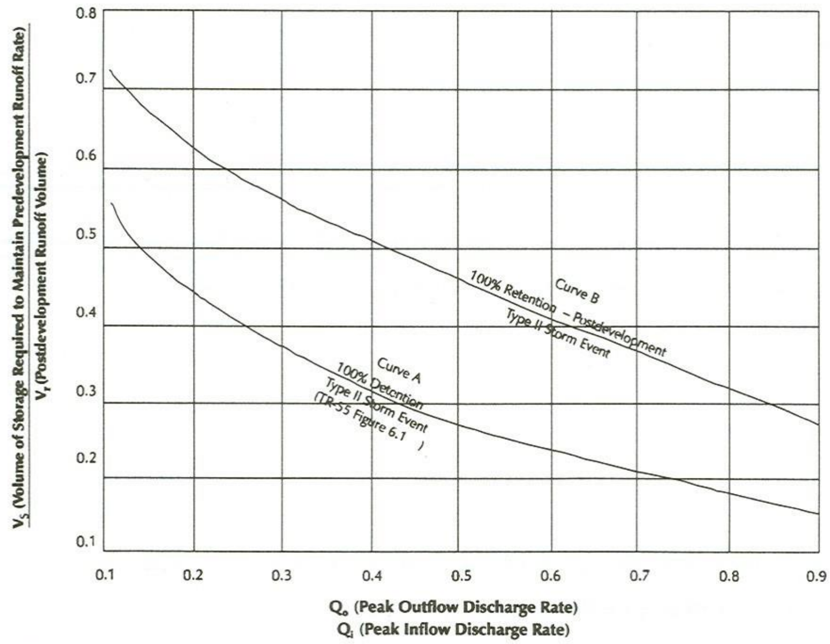

Figure C3-S8-6: Comparison of storage volumes required to maintain peak runoff rate using retention or detention
Source: NRCS, 1986

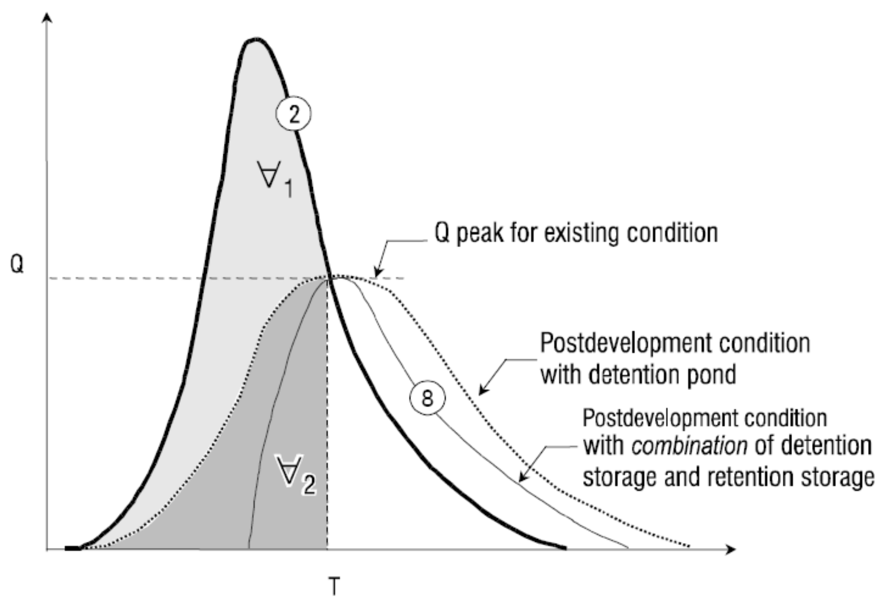

Figure C3-S8-7: Storage volume required to maintain peak runoff rate
Source: PGC, Maryland, 1999

The following calculations apply to Design Chart Series B:

- The T_c for the post-development condition is equal to the T_c for the predevelopment condition. This equality can be achieved through techniques such as maintaining sheet flow lengths, increasing surface roughness, decreasing the amount and size of storm drain pipes, and decreasing open channel slopes.
- BMPs are to be distributed evenly across the development site.

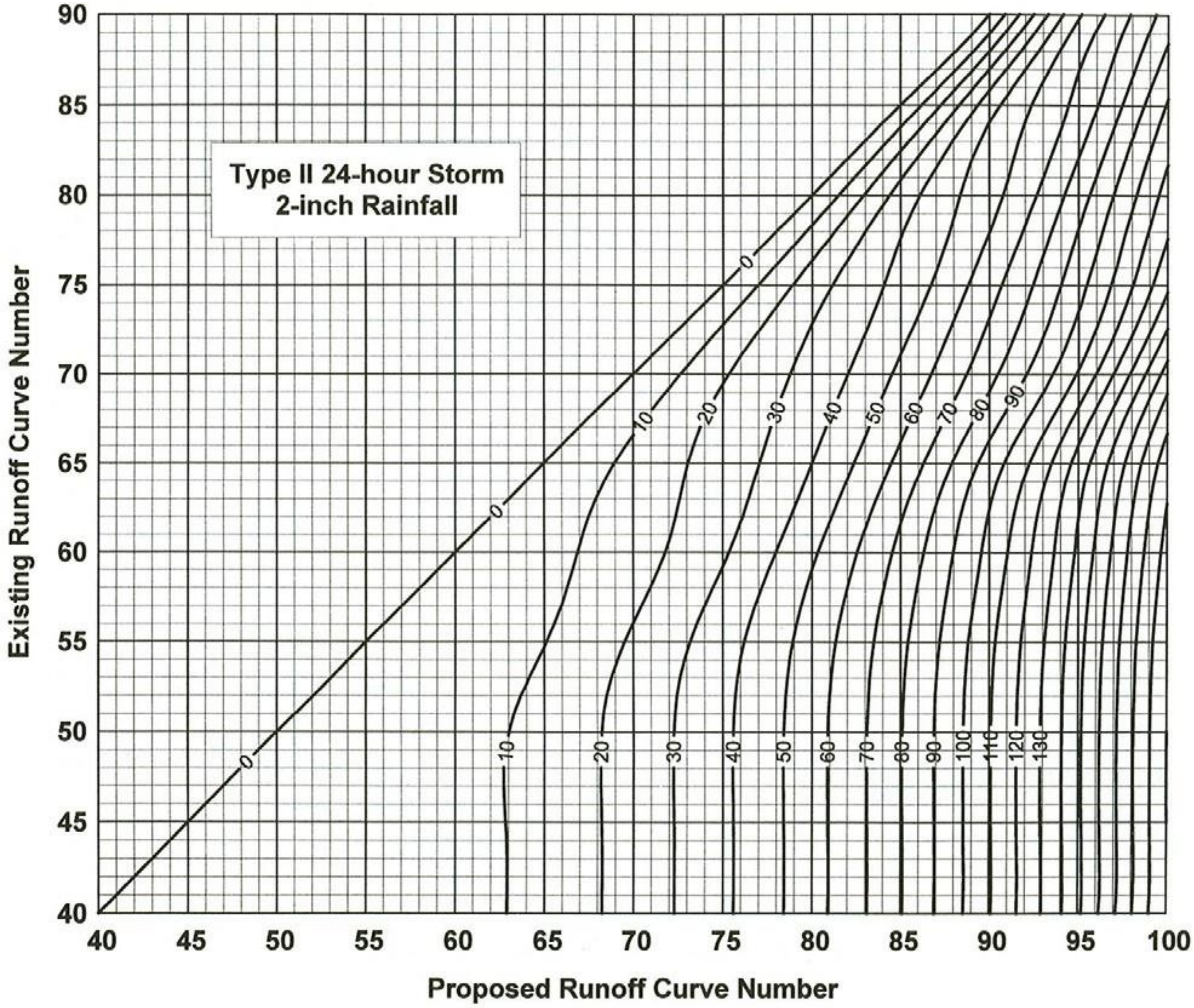

Figure C3-S8-8: Chart Series B: storage volume required for maintaining the predevelopment peak runoff rate using 100% retention for Type II 2-inch rainfall (hundredths of an inch)
Source: PGC, Maryland, 1999

If the T_c is equal for the predevelopment and post-development conditions, the peak runoff rate is independent of T_c for retention and detention practices. The difference in volume required to maintain the predevelopment peak runoff rate is practically the same if the T_c's for the predevelopment and post-development conditions are the same. These concepts are illustrated in Figure C3-S8-9. In Figure C3-S8-9, the difference in the required IMP area between a T_c of 0.5 and a T_c of 2.0 is minimal if the predevelopment and post-development T_c's are maintained.

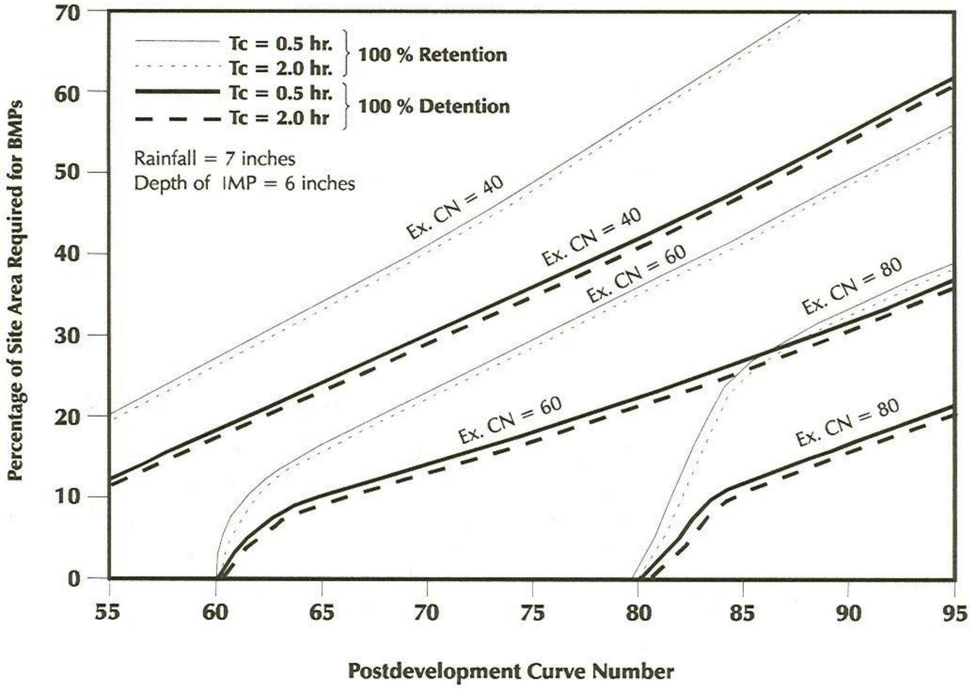

Figure C3-S8-9: Comparison of storage volumes for various T_c's
Source: PGC, Maryland, 1999

Example 3

Given:
Site area = 28 acres
Existing CN = 62
Proposed CN = 68
Design storm is 1.83 inches (round up to 2 inches to use charts)
Design depth of BMP will be 6 inches

Solution: Use Chart Series B: Storage volume required to maintain runoff volume or CN.

From Chart B:
0.11 inch (from Chart B for 2-inch rainfall and CN's of 62/68) of storage over the site is required to maintain the predevelopment peak runoff rate. Therefore, if 6-inch design depth is used: 0.51 acres (28 acres x 0.11 in/6 in) of BMPs distributed evenly throughout the site are required to maintain the runoff peak runoff rate for the LID design storm.

4. **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 CN's diverge, the storage requirement to maintain the volume is much greater than the storage volume required to maintain the peak runoff rate. As the CN's 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 C3-S8-2 illustrates the percentage of site area required for volume and peak control for representative curve numbers. For example, using a 5-inch Type II 24-hour storm event and 6-inch design depth with a predevelopment CN of 60, the following relationships exist:

- For a post-development CN of 68, 9.7 percent (interpolation) 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), 12.1 percent (interpolation) of the site is required. Therefore, additional detention storage or a hybrid approach (calculated in column 7) is required.
- For a post-development CN of 84, 33% 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) 30% of the site is required. Therefore, the storage required to maintain the runoff volume is also adequate to maintain the peak runoff rate. However, 30% of the site for BMPs 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.

5. **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 T_c for the post-development condition is equal to the T_c 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 the chart: Approximate Detention Basin Routing for Rainfall Types I, Ia, II and III in the TR-55 version 2.31 user manual, Chapter 6 (NRCS, 1986).

Table C3-S8-2: Representative percentages of site required for volume and peak rate control

Type of 24-hour Storm Event (1)	Runoff Curve No.		% of Area Needed for IMP				Percent of Volume Retention for Hybrid Design (Eq. 4.5) (8)
	Existing (2)	Proposed (3)	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)	
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

Type of 24-hour Storm Event (1)	Runoff Curve No.		% of Area Needed for IMP				Percent of Volume Retention for Hybrid Design (Eq. 4.5) (8)
	Existing (2)	Proposed (3)	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)	
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

Source: PGC, Maryland, 1999

6. **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 C3-S8-5 is used to determine the ratio of retention to total storage. Equation C3-S8-6 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.

Equation C3-S8-5

$$X = \left[\frac{50}{V_{R100} - V_{D100}}\right]\left\{-V_{D100} + \left[{V_{D100}}^2 + 4(V_{R100} - V_{D100})VR\right]^{0.5}\right\}$$

where:
VR = storage volume required to maintain predevelopment runoff volume (Chart Series A)
V_{R100} = storage volume required to maintain predevelopment peak runoff rate using 100% retention (Chart Series B)
V_{D100} = 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:

Equation C3-S8-6

$$H = VR \times \left(\frac{100}{X}\right)$$

Equation C3-S8-5 and Equation C3-S8-6 are based on the following assumptions:

- *x*% of the total storage volume is the retention storage required to maintain the predevelopment CN/volume calculated from Chart Series A.
- 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.

Example 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 inches (from Chart Series A)
Storage volume required to maintain peak runoff rate using 100% retention = 0.62 inches (from Chart Series B)
Storage volume required to maintain peak runoff rate using 100% detention = 0.31 inches (from Chart Series C)

a. Step 1: Solve for *x* (ratio of retention to total storage) using Equation C3-S8-5:

$$X = \left[\frac{50}{(0.62 - 0.31)}\right]\{-0.31 + [0.31^2 + 4(0.62 - 0.31)(0.35)]^{0.5}\}$$

$$X = \left[\frac{50}{0.31}\right]\{-0.31 + 0.728\} = 68$$

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

b. Step 2: Solve for the total area to maintain both the peak runoff rate and volume using Equation C3-S8-6.

$$H = 0.35 \times \frac{100}{68}$$

$$H = 0.51in$$

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

7. **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 a subdrain system must be installed. In this case, the bioretention basin is considered detention storage.

   When this occurs, the site area available for retention BMPs 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 (VR*) is determined by the designer by analyzing the site constraints. Equation C3-S8-7 is used to determine the ratio of retention to total storage. Equation C3-S8-8 is then used to determine the total site BMP area in which the storage volume available for retention practices (VR*) substitutes the for the storage volume required to maintain the runoff volume.

   Equation C3-S8-7

$$X^{*} = \left[\frac{50}{(V_{R100} - V_{D100})}\right]\{-V_{D100} + \left[{V_{D100}}^{2} + 4(V_{R100-}V_{D100})VR^{*}\right]^{0.5}\}$$

   Where:
   VR* = storage volume acceptable for retention BMPs
   V_{R100} = storage volume required to maintain predevelopment peak runoff rate using 100% retention (Chart Series B)
   V_{D100} = storage volume required to maintain predevelopment peak runoff rate using 100% detention (Chart Series C)
   X = area ratio of retention storage to total storage

   The total storage with limited retention storage is then:

   Equation C3-S8-8

$$H^{*} = VR^{*} \times \left(\frac{100}{X^{*}}\right)$$

   Where:
   H* is the hybrid area with limited storage volume available for retention BMPs

   Example 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 in (From Chart Series A)
   Storage volume required to maintain peak runoff rate using 100% retention = 0.62 in (from Chart Series B)
   Storage volume required to maintain peak runoff rate using 100% detention = 0.31 in (from Chart Series C)

   Only half of the required site area is suitable for retention practices, remainder must incorporate detention.

$$VR^* = 0.35in \times 0.50 = 0.18in$$

a. **Step 1:** Determine appropriate amount of overall BMP area suitable for retention practices. Half of area is appropriate (given above). Use Equation C3-S8-7:

$$X^* = \left[\frac{50}{(0.62 - 0.31)}\right]\{-0.31 + [0.312 + (4)(0.62 - 0.31)(0.18)]^{0.5}\}$$

Therefore, 0.18 in of storage available for runoff volume control is 41% of the total volume needed for maintaining the predevelopment peak runoff rate.

b. **Step 2:** Solve for the total area required to maintain the peak runoff rate using Equation C3-S8-8.

$$H^* = 0.18in \times \left(\frac{100}{41}\right)$$

$$H^* = 0.44in$$

Therefore, a total storage of 0.44 inches is required to maintain the predevelopment peak runoff rate but not the runoff volume. Of the total 0.44-inch storage, 0.18 inches of the storage is used for retention volume.