Next, compute the time of flow in reach 1, using the relationship

$$\text{time} = \frac{\text{distance}}{\text{velocity}} = 120 \text{ m} + 1.05 \text{ m/s}$$

$$= 114 \text{ s} = 1.9 \text{ min}$$

The total time of flow to inlet 2 is the inlet time for area 1 plus the channel flow time in reach 1, or $5 + 1.9 = 6.9 \text{ min}$. This is larger than the inlet time for area 2; therefore, use a time of concentration $T_c = 7 \text{ min}$ for the composite area draining to inlet 2.

From Figure 3-6, read $i = 145 \text{ mm/h}$ for the 10-year storm.

Applying the rational formula yields

$$Q = 0.34 \times 0.145 \text{ m/h} \times 25,000 \text{ m}^2$$

$$= 1230 \text{ m}^3/\text{h}$$

and

$$Q = 1230 \text{ m}^3/\text{h} \times 1 \text{ h}/3600 \text{ s}$$

$$= 0.34 \text{ m}^3/\text{s} \text{ for reach 2}$$

Now enter Manning’s nomograph with $Q = 0.34 \text{ m}^3/\text{s}$ and the given slope of $S = 0.002$; read the required diameter $D = 65 \text{ cm}$ and flow velocity $V = 1.02 \text{ m/s}$.

Reach 3: The total tributary area to inlet 3 is

$$1 + 1.5 + 2 = 4.5 \text{ ha}, \text{ or } 45,000 \text{ m}^2$$. The composite runoff coefficient is computed to be

$$C = \frac{1}{4.5} \times (0.4 \times 1 + 0.3 \times 1.5 + 0.2 \times 2)$$

$$= 0.28$$

The time of flow in reach 2 is $180 \text{ m} + 1.02 \text{ m/s} = 176 \text{ s} = 2.9 \text{ min}$. The total flow time to inlet 3 is then

$$5 + 1.9 + 2.9 = 9.8 \text{ min}$$

(inlet time for area 1 + travel time in reach 1 + travel time in reach 2). But this is less than the individual inlet time for area 3, which is 12 min. Therefore, the 12-min inlet time dominates and is taken as the time of concentration (or storm duration) for the design of reach 3.

Enter Figure 3-6 with $T_c = 12 \text{ min}$ and read $i = 135 \text{ mm/h}$ or $0.135 \text{ m/h}$ for the 10-year storm. Now, applying the rational formula yields

$$Q = 0.28 \times 0.135 \text{ m/h} \times 45,000 \text{ m}^2 = 1700 \text{ m}^3/\text{h}$$

and

$$Q = 1700 \text{ m}^3/\text{h} \times 1 \text{ h}/3600 \text{ s} = 0.47 \text{ m}^3/\text{s}$$

From Manning’s nomograph, with $Q = 0.47 \text{ m}^3/\text{s}$ and $S = 0.0015$, read $D = 80 \text{ cm}$ and $V = 1 \text{ m/s}$.

Several software packages are available for design and analysis of stormwater collection systems. Piping networks can easily be laid out graphically, and the hydraulics of a system can be calculated at the click of a button. Rainfall information is calculated using rainfall tables, equations, or National Weather Service data, and the intensity-duration-frequency (IDF) curves can be plotted.

Most of the packages include a library of conveyance elements, including circular pipes, pipe arches, boxes, and others. Automatic flow calculations handle pressure and varied flow situations, including hydraulic jumps, backwater, and drawdown curves. Nearly all of the packages include automatic design features that allow design of all or part of a system based on a set of user-defined constraints, including velocity, slope, cover, invert/crown matching, inlet efficiency, gutter spread, gutter depth, and others. Some software packages can determine invert elevations and diameters of pipes, as well as the size of a drainage inlet necessary to maintain a given spread or capture efficiency depending on its location in sag or on grade.

### 9-3 STORMWATER MITIGATION TECHNIQUES

As discussed in Section 9-1, one of the most serious problems associated with land development is that it changes the rate and amount of stormwater runoff reaching streams and rivers. Conventional stormwater conveyance systems are designed to collect, convey and discharge runoff as efficiently as possible from developed areas. The intent is to create a highly efficient drainage system, which will prevent localized flooding, promote good drainage and quickly convey runoff to a discharge point. However, this approach decreases groundwater recharge, increases runoff volume, and changes the timing, frequency, and rate of discharge, which leads to downstream flooding, stream erosion, and overall degradation of water quality. In fact a series of independent systems, each designed and installed to deal with site-specific stormwater problems, can collectively create bigger problems on a watershed level.

Many techniques are often implemented to mitigate stormwater volume and quality issues at the site and watershed levels. These techniques are referred to as best management practices (BMPs). They are any procedure, protocol, structural device, or site design that prevents or mitigates stormwater runoff. In low-impact design, these are also referred to as integrated management practices. BMPs can be broadly categorized by whether they prevent stormwater pollution (source controls) or treat stormwater to make it cleaner (treatment controls).

- Source controls provide cost-effective ways to manage stormwater because they usually require no land or construction. Debris removal from streets, landscaping and lawn management control, vegetated swales, and pervious soil buffers are just some of the preventive measures that can be implemented to achieve the objectives of BMPs. In some drainage basins, however, more sophisticated control measures are necessary to meet the requirements of local water quality control standards.

**Low-impact development** (LID) is an innovative stormwater management approach with a basic principle that is modeled after nature. LID’s goal is to mimic a site’s predevelopment hydrology by using design techniques that infiltrate, filter, store, evaporate, and detain runoff close to
its source (source control). Examples of LID include bioretention cells (commonly known as rain gardens), permeable pavers, and vegetated roofs.

**Stormwater Flow Attenuation**

The most common approach to stormwater flow control generally utilizes temporary storage of the water on site, in the vicinity where it falls, rather than quick discharge to a nearby body of water. To some extent, stormwater storage occurs naturally in most drainage basins. In some cases, intentional ponding of rain water on rooftops or in parking lots for a short period of time can provide enough storage to reduce peak runoff flow rates. Using open grass-swale drainage channels also can effectively retard the flow of stormwater runoff.

The construction of relatively small reservoirs or basins to hold stormwater after it has been collected from streets, parking lots, and other surfaces is being required in a growing number of communities undergoing urbanization. These basins store or retain the stormwater and allow it to be released slowly under controlled conditions. They can be effective in controlling relatively short, but intense, local storms, which tend to cause the most frequent flooding, erosion, and pollution damage in small streams.

Some specific benefits of stormwater storage basins are as follows:

1. Reduction of peak runoff rates
2. Reduction of the severity and frequency of flooding
3. Reduction of soil erosion and stream sedimentation
4. Protection of surface water quality
5. Groundwater aquifer recharge, if soil conditions permit

The basic disadvantage of on-site stormwater storage basins is related to the problem of maintenance. The outlet structures are prone to clogging, and the basins themselves often become the depository for sediment and debris. Weed control is a problem, and mosquitoes can breed in pools of water that remain stagnant for a long time. In some cases, safety for children in the area must be considered. Maintenance may be the responsibility of the local municipality or of nearby property owners.

There are basically three different types of stormwater storage basins: **retention basins**, **detention basins**, and **recharge basins**. A retention basin holds some water all the time, forming a permanent pond or small lake. In addition to stormwater control, it may also provide esthetic and recreational benefits on the site. A detention basin, however, only holds the stormwater for a relatively short period of time, during and shortly after periods of rainfall. It is empty and dry most of the time. Sometimes there may be a small stream flowing through the basin, even in dry weather. A section view of a detention basin is shown in Figure 9-13.

The third type of basins, recharge or infiltration, are specifically designed to allow the collected water to percolate into an underlying aquifer. They serve to recharge and replenish groundwater reserves as well as to control storm runoff. For a recharge basin to be effective, the soils underlying the basin must be permeable to allow relatively rapid infiltration, and the seasonal high water table should be at least 0.5 m below the bottom. In some communities, a portion of a recharge basin may be built underground, freeing up valuable land area for other uses; these subterranean basins are sometimes called **dry wells**.

Even with the use of recharge basins and dry wells, it is difficult to re-create the soil recharge rates of predevelopment conditions in any stormwater management project. Basins are fairly good at controlling the peak rate of runoff by extending the discharge over time, but the volume of runoff is increased in most postdevelopment conditions.

**Design Procedure** Local subdivision regulations and municipal land-use ordinances must be reviewed at the very beginning of the project to determine the specific performance requirements for the basin with regard to stormflow reduction. The computations to determine the **predevelopment peak discharge** (before construction) and the **postdevelopment peak discharge** (after construction) can be made as illustrated in Examples 9-4 and 9-6.

Most communities require that a detention basin provide enough storage volume and outlet control to keep postdevelopment runoff equal to or less than predevelopment runoff. In other words, the developer must build a facility that will effectively maintain the rate of runoff from the site just about as it was in its natural condition, before construction.

This requirement usually pertains to the 100-year storm, but some ordinances also specify that the basin should reduce runoff flows from the 2- and 10-year storms as well. If the basin is designed only for the large 100-year storm, it will have no attenuating effect on the smaller, but more frequent stormflows. Accommodation of more than one storm return period in the basin is accomplished by proper hydraulic design of the basin volume and outlet structure. A concrete structure with several outlets for handling different size storms is illustrated in Figure 9-14.

Using a topographic map of the site, a suitable location for the detention basin should be established. This should be in the lower part of the tributary drainage area. The on-site
storm sewer system should be designed, as described in Section 9-2, to direct the runoff into the detention basin. A preliminary estimate of the required basin volume can be made at this point. A simple and quick way of doing this is described later in this section.

After a preliminary basin size is determined, a grading plan should be sketched on the topographic map. The basin can be constructed by balancing excavation and fill in the low-lying area of the site, forming a confining earth embankment that gradually blends into the natural topography of the land. A thorough hydraulic analysis of flow through the basin and outlet structure should then be conducted.

If the discharge at the outlet is determined to be equal to or less than the maximum allowable discharge, then the basin design is accepted as satisfactory; otherwise, changes are made and the process is repeated until an acceptable design is reached. Finally, an emergency spillway is designed for the greatest design storm; freeboard is added to account for the estimations in the calculations.

Preliminary Design Computations

| Preliminary Design Computations | The basic relationship that expresses the function and operation of a stormwater detention basin is that at any given time the volume of water in storage is equal to the difference between the inflow volume and the outflow volume up to that time, or |
| inflow − outflow = storage (9-4) |

The rate of inflow changes with time. It depends on the intensity and duration of rainfall, as well as on the physical characteristics of the drainage area. The relationship between inflow and time is shown graphically in an inflow hydrograph.

The rate of outflow from the basin also changes with time. It depends on the hydraulic characteristics of the basin outlet structure. The outflow is generally a function of the height or depth of water in the basin; the deeper the water, the faster it flows over or through the outlet.

In mathematical terms, the storage equation is

\[ I(\Delta t) - O(\Delta t) = \Delta S \] (9-5)

where \( \Delta t \) is a small time interval, such as 5 or 10 min (pronounced "delta t")

\[ I = \text{average inflow rate during } \Delta t \]

\[ O = \text{average outflow rate during } \Delta t \]

\[ \Delta S = \text{change in storage volume during } \Delta t \]

(pronounced "delta S")

The solution of this equation leads to the determination of the basin outflow hydrograph, which shows the rate of flow out of the basin as a function of time. The procedure for solving the equation and preparing the outflow hydrograph is called flood routing or reservoir routing.

Typical inflow and outflow hydrographs for a detention basin are shown in Figure 9-15. Initially, the rate of inflow exceeds the rate of outflow and water accumulates in the basin (\( \Delta S \) is positive). The outlet structure serves, in effect, as a bottleneck that prevents the water from flowing out of the basin as fast as it flows in. Eventually, the inflowing stormwater subsides, and the basin gradually empties as the water flows through the outlet (\( \Delta S \) is negative). A comparison of the inflow and the outflow hydrographs clearly shows the effect of the basin in attenuating or reducing the peak flow rate.

The reservoir routing procedure just outlined involves a lot of computation to arrive at a solution of the storage equation and the outflow hydrograph. For this discussion, a simplified procedure is used to illustrate the fundamental concept of stormwater detention without getting bogged down in computations. This procedure is sufficient to provide a preliminary or ballpark estimate of the required storage volume or peak outflow rate of a detention basin. It is not an exact method and would not be used for final design or analysis.

In this method, two factors related to the effectiveness of a stormwater detention basin are defined as follows:

\[ \text{storage factor (SF)} = \frac{\text{basin storage volume}}{\text{total rainfall volume}} \] (9-6)

| FIGURE 9-15 Typical inflow and outflow hydrographs for a stormwater detention basin. The basin and outlet structure reduce the peak rate of runoff from a developed site. |
If there is no storage volume at all, then SF = 0, and therefore FF = 1.0. In other words, the outflow rate will equal the inflow rate, and there will be no flow attenuation. However, if a basin big enough to store the total rainfall volume from the storm is provided, then SF = 1.0. Under this circumstance, FF = 0, and there is no outflow at all. The straight-line relationship approximates what happens in between these two extreme conditions when some storage volume is provided.

Total Rainfall Volume The total rainfall volume is equal to the area under the inflow (or outflow) hydrograph because the product of discharge (volume per unit time) and time is equivalent to volume. For practical purposes, it is reasonable to make the simplifying assumption that the inflow hydrograph is triangular in shape.

The peak inflow can be easily computed using the rational method. The time for the rising limb of the hydrograph to reach the peak flow value is taken as the time of concentration \( T_c \) of the drainage area. The time for the receding limb to reach the base is conservatively taken as twice the time of concentration, or \( 2T_c \). This triangular hydrograph is illustrated in Figure 9-17.

The total rainfall volume is the area of the triangular inflow hydrograph. The area of a triangle is equal to the product of one half the base times the height \( (A = bh/2) \). Because in this case the base \( b = 3T_c \) and the height \( h = Q_{\text{max}} \), the area is \( \frac{1}{2} = 3T_c \times Q_{\text{max}} \) and

\[
\text{total rainfall volume} = 1.5 \times T_c \times Q_{\text{max}} \tag{9-9}
\]

---

**FIGURE 9-16** The relationship between flow factor and storage factor offers a simplified procedure for stormwater detention calculations.

(From A. Pagan, “Flow factor line used in storage calculations,” Irrigation Journal, 1980, with permission of the American Society of Civil Engineers.)

Flow factor \( (FF) = \frac{\text{peak outflow rate}}{\text{peak inflow rate}} \) \tag{9-7}

The relationship between the storage factor and the flow factor can be approximated by a straight line, as shown in Figure 9-16. The line is a graph of the equation

\[
FF = 1.0 - SF \tag{9-8}
\]

where FF and SF are the flow factor and storage factor, respectively.
The following examples illustrate the application of this simplified method for preliminary detention basin computations.

**Example 9-8**

A storm causes a peak runoff rate of 5 m³/s in a drainage basin that has a time of concentration of 30 min. A detention basin with 10,000 m³ of volume can be built on-site for a residential land subdivision. Estimate the peak outflow from the basin for this storm.

**Solution**

\[ T_c = 30 \text{ min} \times 60 \text{ s/min} = 1800 \text{ s} \]

Applying Equation 9-9 yields

\[
\text{total rainfall volume} = 1.5 \times 1800 \text{ s} \times 5 \text{ m}^3/\text{s} = 13,500 \text{ m}^3
\]

Now, applying Equation 9-6 gives

\[
\text{SF} = \frac{10,000 \text{ m}^3}{13,500 \text{ m}^3} = 0.74
\]

From Figure 9-16 (or Equation 9-8), we get FF = 0.26, and from Equation 9-7

\[
\text{peak outflow rate} = 0.26 \times 5 \text{ m}^3/\text{s} = 1.3 \text{ m}^3/\text{s}
\]

In summary, it can be expected that the 10,000-m³ basin will reduce the peak runoff discharge from 5 m³/s to about 1.3 m³/s.

**Example 9-9**

Estimate the storage volume needed in a detention basin to reduce peak inflow rate of 150 cfs to 100 cfs if the total rainfall volume is 300,000 ft³.

**Solution**

Applying Equation 9-7 yields

\[
\text{FF} = \frac{100}{150} = 0.67
\]

From Figure 9-16,

\[
\text{SF} = 0.33
\]

Now, applying Equation 9-6 gives

\[
0.33 = \frac{\text{storage volume}}{300,000 \text{ ft}^3}
\]

and

\[
\text{basin storage volume} = 0.33 \times 300,000 \text{ ft}^3 = 100,000 \text{ ft}^3
\]

**Example 9-10**

Reverting to the data given in Examples 9-4 and 9-6, assume that the local planning board has required that the land developer provide an on-site stormwater storage basin. The peak runoff after development (Example 9-6) is to be no greater than it was before development (Example 9-4). Assume that the detention basin will have an average water depth of 6.5 ft when filled to capacity. How much area of the site, in acres, will have to be used for the detention basin (a) for a 5-year storm and (b) for a 100-year storm?

**Solution**

(a) 5-year storm: From Examples 9-4 and 9-6, the predevelopment discharge of 47 ft³/s is set equal to the basin outflow rate, and the postdevelopment discharge of 127 ft³/s is set equal to the inflow rate. From Equation 9-7, FF = 47/127 = 0.37, and from Equation 9-8, SF = 0.63. The time of concentration \( T_c = 20 \text{ min} = 1200 \text{ sec} \) Applying Equation 9-9 yields

\[
\text{total rainfall volume} = 1.5 \times 1200 \text{ s} \times 127 \text{ ft}^3/\text{s} = 228,600 \text{ ft}^3
\]

Now, from Equation 9-6, 0.63 = storage volume/228,600; or storage volume = 0.63 \times 228,600 ft³ = 144,018 ft³.

Since volume = area \times depth, or area = volume/depth,

\[
\text{basin area} = 144,018 \text{ ft}^3/6.5 \text{ ft} = 22,157 \text{ ft}^2 = 0.5 \text{ acres}
\]

(b) 100-year storm: Following the same procedure as in part (a), using the data for the 100-year storm, the following results are obtained:

\[
\text{FF} = \frac{98}{267.5} = 0.37
\]

and

\[
\text{SF} = 1 - 0.37 = 0.63
\]

\[
\text{total rainfall volume} = 1.5 \times 1200 \text{ s} \times 268 \text{ ft}^3/\text{s} = 482,400 \text{ ft}^3
\]

\[
\text{basin area} = 482,400 \text{ ft}^3/6.5 \text{ ft} = 74,215 \text{ ft}^2 = 1.7 \text{ acres}
\]

This represents only 2.7 percent of the total site area of 62 acres.

**Stormwater Quality Control**

There are a number of stormwater quality control techniques that are able to reduce stormwater pollutant load impacts in a watershed. An effective general approach is to create a system with components that resemble natural processes that promote infiltration and flow attenuation, as well as biological and physical removal of pollutants. By dividing the watershed into a series of small, linked subwatersheds, it is often possible to apply and successfully utilize BMPs that are otherwise incapable of managing large volumes of runoff. The following is a brief description of typical BMP components that can be linked in series to provide stormwater quality control.

**Sedimentation Basins** Excavated areas that collect and retain stormwater flows for long enough time periods to trap suspended soil particles are called sedimentation basins.
They are typically used during the construction phase of a project to eliminate off-site transport of eroded soils and sediment. A sedimentation basin can also be designed to function as a permanent integral part of a stormwater management system.

When used as a fore bay (i.e., the first structural component in the system), a sedimentation basin will effectively remove suspended soil particles, leaves, litter, road grit, and other trash and gross particulate pollutants from the incoming runoff. The sedimentation basin also serves as an area where the energy associated with the storm surge can be dissipated, thereby reducing the scour potential and erosive force of the incoming runoff. As is the case with standard detention basins, the pollutant removal efficiencies are highly variable. On average, the removal efficiency for total suspended solids (TSS) is about 70 percent and for total phosphorus (TP) about 30 percent.

**Swales** A swale is a shallow depression or ditch constructed to collect and convey runoff from one point to another. Although swales may have a limited capacity to store and treat stormwater runoff, when combined with other structural stormwater measures, they can substantially improve the quality of stormwater. They do so in two ways. First, the vegetation present in the swale reduces runoff velocity. The extent to which this occurs is dependent on the length, depth, and gradient (or slope) of the swale, as well as the density of the vegetation. Second, a portion of the runoff discharged to a swale infiltrates into the soil, thus reducing the quantity or volume of the surface runoff. The amount of infiltration depends on soil moisture conditions, the gradient of the swale, and the velocity of the runoff.

Most swales are constructed for the purpose of collecting runoff and directing it to another BMP. Thus, stormwater runoff typically has a very short contact time in a swale (about 5 to 20 min). This limits the amount of treatment that can occur. The best designed swale, from a stormwater quality enhancement perspective, is wide and shallow with a slope in the range of 2 to 3 percent. Side slopes should be no greater than 3:1 (horizontal to vertical). A water-tolerant, erosion-resistant grass should be established as a dense ground cover on the bottom of the swale. Swale grasses should not be mowed close to the ground because this impedes the filtering and hydraulic functions of the swale.

Also, if the swale is adjacent to a roadway, grass species that are relatively tolerant to road salts should be used. Swales should be designed to generate sheet flow across their point of discharge. This can be accomplished by using rip-rap (large stones), a concrete apron, or another, similar device at the end of the swale. Once sheet flow degrades into concentrated flows, erosion channels are formed, thereby defeating the pollutant removal attributes of the swale.

Groundwater infiltration and recharge will also be limited by the design of the swale. Again, wide, nominally sloped swales constructed over soils with high infiltration rates are most capable of infiltrating runoff. Underlying soils should have a percolation rate more than 0.5 in./hr. The intensity and magnitude of a storm, or the length of time between storm events, will affect the opportunity for runoff to infiltrate into the soil. The pollutant removal efficiency of grassed swales on average is 70 percent for TSS, 40 percent for TP, and 25 percent for total nitrogen (TN). However, the reported range of removal is highly variable.

**Bioretention Systems** Bioretention systems utilize a combination of settling, filtration, and bioaccumulation processes to treat stormwater runoff. They can be designed with or without a preceding sedimentation basin. In addition, bioretention systems can be built online or offline (operate in series or parallel). In an online system, runoff is directed into and through the bioretention area, whereas in an offline system, runoff is diverted from the main collection system into the treatment area. The general concept of any bioretention system is the slowing and detention of runoff for the purpose of facilitating some form of biologically active treatment. (Biological treatment processes are discussed in Section 10-3.)

In some applications, an offline riparian buffer type of bioretention system can be effective. In addition to attenuating peak flow and filtering particulate pollutants, riparian buffer bioretention systems provide habitat for a wide variety of living organisms. Runoff is diverted, retained, and treated for a period of 18 to 36 h in an area of nominal grade at least 3 to 5 m (10 to 15 ft) wide. Plantings within the created riparian corridor can range from grasses to trees. About 70 percent TSS, 50 percent TP, and 80 percent TN can be removed from the stormwater in riparian buffer zones.

**Created Treatment Wetlands** A created treatment wetland (CTW) is a constructed shallow wetland area designed specifically to detain and treat stormwater runoff (rather than to create a wildlife habitat). Most CTWs have a broad, gently graded (1 to 2 percent) bottom, and are designed to accommodate and treat the stormwater runoff volume of the 1-year storm, using specially designed outlet control structures or check dams. Most CTWs are planted with a dense assortment of vegetation capable of existing in saturated conditions. Small standing pools of water are often interspersed within the dense vegetation of a CTW.

CTWs provide very high pollutant removal efficiencies, particularly for nutrients and dissolved pollutants. Pollutant removal is achieved as a result of settling, filtering, and biouptake. In general, expected pollutant removal efficiencies for CTWs are 70 to 80 percent for TSS, 40 to 45 percent for TP, and 25 percent for TN.

**Wet Ponds** Wet ponds (or retention basins) provide substantially higher pollutant removal efficiency rates than conventional dry detention basins. In general, wet ponds have relatively high TSS and particulate pollutant removal capabilities. As in any standing water body, incoming particulate pollutants (e.g., nutrients and heavy metals) will initially be removed as a result of the settling of the heavier, coarse-grain particulate matter (i.e., total...
suspended solids). Studies have shown that the majority of suspended particulate pollutants will settle out during the first 6 to 12 h. Most wet ponds are designed to store water from storm events of a given magnitude (e.g., 1-, 5-, and 10-year storms).

Unlike most conventional structural stormwater measures, wet ponds can also remove significant amounts of dissolved pollutants, especially soluble nutrients, from the water. This occurs due to bacterial, algal, and aquatic plant uptake of dissolved constituents. Biological assimilation of dissolved pollutants and soluble nutrients represents an important removal pathway, since these types of pollutants are not greatly affected by settling processes. Once assimilated, either the nutrients are trapped in biomass and in the sediments or microbial activities remove them from the system (e.g., denitrification). This combination of the settling of TSS and the assimilation of soluble forms of nutrients, such as phosphorus and nitrogen, makes wet ponds an effective means of reducing the stormwater-related pollutant load. Pollutant removal efficiencies of wet ponds are approximately 70 percent for TSS, 60 percent for TP, and 40 percent for TN.

**Integration of BMPs** The efficiency of an individual BMP can be increased by creating a routing system that integrates a series of hydrologically linked BMPs, thereby creating a "pollutant removal train." A system of linked BMPs can decrease the load of pollutants discharged from a site to levels no greater than that discharged prior to development. This occurs because each of the interlinked BMPs works in unison with the others to remove pollutants by either different processes or as a result of repeated processes. For example, a vegetated swale linked with a wet pond creates an opportunity for the removal of coarse particulate materials (via filtration) followed by the removal of dissolved nutrients (via biouptake).

Typically, linked BMPs can be used to augment the pollutant removal capabilities of the individual BMPs (as in the previous example) or to pretreat or prefilter stormwater to increase the efficiency of the primary BMP. An example of such a situation would be the installation of a catch basin or sediment chamber prior to a bioretention system, where the sedimentation chamber's primary function would be to remove coarse sediments. This linking of BMPs is a fundamental feature of the stormwater management project at Pennswood Village, which is described below as an example of a low-impact land development project.

Pennswood Village is a retirement community located in Middletown, Bucks County, Pennsylvania. As part of the facility's planned expansion, Pennswood Village entered into a partnership with the township, which in part involved correction of existing runoff and stormwater quality problems associated with lands both on and off the Pennswood site. The resulting stormwater quality management system was designed to mimic the functional properties of a riparian corridor floodplain. The Pennswood Village design integrated a number of different BMPs, including a sedimentation basin, a vegetated swale, an infiltration basin, a created treatment wetland, and a small wet pond. These BMPs work in series to attenuate peak flows, promote groundwater recharge, and passively remove pollutants through a combination of filtering, settling, and biological treatment mechanisms. The final design exceeded the township's stormwater management requirements while providing an attractive, passive recreation and learning environment for Pennswood Village and the community at large.

The functional design of the Pennswood Village stormwater management system mimics that of a natural riparian, stream corridor channel (Figure 9-18). The system consists of an integrated series of BMPs, each sized and located to address a specific stormwater management purpose. The alignment and grading of the swales, basins, and wetlands combined with the careful selection of native grasses, shrubs, and trees diminishes the velocity of the runoff, biofilters and settles the pollutants, and creates opportunities for groundwater recharge. The five major elements of the system and their functional attributes are as follows.

At the uppermost end of the system, where runoff is directed by a series of pipes from Route 413 and the contributing watershed, is a sedimentation basin. The sedimentation basin is a stone-lined structure. Its purpose is to slow the storm surge, settle out gross particulate material, and contain the majority of the trash and road debris conveyed along with the runoff. Runoff discharged from the sedimentation basin is directed into a grassed swale that conveys the runoff to an infiltration basin. The soils that predominate in this section of the site are highly permeable. The depth to the seasonal high water table is in excess of 2 m (6 ft), as is the depth to bedrock. These conditions of good soil permeability and lack of a constraining horizon are conducive to the infiltration of runoff and the recharge of the shallow aquifer. The infiltration basin is sized to manage the first flush runoff volume of a storm event.

Flows exceeding the infiltration capacity of this basin are discharged from the basin over a broad crested weir into a long, winding vegetated swale. On either side of the swale is a broad, flat meadow graded and designed to function in a manner similar to a riparian corridor or steam floodplain. That is, it consists of a series of shallow, stepped channels, each of which accommodates and detains the runoff from increasingly larger storm events. At the terminus of the system is a CTW and small wet pond. Outflow from the wet pond is controlled by an outlet structure designed to safely pass the 100-year storm. Initially, during the early part of a storm, runoff that exceeds the capacity of the infiltration basin flows via the swale into the wet pond. The outlet control structure on the pond causes water to flood back into the CTW. As water is detained in the CTW and wet pond, it will back up further, eventually overflowing into the broad meadow and created riparian corridor.
The result is a highly functional stormwater management system that exceeded the township's stormwater management requirements while providing an attractive environment for Pennswood Village and the community at large. As designed, this system attenuates peak flows, promotes groundwater recharge, and passively removes pollutants through a combination of filtering, settling, and biological treatment processes.1

**LEED and Stormwater Mitigation** Under LEED, project certification points can be earned by implementing strategies to reduce stormwater quantity and improve stormwater quality to specific levels. Minimizing impervious area, specifying vegetated roofs and promoting on-site infiltration with rain gardens and pervious pavement are among the techniques that can be used. Reuse of stormwater for nonpotable uses such as landscape irrigation, toilet and urinal flushing, and custodial uses also are techniques recognized by LEED.

---


---

### 9-4 FLOODPLAINS

Flooding is a natural event that occurs periodically when the water in a stream or river overflows its channel banks and inundates adjacent low-lying land. This land is called the **floodplain**. The portion of the floodplain that is inundated by the 100-year flood is usually called the **flood hazard area**, as illustrated in Figure 9-19. The flood hazard area includes the **floodway**, which carries the major portion of the flood at

---

**FIGURE 9-19** The 100-year floodplain or flood hazard area includes the floodway and the flood fringe areas.