Pennsylvania Stormwater Best Management Practices Manual

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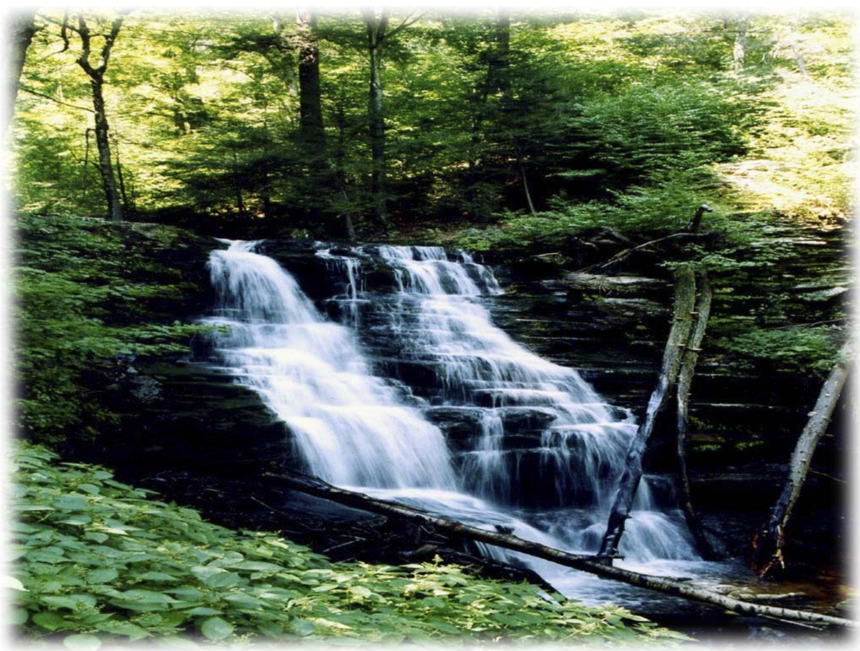
Section 2
Stormwater and Pennsylvania's Natural Systems



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Section 2 Stormwater and Pennsylvania's Natural Systems

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Impervious surfaces greatly increase the volume and rate of stormwater produced by the land surface, which can have damaging impacts related flooding, groundwater recharge, stream baseflow, and stream channel shape. This stormwater runoff carries with it the various pollutants that have accumulated on the man-made landscape. The development of measures that prevent or reduce these hydrologic and chemical impacts is the primary purpose of this Manual, but before specific BMPs can be described, the processes of rainfall and surface runoff must be understood.

2.1 The Hydrologic Cycle

- **The hydrologic cycle is a dynamic system in constant movement.**
- **The hydrologic cycle is comprised of five major components: precipitation, infiltration, evapotransporation, groundwater recharge, and surface runoff.**
- **Impacting one part of this system means impacting other parts of the system, to maintain the "water balance."**

The hydrologic cycle is a dynamic system in constant movement. The cycle's dynamic quality — the movement of rainfall from atmosphere to the land surface, where vegetative systems transpire and surface and groundwater pathways convey water back to the ocean — must be sustained for truly effective stormwater management. A simplified schematic of the hydrologic cycle is shown in Figure 2-1. The cycle for an average year in a typical Pennsylvania watershed, the Brandywine Creek, is shown as a flow chart in Figure 2-2.

Impacting one part of the system means impacting other parts of the system, as the "water balance" is maintained. There are five major components to the water cycle - precipitation, infiltration, evapotranspiration, groundwater recharge, and runoff. Altering one component of the water cycle invariably translates into changes in other elements of the cycle. For example, paving the land surface reduces the amount of infiltration and evapotranspiration while increasing the amount of runoff. Stormwater BMPs are intended to help maintain the natural water cycle balance.

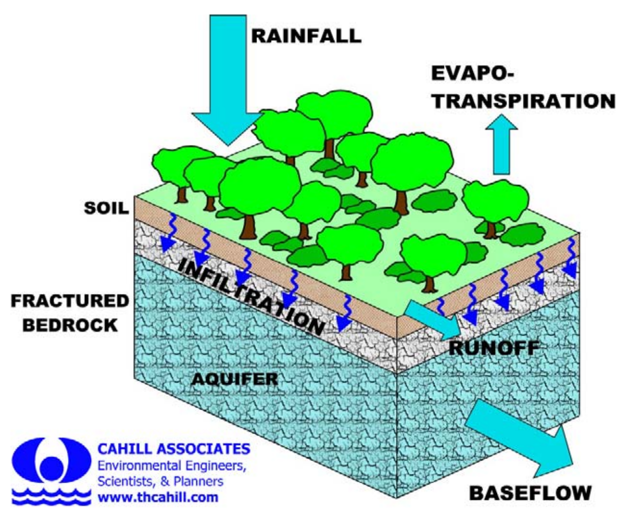

Figure 2-1. Natural Hydrologic Cycle for an Undisturbed Acre of Land

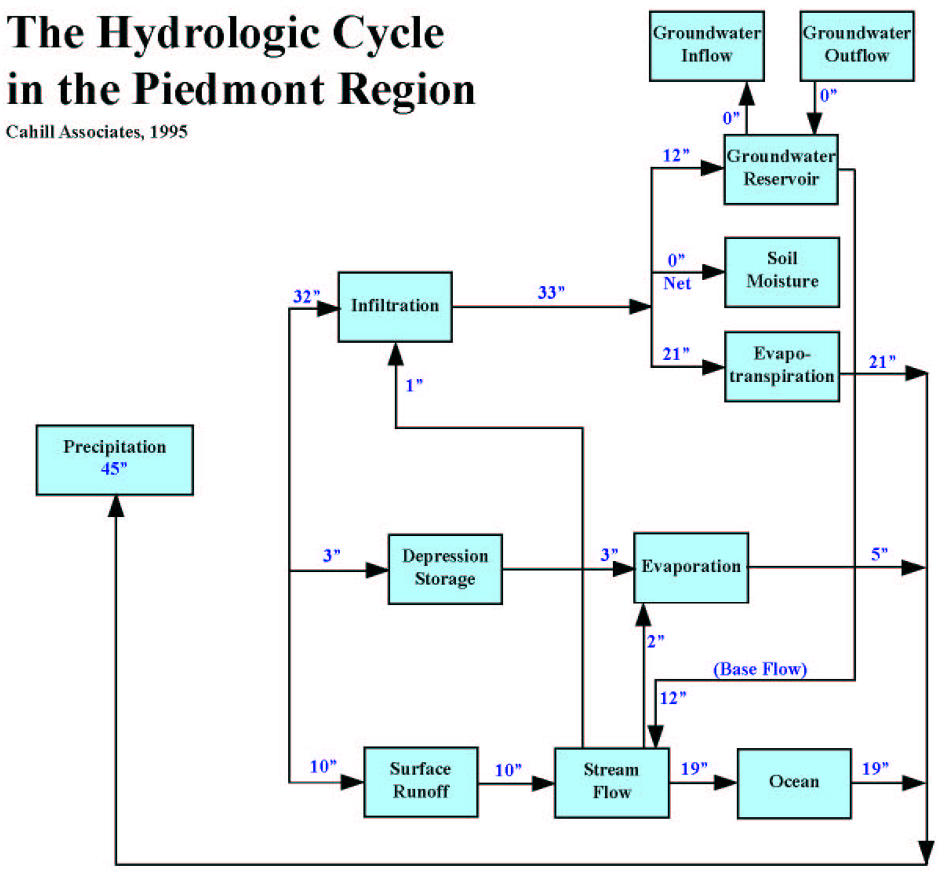

Figure 2-2. Annual Hydrologic Cycle as Flowchart for the Brandywine Creek, (Cahill, 1995).

2.1.1 Precipitation

- **Precipitation in Pennsylvania reflects a relatively humid pattern, with average annual precipitation ranging from under 34 inches to more than 50 inches per year.**
- **Tropical hurricanes occasionally track across the state, bringing with them heavy rainfalls and flooding.**
- **Precipitation varies by season, but is well distributed throughout the year, with most of the annual volume of rainfall occurring in small storm events of modest size.**

Precipitation in Pennsylvania reflects a relatively humid pattern, with average annual precipitation ranging from under 34 inches to more than 50 inches per year (Figure 2-3, NOAA, 2002). Storm frequency data demonstrates some consistency from one city or region to another (Table 2-1). Storm frequency is derived based on the statistical probability of a storm occurring in a given year. That is, a 10-year, 24-hour storm has a 10 percent chance of occurring in any single year, a 50-year storm has a 2 percent chance, and a 100-year storm, a 1 percent chance. Stormwater management has historically focused on managing the flood effects from these large storms.

Tropical hurricanes occasionally track across the state, bringing with them heavy rainfalls and flooding. The pathways of major flood producing hurricanes that have impacted the state over the past four decades as shown in Figure 2-4. These coastal storms have been responsible for much of the actual flood damage experienced in Pennsylvania over the years. These extreme flood events are only one component of stormwater management.

Precipitation also varies by season, but rainfall is well distributed throughout the year, occurring in frequent events of modest size. Most of the rainfall in Pennsylvania occurs in relatively small storm events, as indicated in Figures 2-5 and 2-6. Over half of the average annual rainfall occurs in storms

Table 2-1. Rainfall Events of 24-Hour Duration in PA (inches) (Source: NOAA National Weather Service Precipitation Frequency Data Server, 2004)

Location	Frequency of Occurrence (Years)				
	2-year	5-year	10-year	50-year	100-year
Philadelphia	3.3	4.1	4.8	6.7	7.6
Pittsburgh	2.4	2.9	3.3	4.4	4.9
Scranton	2.6	3.2	3.7	5.4	6.4
State College	2.7	3.3	3.8	5.2	5.9
Williamsport	2.8	3.5	4.1	6.0	7.0
Erie	2.6	3.2	3.7	5.1	5.8

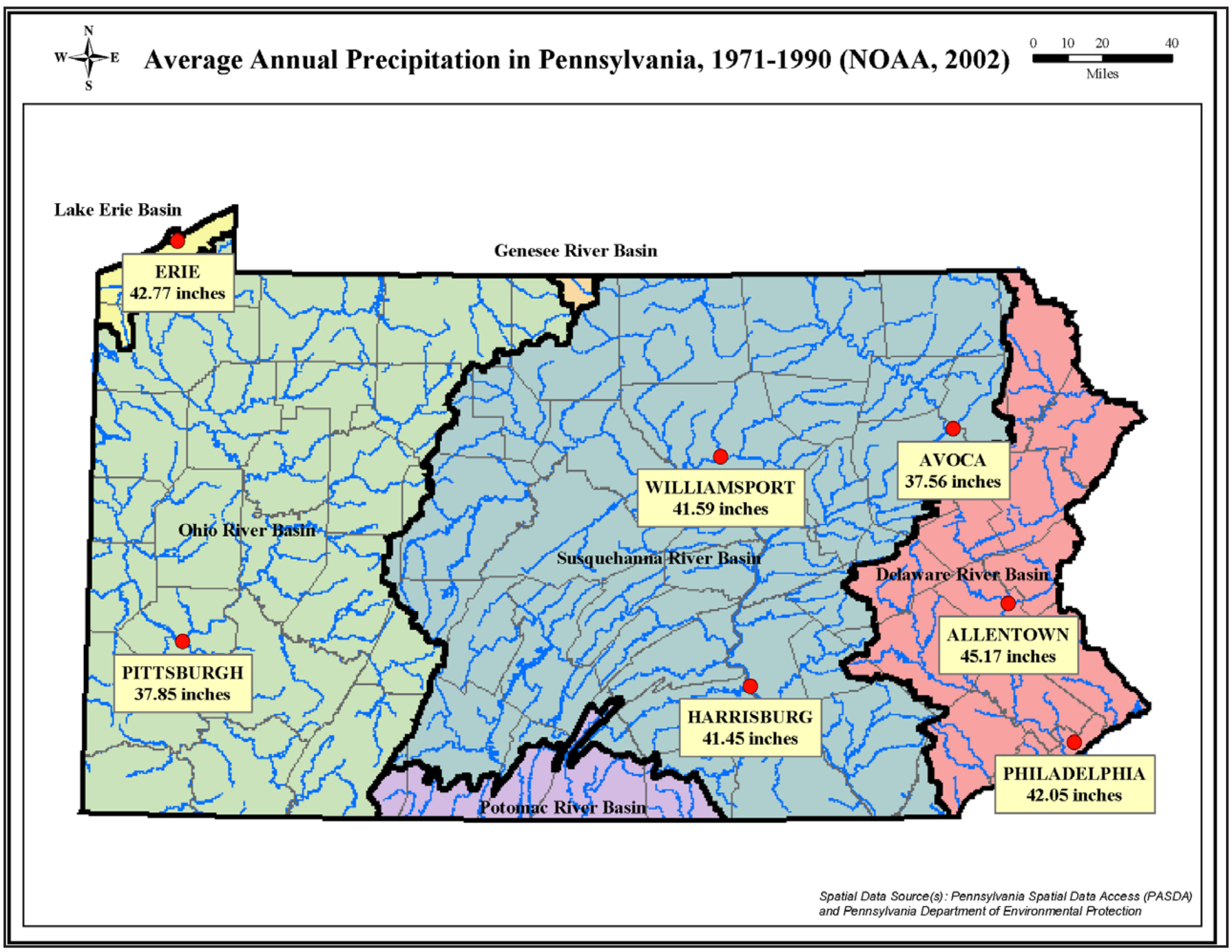

Figure 2-3. Average Annual Precipitation in Pennsylvania, 1971 – 1990 (NOAA, 2002)

of less than 1 inch (in 24 hours). Well over 75 percent of the average annual rainfall occurs in storms of 2 inches or less, and over 95 percent of average annual rainfall occurs in storms of 3 inches or less. A 2-year frequency rainfall is approximately 2.5 to 3 inches of precipitation. When stormwater management only addresses large events (2-year storms and greater), much of the actual rainfall and runoff are overlooked (as much as 95% of the annual rainfall). Managing smaller storms that compromise the vast majority of the annual rainfall in Pennsylvania is also crucial.

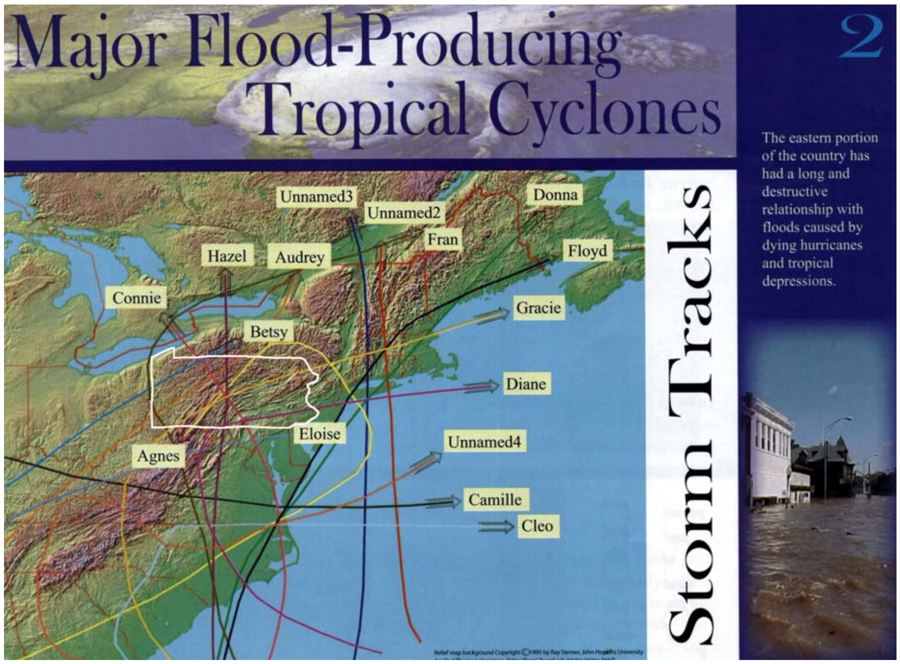

Figure 2-4. Major Flood-Producing Hurricanes through Northeastern United States

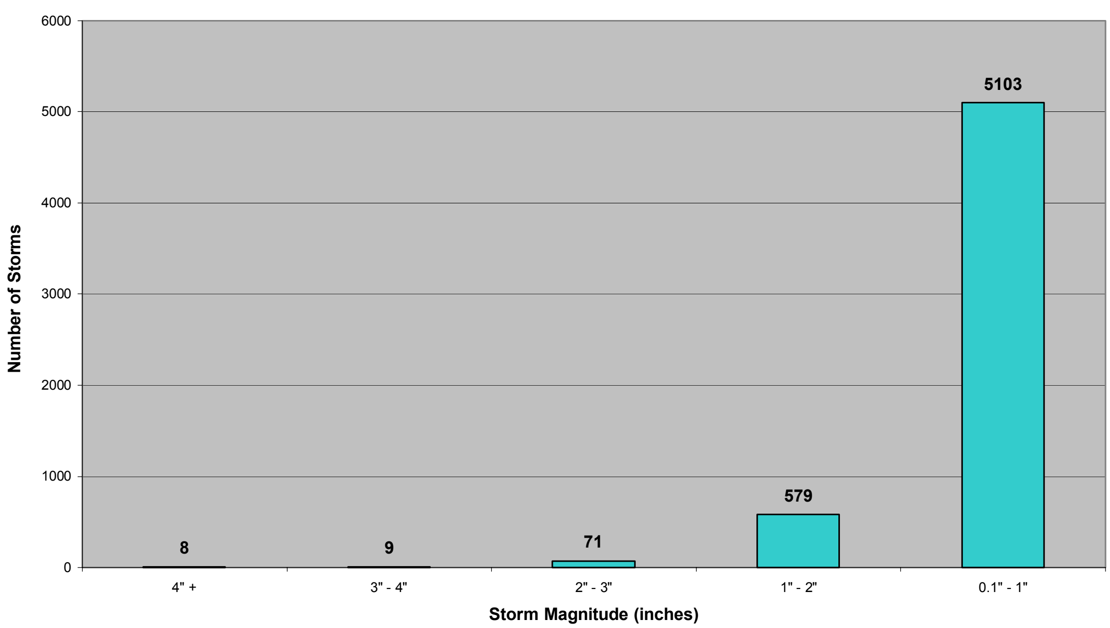

Figure 2-5. Number of Storm Events by Event Magnitude, (Cahill, 2004)

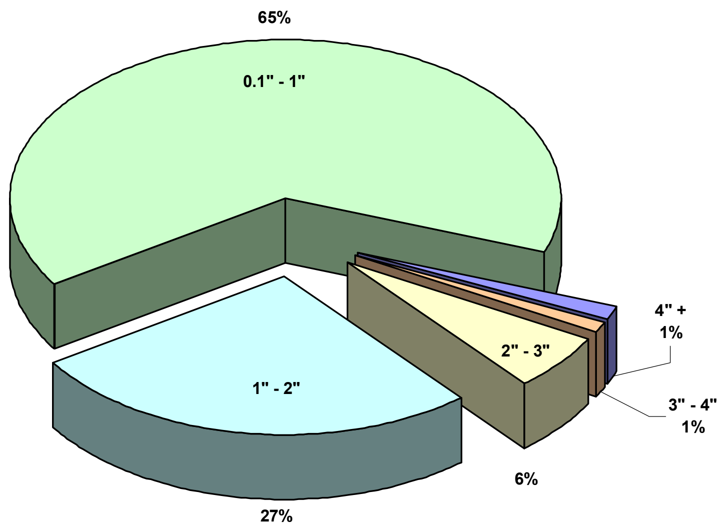

Figure 2-6. Distribution of Precipitation by Event Magnitude (PA State Climatological Office, 1926 - 2003)

2.1.2 Infiltration

- **On an average annual basis, most rainfall soaks into the soil mantle under natural conditions.**

On an average annual basis, most rainfall soaks into the soil mantle under natural conditions. This is because there are so many small storm events that produce little if any runoff from natural surfaces, as indicated in Figure 2-1. The dominance of infiltration in the overall water cycle is especially true when considering that most rainfall events are small. One inch of rain, falling in undisturbed woodlands on the moderately draining soils typical in much of the state, produces little or no runoff. Most rainfall soaks into the soil, is stored in surface depressions, or is intercepted by vegetation as shown in Figure 2-7. Even in a larger rainfall event of 3.27 inches in 24 hours, the natural system absorbs 2.24 inches according to the Runoff Curve Number Method, or almost 70 percent of the rainfall.

2.1.3 Evapotranspiration

- **Most of the rainfall that soaks into the soil returns to the atmosphere through evaporation and transpiration through vegetation.**
- **Evapotranspiration varies with season and with type of vegetative cover.**

Most of the rainfall that soaks into the soil returns to the atmosphere through evaporation and transpiration through vegetation as shown in Figure 2-2. The vegetation itself also intercepts and slows the rainfall, reducing its erosive energy, reducing overland flow of runoff, and allowing infiltration and evaporation to occur. The root systems of plants provide pathways for water movement.

Some precipitation passes the root zone and is able to move farther downward to the zone of saturation, or water table. Weeks or months later this precipitation emerges from springs or seeps as groundwater recharge or baseflow. When the natural vegetative cover is removed, all of these processes are altered, and the net result is a significant increase in stormwater runoff volume.

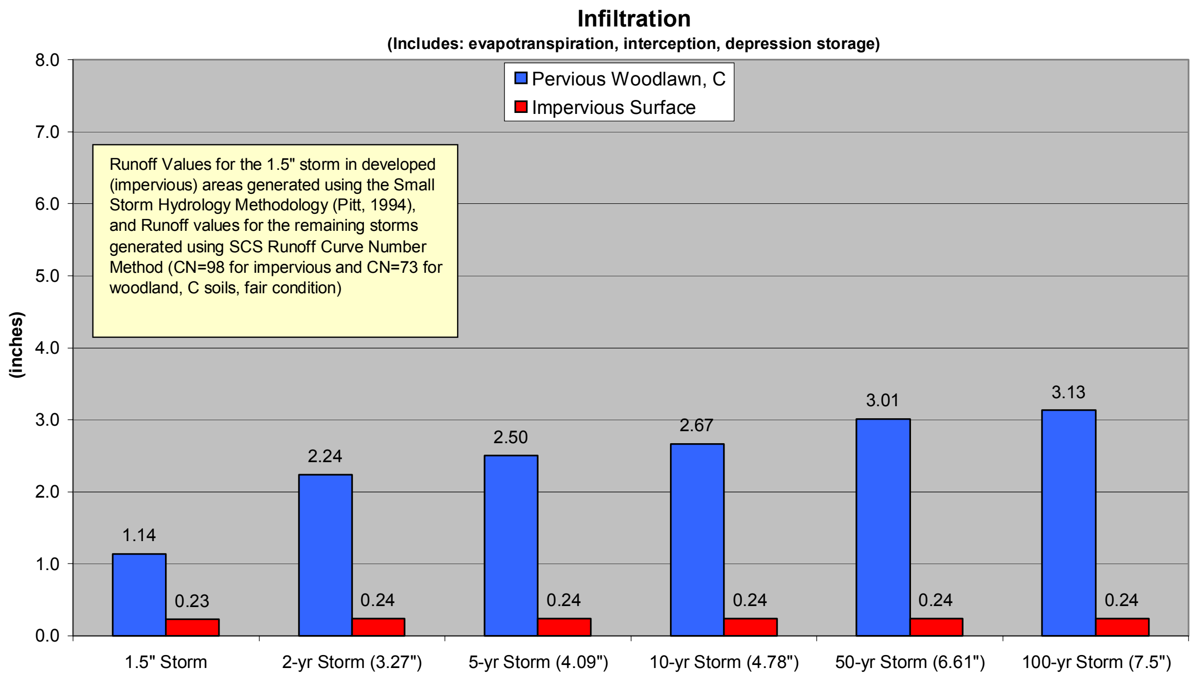

Figure 2-7. Maximum Infiltration Values for Two Land Covers for Various Size Storms

Evapotranspiration varies tremendously with season and with type of vegetative cover. Evapotranspiration can be a dominant force in warm weather months with good woodland cover, fully developed leaf mass, and the hot summer temperatures of July and August. Trees can effectively evapotranspire most, if not all, of the precipitation, which falls in summer thunderstorms and rain showers. As the leaf mass diminishes and as temperatures decline, evapotranspiration dramatically declines in November and December. During these periods, much more of the precipitation infiltrates and moves through the root zone to recharge groundwater and the groundwater level generally rises. Evapotranspiration also varies by the type and extent of vegetation comprising the land cover. A lawn, with its short root system, provides substantially less evapotranspiration than healthy woodland or meadow.

By measuring rainfall and stream flow, which includes both stormwater runoff and the flow of groundwater to streams, hydrologists can estimate the amount evapotranspiration occurring in a watershed. The water cycle as indicated in Figure 2-2 estimates an evapotranspiration volume of 21 inches per year for the Brandywine Creek Watershed. This value is derived by subtracting the volumes of runoff and groundwater discharge (as measured by a stream gage) from the total measured rainfall.

2.1.4 Groundwater Recharge and Stream Base Flow

- **After soaking into the soil, precipitation continues to move by gravity through the soil, ultimately reaching the groundwater table and replenishing the aquifer.**
- **At the groundwater table, water continues to move down gradient by gravity, and eventually intersects the land surface at springs, seeps, and wetlands.**

After soaking into the soil, precipitation continues to move by gravity through the soil, ultimately reaching the groundwater table and replenishing the aquifer. As less permeable soils, clay layers, and rock strata are encountered, water will move both vertically and diagonally, following the path of least resistance. The actual movement of water through the subsurface pathways is vastly more complex than illustrated in Figure 2-8, though the basic concept is correct. The zone of saturation is commonly referred to as the groundwater table. The groundwater table rises and falls depending on the amount of rainfall , the time of year, and other local influences (wells, mining, etc.). The water cycle shown in Figure 2-8 estimates that approximately 12 inches of the 45 inches of average annual precipitation in this natural watershed system finds its way to the groundwater table. It is important to keep in mind that groundwater recharge (the estimated 12 inches) is a small part of the volume of infiltration into the soil mantle (estimated at 32 inches).

At the groundwater table, water continues to move down gradient by gravity, and eventually intersects the land surface at springs, seeps, and wetlands. This groundwater outflow or discharge forms first order streams and wetlands. This movement tends to be quite slow and gradual (weeks and months). The water table will eventually intersect with the land surface and groundwater and discharge as springs, seeps, and wetlands (Figure 2-9) to form "first order" streams. This groundwater discharge becomes stream base flow and occurs during both wet and dry periods. Much of the time, all of the

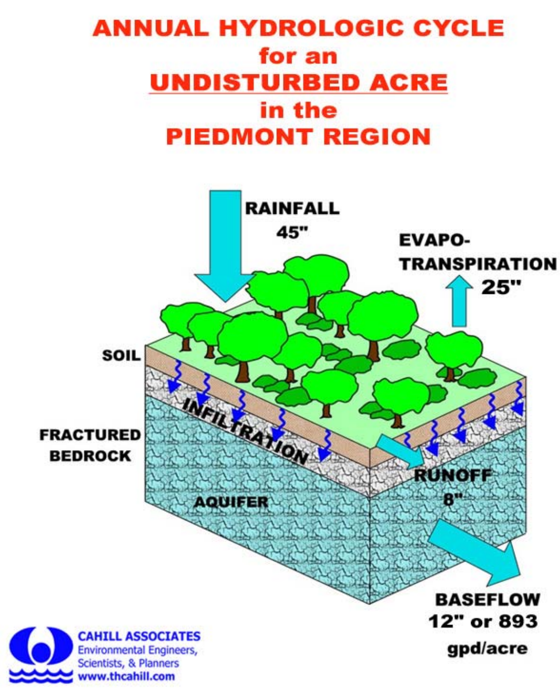

Figure 2-8. Annual Hydrologic Cycle for an Undisturbed Acre in the Piedmont Region.

natural flow in a stream is from groundwater discharge. In this sense, groundwater discharge can be seen as the "life blood" of streams, supporting all water-dependent uses, including critical aquatic communities which are so vital to Pennsylvania rivers. Impacts to stream base flow take a heavy toll on the stream quality and the ecological communities dependent on continuous flow. Reducing groundwater recharge reduces the stream base flow.

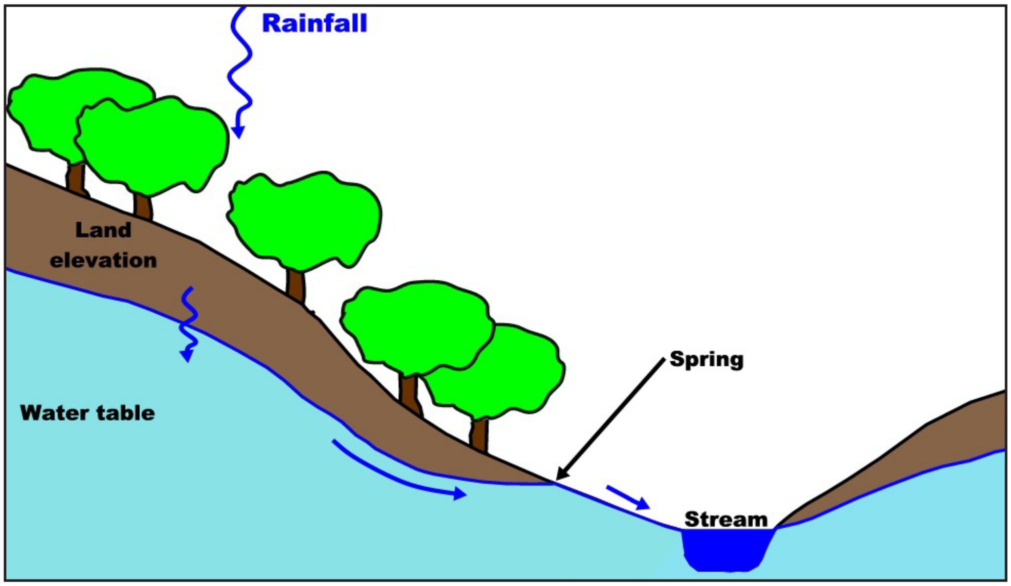

Figure 2-9. Groundwater Feeding Stream Baseflow, (Cahill, 2000)

2.1.5 Surface Runoff

- **Surface runoff (stormwater) comprises a relatively small part of the total water cycle in a natural system, and contributes to stream flow about 25 to 30 days a year.**

Surface runoff (stormwater) comprises a relatively small part of the total water cycle in a natural system, and contributes to stream flow about 25 to 30 days a year. Runoff occurs when the rate of rainfall or amount of rainfall exceeds what the soil can absorb as the soil becomes saturated. In undeveloped watersheds, smaller storms of less than 1-inch rainfall may not produce any significant runoff. On an annual basis, about 20 percent of the total average annual rainfall (8 to 10 inches) becomes surface runoff and stream flow in undeveloped watersheds (see Figure 2-8). In terms of timing and frequency, surface runoff comprises a significant portion of the total daily stream flow for only about 25 to 30 days in an average year in most natural watersheds.

2.2 Hydrologic Impacts of Development and Impervious Surfaces

- **As land development occurs, the amount of impervious surfaces – pavement and buildings - increases. Because of this, the amount of stormwater runoff also increases.**
- **As the amount of runoff increases, the amount of water that soaks into the soil decreases. Groundwater recharge, evapotranspiration, and stream baseflow all decrease.**
- **Modern construction methods often reduce the ability of soils to absorb rainfall. Often, more runoff occurs from lawns than from undisturbed natural areas.**
- **After development, stormwater runoff occurs during small rainfall events that previously did not generate runoff. The <u>frequency</u> of runoff events increases.**
- **Paved surfaces and storm sewers convey water <u>faster</u> than natural systems. Both the amount of runoff and the rate of flow increase.**
- **The increased amount of runoff and increased rate of flow often exceed the capacity of local swales and streams. Erosion and stream channel changes may occur.**
- **As the shape of the stream channel changes to accommodate more runoff, aquatic habitat is often lost or altered, and aquatic species may decline.**
- **As groundwater recharge is reduced, stream baseflow also decreases and may further stress aquatic communities.**
- **The runoff from impervious surfaces may be warmer or colder than the streamflow, and can impact and change the aquatic community.**
- **Impervious surfaces and maintained landscapes generate pollutants that are conveyed downstream.**

As land development occurs, the amount of impervious surfaces – pavement and buildings - increases. Because of this, the amount of stormwater runoff also increases, as shown in Figure 2-10. Small frequent storm events produce little if any runoff from woods and meadows. As these areas become impervious, water that previously soaked into the soil becomes runoff. The volume of runoff – from a single rainfall event or on an annual basis – increases dramatically. Nearly all of the rainfall on impervious surfaces may become runoff, causing a dramatic increase in the volume of runoff.

As the amount of runoff increases, the amount of water that soaks into the soil decreases. Groundwater recharge, evapotranspiration, and stream baseflow all decrease. Because the amount of rainfall is finite, increasing one component of the "water cycle" decreases one or more of the other elements. An increase in the volume of runoff (due to impervious surfaces) means that the amount of water soaking into the soil is decreased. Evapotranspiration, groundwater recharge, and even stream flow supported by groundwater discharge decrease.

The impacts of impervious cover on the water cycle are illustrated in Figure 2-10. On an annual basis, rainfall remains constant, but the volume of runoff increases dramatically while evapotranspiration, groundwater recharge, and stream baseflow all decline. Springs, seeps, wetlands and the streams themselves – especially first order headwater streams – are jeopardized, with major ecological impacts. In watersheds that experience significant reductions in infiltration and groundwater recharge, wetlands will also be adversely impacted.

The net impact of this change in the water cycle is most profound for the smaller storms. During large storm events, even natural landscapes of woods and meadows will produce runoff as the soils become more saturated. But these natural landscapes produce little if any runoff during the smaller storms. Therefore, the <u>net</u> change in the volume of runoff that occurs during smaller storms is more significant in comparison to the rainfall amount. For the example shown in Figure 2-11, the total increase in runoff from woodland cover (with C soils) that is changed to pavement is 2.01 inches for the 2-year storm, and increases to 2.89 inches for the 100-year storm. This means that the runoff from a 2-year storm with 3.27 inches of rainfall increases by almost 200% (from 1.03 to 3.04 inches), while the increase for a much greater 100-year rainfall of 7.5 inches is only 66% (4.37 to 7.26 inches). A much greater proportion of small storm rainfall occurs as runoff related to impervious surfaces.

Modern construction methods often reduce the ability of soils to absorb rainfall. Soils are often compacted during the land development process and the soil permeability is reduced. Soils contain "macropores", many small openings that provide a mechanism for water to move through the soil, especially under saturated conditions. These macropores are formed by small organisms, weathering processes, roots, and the movement of water. When soil is disturbed through the land development process - grading, stockpiling, heavy equipment traffic, etc. - the soil is compacted and its natural soil texture and permeability characteristics are altered and substantially reduced. Compaction can be approximated by the soil density, which can be impacted and increased so significantly that bulk density of soil approaches the bulk density of impervious constructed materials, such as concrete (Ocean County, New Jersey Soil Conservation District, 2001; Hanks and Lewandowski, 2003)

The impact of this soil compaction is that lawns and other areas that are typically considered "pervious" may have a very limited ability to absorb rainfall. These areas are sometimes referred to as "functionally impervious" because the water absorbing capacity of the soils is so low.

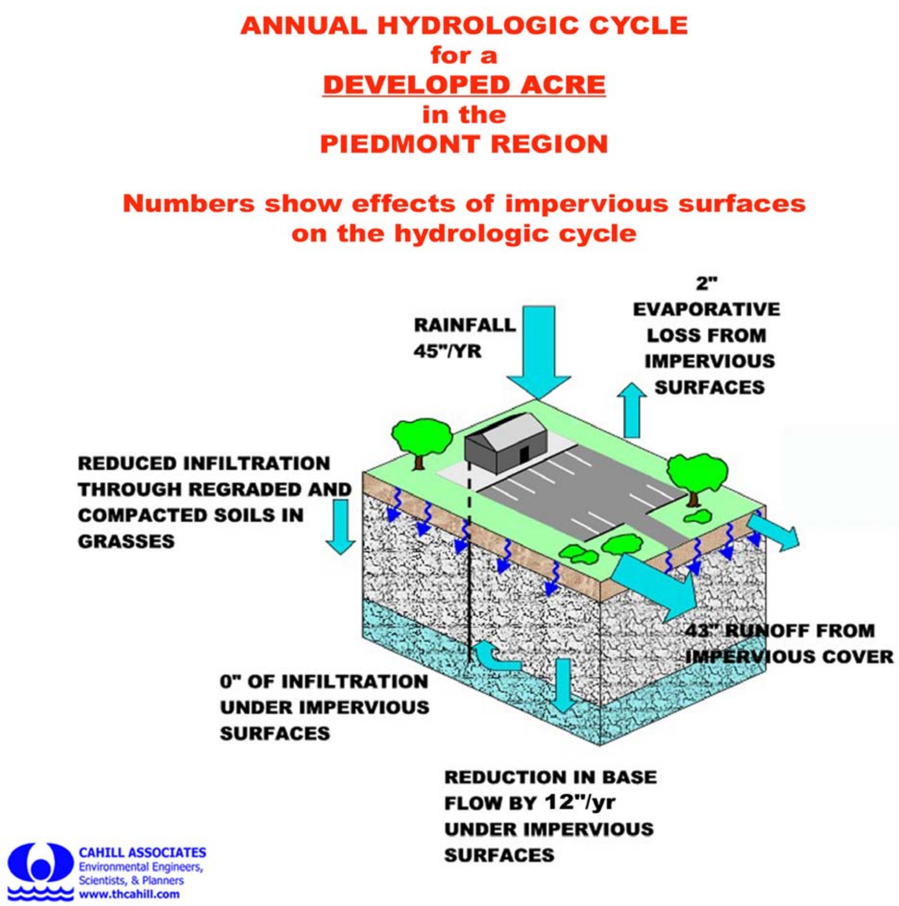

Figure 2-10. Impact of Development on Groundwater Recharge

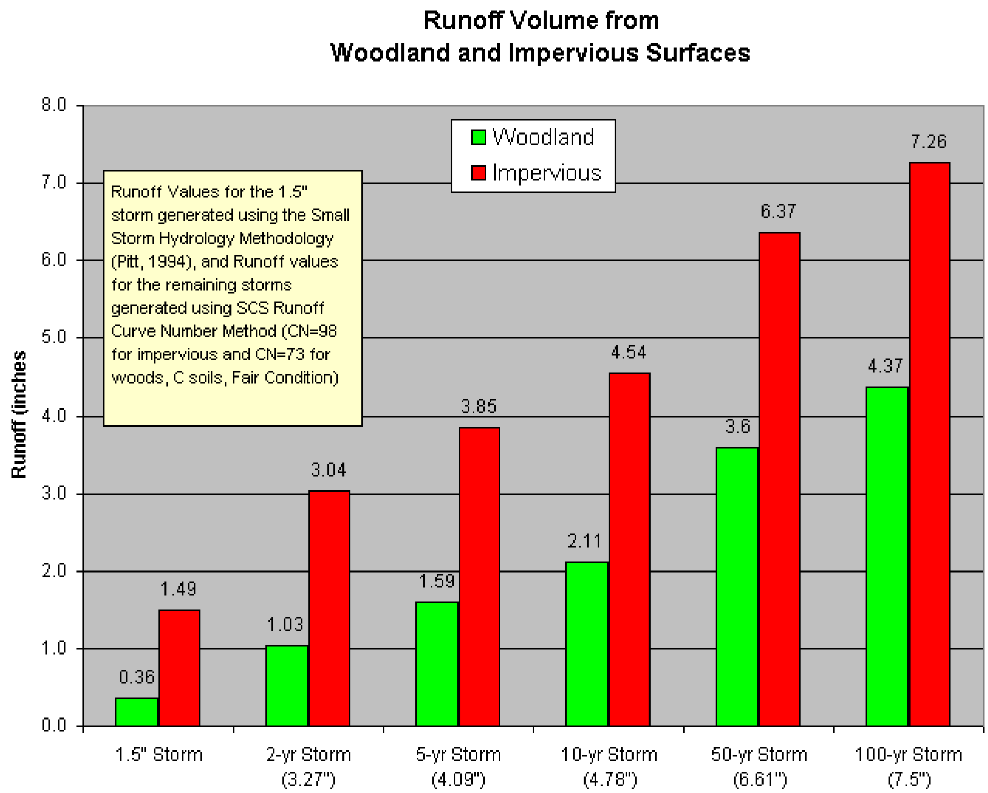

Figure 2-11. Runoff Values for Two Land Covers for Various Size Storms

After development, stormwater runoff occurs during small rainfall events that previously did not generate runoff. The frequency of runoff events increases. Because more water runs off more often, streams and swales that received surface runoff some 25 or 30 days per year begin to receive runoff nearly every time it rains significantly (approximately 75-80 times per year). Gullies begin to form in areas where once there was only sheet flow. This concept is familiar to anyone who has stood in a woodland during a rainfall – little runoff is seen in a woodland until a significant amount of rain has fallen for a significant time period. In contrast, water can be observed running along street gutters nearly as soon as rainfall begins.

Paved surfaces and storm sewers convey water faster than natural systems. Both the amount of runoff and the rate of flow increase. Not only is there more runoff more often from impervious and developed landscapes, but this runoff is often conveyed faster. Sometimes this is a function of grading – where the natural irregularities in the landscape are removed to create lawns and other landscapes– and sometimes this is a function of designed stormwater conveyance systems, intended to collect and convey water away from developed areas as quickly as possible. While this may be desired for a particular site, the downstream implications can be profound. Both large and small storm events are conveyed more quickly, and conventional detention does not reduce the flow rate for small storms. Downstream flooding and erosion may occur. Slowing the conveyance of water across a site is a significant part of better stormwater management, and a critical component of many of the BMPs in this manual.

The increased amount of runoff and increased rate of flow often exceed the capacity of local swales and streams. Erosion and stream channel changes may occur. The shape of a stream channel – its width, depth, slope, and how it moves through the landscape – is influenced by the amount of flow the stream channel is expected to carry. This stream channel "morphology" is largely determined by flows that range from the stream being "half-full" to "bank-full". These flows depths are associated with significant energy in the stream channel, and this energy shapes the channel itself. Statistically, these bank-full events occur with a frequency of approximately 18 months in a natural watershed. During larger flood events, the flow overtops the streambanks and flows into the floodplain with less impact on the shape of the stream channel.

When the volume of stormwater runoff and the rate of stormwater runoff both increase during small storm events, stream channels typically change to accommodate these flows. Because the stream is flowing at deeper depths more often, the stream will try to accommodate these higher more frequent flows by eroding stream banks or cutting down the channel bottom. Again, since traditional detention basins do not manage small storms effectively, these impacts are often most profound downstream of detention basins.

Numerous studies have documented the link between impacted stream channels and land development. The Center for Watershed Protection (Article 19, Technical Note 115, Watershed Protection Techniques 3(3): 729-734) argues that land development impacts both the geometry (morphology) and stability of stream channels, causing downstream channels to enlarge through widening and stream bank erosion. These impacts in turn degrade stream habitat and produce substantial increases in sediment loads resulting from worsened channel erosion.

As the shape of the stream channel changes to accommodate more runoff, aquatic habitat is often lost or altered, and aquatic species may decline. Studies, such as USEPA's *Urbanization and Streams: Studies of Hydrologic Impacts* (1997), conclude that land development is likely to be responsible for dramatic declines in aquatic life observed in developing watersheds. These stream channel impacts have been observed even where conventional stormwater management is applied.

The effects occur at many levels in the aquatic community. As the gravel stream bottom is covered in sediment, the amount and types of microorganisms that live along the stream bottom decline. The stream receives sediment from runoff, but additional sediment is generated as the side slopes are eroded, and much of this material is deposited along the stream bottom. Pools and riffles important to fish are lost, and the amount and type of fish diminish to less sensitive species. Trees and shrubs along the banks are undercut and lost, removing both important habitat and natural shading and cooling for the stream.

As groundwater recharge is reduced, stream baseflow also decreases and may further stress aquatic communities. As discussed above, a change in the amount of runoff changes other components of the water cycle. If groundwater recharge is reduced, stream baseflow will also eventually be reduced. This means lower flows in the stream channel when it is not raining and the stream is dependent on groundwater. Wetlands and first-order streams may reflect changes in groundwater levels most profoundly. This reduced flow also adversely stresses the aquatic community.

Many of the watersheds in urban regions already reflect this condition of exaggerated flood flow and reduced base flow, with serious water quality degradation, habitat loss, and stream channel degradation.

The runoff from impervious surfaces may be warmer or colder than the streamflow, and can impact and change the aquatic community. When the flow in a stream is comprised primarily of groundwater discharge, the temperature of the stream is buffered by the relatively constant, cool temperature of the groundwater. As the flow of groundwater decreases and the amount of surface runoff increases, the temperature regime of the stream changes. Runoff from impervious surfaces in the summer months can be much hotter than the stream temperature, and in the winter months this same runoff can be colder. These changes in temperature dramatically affect the aquatic habitat in the stream, ranging from the fish community that the stream can support to the microorganisms that form the foundation of the food chain. Important fungal communities can be lost altogether.

Impervious surfaces and maintained landscapes generate pollutants that are conveyed downstream. These pollutants include sediments, nutrients, and toxic compounds such as metals and organic compounds that are washed from the land surface by rainfall. A more detailed discussion of the types and sources of pollutants in found stormwater is provided in Section 2.4. Managing stormwater pollutants includes reducing the sources of these pollutants as well as restoring and protecting the natural systems that are able to remove pollutants. These include stream buffers, vegetated systems, and the natural soil mantle, all of which can be put to use to reduce the discharge of pollutants to waterways.

2.3 Stormwater Management

- **Comparing pre- and post-development hydrographs for development sites illustrates the post-development runoff rate increase.**
- **Detention facilities control runoff rates, but do not reduce runoff volumes.**
- **Infiltration facilities control both runoff rate and volume.**
- **The cumulative effects of increased runoff volumes from multiple detention structures frequently combine to increase downstream**

A comprehensive approach to Stormwater Management includes measures for rate control, volume, groundwater recharge, channel protection, and water quality. Although rate control for large storm events associated with extreme flooding has been the primary focus of stormwater management in the past, both rate and volume control are now understood to be critical for stormwater management.

The hydrograph defines the relationship of stormwater flow rate and volume over time. The hydrograph figure relating flow (in cubic feet per second or cfs) over time (usually in hours) is used by engineers and hydrologists to describe and quantify the surface runoff process (Figure 2-12). The hydrograph is an important tool used to understand the hydrologic response of a given rainfall event. Note that the hydrograph is a graph of the rate of runoff over time. The area beneath the hydrograph curve represents the total volume of runoff being discharged.

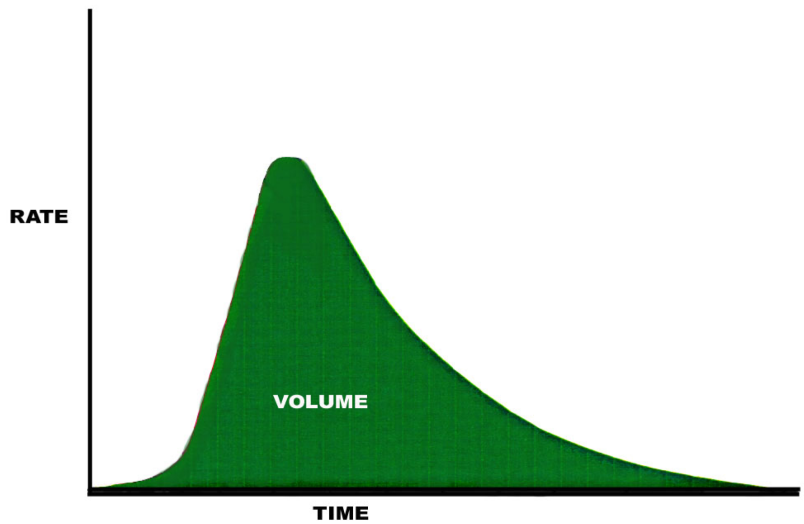

Figure 2-12. Stormwater Runoff Hydrograph

Comparing the hydrographs for development sites pre- and post-development indicates the post-development increase in runoff rate and volume. A hydrograph for a typical site before and after development has occurred is presented in Figure 2-13.

Notice that the post-development uncontrolled runoff rate rapidly increases and peaks at a runoff rate which is considerably higher than the peak rate of runoff for pre-development. This peak rate increase is primarily linked to the amount of new impervious surface created, as well as to other pervious cover changes involved in the land development process. As more of the site is disturbed and made impervious, the increase in the peak surface runoff rate grows more dramatic.

The area under the post-development uncontrolled surface runoff hydrograph is larger than the area under the pre-development surface runoff hydrograph, indicating that the total volume of surface runoff being discharged is much larger than before development. This volume is water that previously was intercepted by vegetation and surface depressions or soaked into the soil mantle.

Detention facilities control runoff rates, but do not significantly reduce runoff volumes. In an effort to prevent downstream flooding, detention systems have been used to reduce the rate of flow after development in large storms. A detention system allows the runoff to pass through an outlet flow control structure, designed to reduce the peak or maximum flow rate of discharge. As a result, some surface runoff be temporarily stored or detained in the structure. Essentially, a detention system can be compared to a large bathtub, where water is flowing in faster than flowing out in large storms so the water level in the tub rises.

The impact of a detention structure to the comparison of pre-development and post development uncontrolled hydrographs is shown in Figure 2-14. This detention control maintains the pre-development rate of runoff constant. However, because such a detention structure simply collects and slows down the increased volume of runoff, this increased volume is still discharged from the post-development site over an extended period of time.

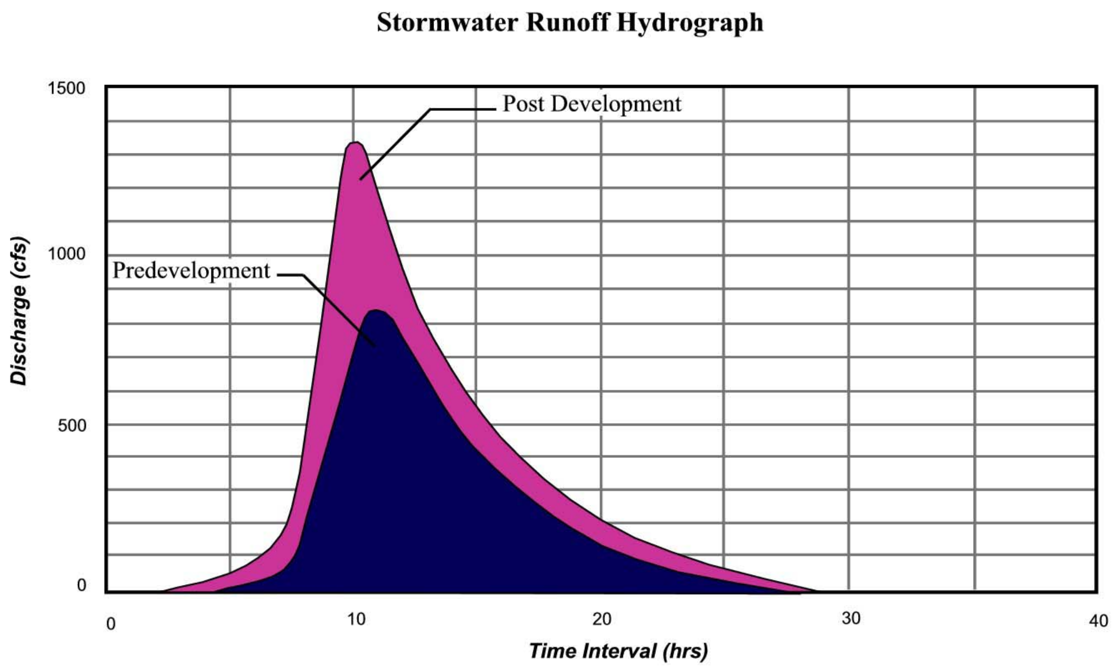

Figure 2-13. Hydrographs Comparing Pre-development Conditions to Post-development Conditions, with No Stormwater Management.

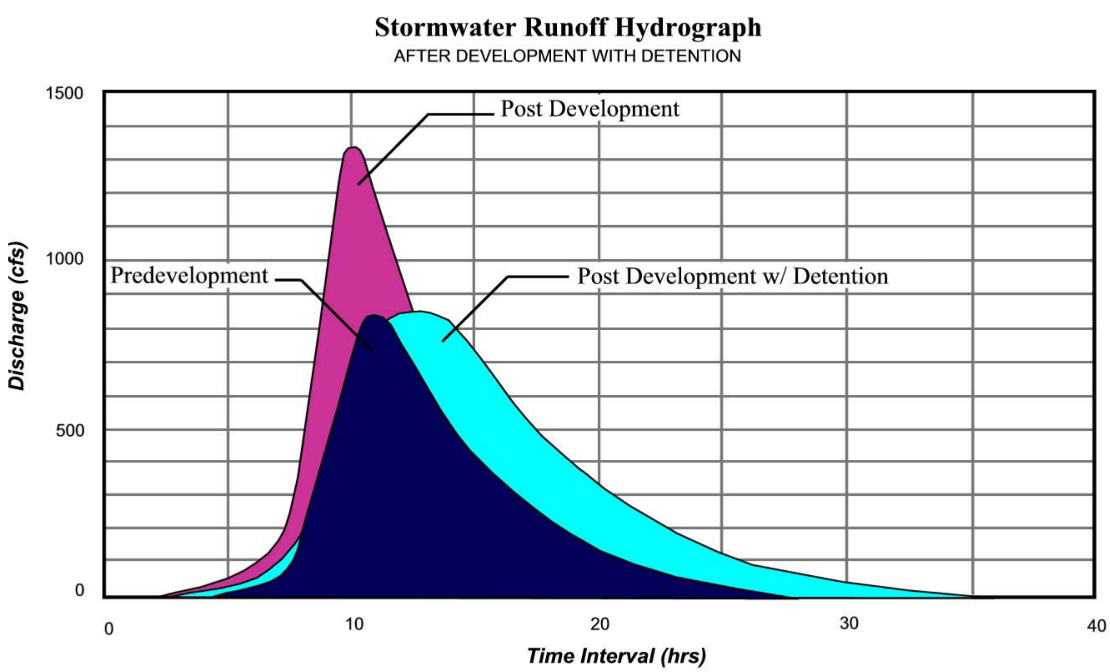

Figure 2-14. Hydrographs Comparing Pre-development Conditions to Post-development Conditions, with Detention Stormwater Management.

Also, because detention systems have traditionally been designed for large storm events (such as the 2-year through 100-year storms), smaller storms often pass through detention basins with little or no rate control. Often, the rate of flow after development is greater than the rate of flow before development for small, frequent storms.

Controlling peak flow rates may not reduce peak flow rates in the watershed. Peak rate control as a stormwater management strategy is designed site by site. If properly designed, the peak rate of flow immediately downstream from a development will not be greater than the flow rate before development (for large storm events). However, if the management perspective is extended to a broader sub-watershed or watershed scale, **the cumulative effects of the increased volume of runoff that is discharged from multiple detention structures at multiple development sites frequently combine to increase downstream peak rates of flooding.** This concept is illustrated in Figure 2-15. This figure illustrates a small watershed comprised of five hypothetical sub-basin development sites, 1 through 5, each of which undergoes development and relies on a separate peak rate control detention basin. As the storm occurs, five different hydrographs result for each sub-area and combine to create a resultant pre-development hydrograph for the overall watershed. The net result of the combined hydrographs is that the watershed peak rate actually increases considerably, because of the way in which these increased volumes are routed through the watershed system and combine downstream. Flooding worsens considerably, even though these detention facilities control the peak rate at each individual development.

As discussed and shown in Figure 2-15, multiple detention systems in a watershed can increase the severity of downstream flood flows. Perhaps an equally important finding, however, is that the duration of high flows is substantially increased. Where stream beds and banks are exposed to highly erosive flows more frequently and for longer periods, the net result is deeply incising streambeds and/or undercutting of stream banks (Maryland Department of the Environment, 2000).

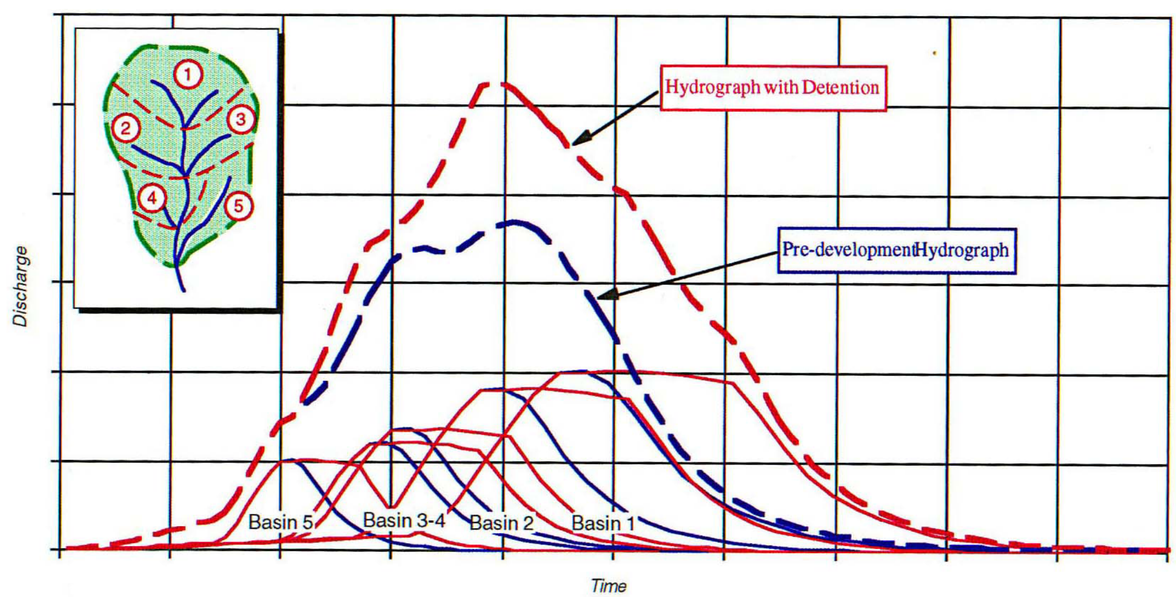

Figure 2-15. Peak Rate Control Hydrograph

Infiltration facilities control both runoff rate and volume. The limitations of detention structures and the inability to reduce the increase in runoff volume produced by impervious surfaces and compacted pervious surfaces led to the development of BMP measures that utilize the natural infiltration capacity of the soil mantle to reduce runoff volume. While this soil infiltration varies by soil series and especially by Hydrologic Soils Group, and can be constrained by site conditions such as seasonal water table (which prevents exfiltration during wet periods) and shallow bedrock (which may not allow adequate pollutant removal before entering aquifers), such measures are consistent with the hydrologic cycle. While most rainfall soaks into the soil mantle most of the time, the process of infiltration can be very slow in soils with high clay content, or underlain by "fragipan" horizons that retard infiltration. The BMPs that utilize this method of volume reduction require detailed study and testing of the soil mantle to identify any such constraints, and design the BMP accordingly.

The design of infiltration BMPs is discussed in a later section, but the resulting hydrograph can be developed from a typical design (Figure 2-16). Here the actual runoff volume that result from a parcel under development is actually less than the pre-disturbance runoff rate and volume. Derived from an actual project analysis, this figure is typical for soils that are reasonably well drained (e.g. HSG B) and fully utilized infiltration opportunities.

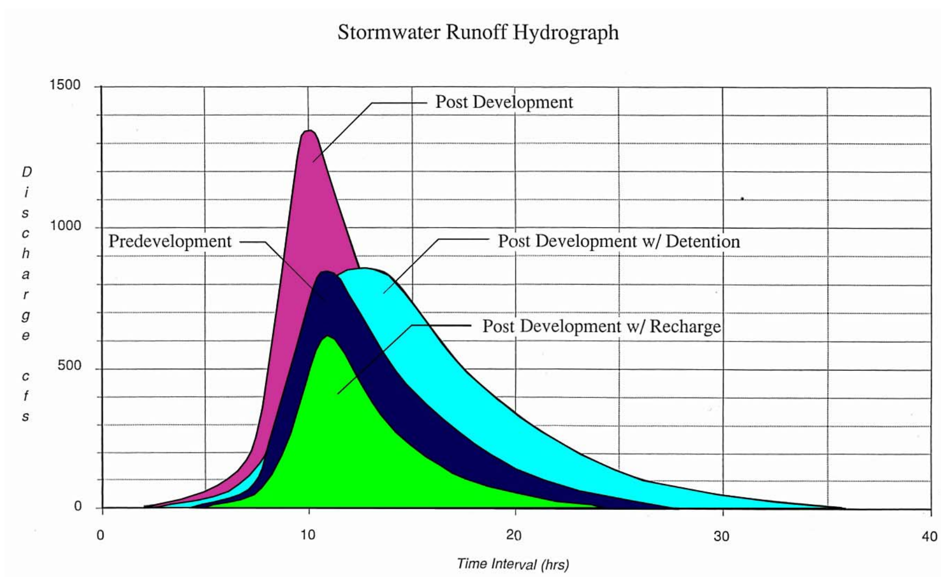

Figure 2-16. Stormwater Runoff Hydrographs Comparing Pre-development Conditions to Post-development Conditions, with Detention and Recharge Stormwater Management.

Stream channel and overall morphological impacts increase with increased frequency of bank full flow. Although Valley Creek in the Schuylkill River watershed contains some 150 or more detention basins built over the past twenty-nine years, the frequency of bank full stream flow has decreased from 18 months to less than three months (Figure 2-17), with corresponding riparian damage in the lower reaches of the stream. This increased flooding results in serious impacts to both the channel itself and the aquatic community within that system. Impacts can include significant stream bank erosion, bank undercutting, elimination of meanders, channel widening, increased sedimentation and deposition, elimination of pools and riffles, and reduced stream ecological value. Over time, these impacts can transform the stream from a high quality water, with excellent species diversity and richness, literally to functional storm sewers (McCandless and Everett, 2002; McCandless, 2003).

Figure 2-17. Impacts to Streambank Morphology in Valley Creek.

2.4 Stormwater and Water Quality

- **Stormwater quantity and quality are inextricably linked and need to be managed together.**
- **Non-point source (NPS) pollutants include: sediment, organic detritus, phosphorus and nitrogen forms, metals, hydrocarbons, and synthetic organics.**
- **The two physical forms of NPS pollutants are particulates and solutes.**
- **Pollution prevention through use of Non-Structural BMPs is very effective.**
- **A variety of Structural BMPs, incorporating settling, filtration, biological transformation and uptake, and chemical processes, can also be used.**
- **NPS pollutant loadings for land surfaces can be estimated by applying average concentrations for the volume of runoff produced.**

Stormwater quantity and quality are inextricably linked and need to be managed together. Although the most obvious impact of land development is the increased rate and volume of surface runoff, the pollutants transported with this runoff comprise an equally significant, if not more significant impact. In fact, the distinction between water quality and water quantity is imposed and somewhat artificial. Management strategies that address quantity will in most cases address quality, especially through the use of infiltration BMPs.

Non-point source (NPS) pollutants include: sediment, organic detritus, phosphorus and nitrogen forms, metals, hydrocarbons, and synthetic organics. As land development increases the rate and volume of stormwater runoff, increased runoff scours the land surfaces, both impervious and pervious. The kinetic energy of the raindrops and runoff suspends the solid pollutant particles and transports them with the runoff. The pollutants that can dissolve in the rainfall become solutes - and move in the runoff in a more distributed concentration depending on the contributing areas. The resulting turbid flow of runoff carries a mix of pollutants. These NPS pollutants generally are materials that are deposited on the land surface. NPS loads are generated in higher quantities from some impervious areas that are often defined as "hot spots," such as fueling islands, trash dumpsters, industrial sites, fast food parking lots, and heavily traveled roadways.

Many so-called pervious surfaces, such as the chemically maintained lawns and landscaped areas, also add significantly to the NPS load, especially where these pervious areas drain to impervious surfaces (such as gutters) with storm sewers that drain directly to surface waters. The soil compaction process applied to many land development sites results in a vegetated surface that is close to impervious in many instances, and produces far more runoff than the original soil and vegetative cover. New lawn surfaces are often heavily loaded with fertilizers that result in polluted runoff that degrades downstream waterbodies.

Some NPS pollutants such as oxides of Sulfur and Nitrogen are even air-borne (dust fall), deposited onto the land (or water) surface and then carried into receiving waters, although air-borne pollutants in most cases comprise a relatively small fraction of the total NPS pollutant load. Once in the stream, the increased volume and rate of runoff produce additional sediment pollution from stream bank erosion by undercutting and re-suspension of sediment.

The two physical forms of NPS pollutants are particulates and solutes. One very important distinction for NPS pollutants is the extent to which pollutants are particulate in form, or dissolved in the runoff as solutes. The best example of this comparison is two common fertilizers components: phosphorus (TP) and nitrate (NO_3-N). Phosphorus typically occurs in particulate form, usually bound to colloidal soil particles. Because of this physical form, stormwater management practices that rely on physical filtering and/or settling out of sediment particles can be quite successful for phosphorus removal, although the Phosphorus is largely bound to the smallest particles (colloids) and may require more extensive removal measures. In stark contrast is nitrate, which tends to occur in highly soluble forms, and is unaffected by many of the structural BMPs discussed later. As a consequence, stormwater management approaches for nitrate must be quite different in approach, with wetlands/wet ponds and other biological approaches being more effective, especially where anaerobic conditions can be achieved and where denitrification can occur. Non-Structural BMP's (Section 5) are in fact the best approach for nitrate reduction in runoff, and where the surface application of Nitrate fertilizer can be reduced or avoided, that is the easiest and most effective BMP.

Particulates: NPS pollutants that move in association with or attached to particles include total suspended solids (TSS), phosphorus (TP), most organic matter (as estimated by COD), metals, and some herbicides and pesticides. Kinetic energy keeps particulates in suspension and they do not settle out easily. For example, an extended detention basin offers a good method to reduce total suspended solids, but is less successful with TP, because much of the TP load is attached to small colloids.

If the concentration of particulate-associated NPS pollutants in storm runoff, such as TSS and TP, is measured in the field during a storm event, a significant increase in pollutant concentration corresponding to but not synchronous with the surface runoff hydrograph is usually observed (Figure 2-18). This change in pollutant concentration is referred to as a "chemograph", and has contributed to the concept of a "first flush" of NPS pollution. In fact, the actual transport process of NPS pollutants is somewhat more complex than "first flush" would indicate, and has been the subject of numerous technical papers (Cahill et al, 1974; 1975; 1976; 1980; Pitt, 1985, 2002). To accurately measure the total mass of NPS pollution transported during a given storm event, both volume and concentration must be measured simultaneously, and an integration performed to estimate the mass conveyed in a given event. To fully develop an NPS pollutant load for a watershed, a number of storm events must be measured over several years. The dry weather

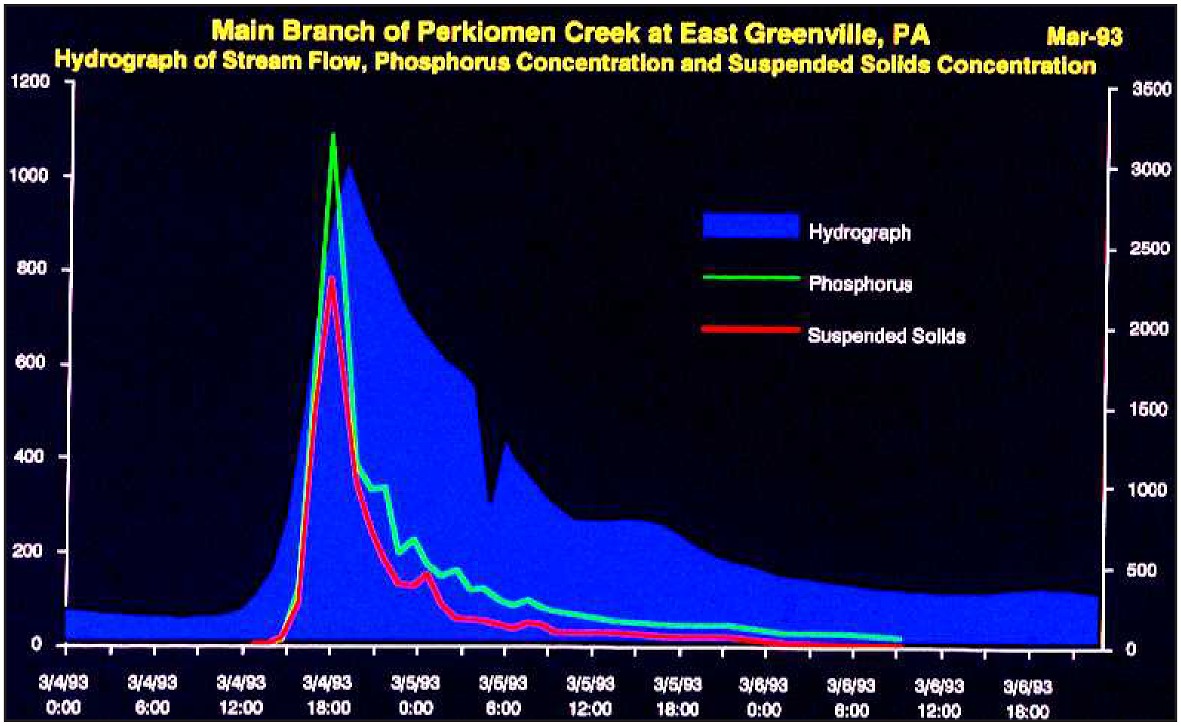

Figure 2-18. Chemograph of Phosphorous and Suspended Solids in Perkiomen Creek (Cahill, 1993).

chemistry is seldom indicative of the expected wet weather concentrations, which can be two or three orders of magnitude greater.

Because a major fraction of particulate-associated pollutants is transported with the smallest particles, or colloids, their removal by BMP's is especially difficult. These colloids are so small that they do not settle out in a quiescent pool or basin, and remain in suspension for days at a time, passing through a detention basin with the outlet discharge. It is possible to add chemicals to a detention basin to coagulate these colloids to promote settling, but this chemical use turns a natural stream channel or pond into a treatment unit, and subsequent removal of sludge may be required. A variety of BMP's have been developed that serve as runoff filters, and are designed for installation in storm sewer elements, such as inlets, manholes or boxes. The potential problem with all measures that attempt to filter stormwater is that they can quickly become clogged, especially during a major event. Of course, one could argue that if the filter systems become clogged, they are performing efficiently, and removing particulate material from the runoff. The major problem then with all filtering (and to some extent settling) measures is that they require substantial maintenance. The more numerous and distributed within the built conveyance system that these BMP's are situated, the greater the removal efficiency, but also the greater the cost for operation and maintenance.

Solutes: The NPS pollutants that are soluble, or quickly dissolve during runoff, generally do not exhibit any increase in concentration during storm event runoff, and in fact may exhibit a slight dilution over a given storm hydrograph. Solutes include nitrate, ammonia, salts, organic chemicals, many pesticides and herbicides, and petroleum hydrocarbons (although portions of the hydrocarbons may bind to particulates and be transported with TSS). Regardless, the total mass transport of soluble pollutants is dramatically greater during runoff because of the volume increase. In many watersheds, the storm transport of soluble pollutants can represent a major portion of the total annual discharge for a given pollutant, even though the absolute concentration remains relatively constant. For these soluble pollutants, dry weather sampling can be very useful, and often reflects a steady concentration of soluble pollutants that will be representative of high flow periods.

Some soluble NPS pollutants can be found in the initial rainfall, especially in regions with significant emissions from fossil fuel plants. Precipitation serves as a "scrubber" for the atmosphere, removing both fine particulates and gases (NO_X and SO_X), and creating an NPS load. Chesapeake Bay scientists have measured rainfall with NO_3 concentrations of 1 to 2 mg./l, which could comprise a significant fraction of the total input to the Bay. Other rainfall studies by NOAA and USGS have resulted in similar conclusions. Impervious pavements also generate nitrate load, reflecting a mix of deposited sediment, vegetation, animal wastes, and human detritus of many different forms.

Pollution prevention through use of Non-Structural BMPs is very effective. A variety of Structural BMPs, incorporating settling, filtration, biological transformation and uptake, and chemical processes can also be used. Stormwater-related pollution often can be reduced if not eliminated through preventive Non-Structural BMPs (Section 5), but not all stormwater pollution can be avoided. As the various Structural BMPs (Section 6) that remove NPS pollutants from the runoff are evaluated, many will make use of natural pollutant removal processes. These NPS reduction processes are essential elements in many of Structural BMPs, as discussed in Section 6. These "natural" processes tend to be associated with and rely upon both the existing vegetation and soil mantle. Thus preventing and minimizing disturbance of site vegetation and soils is essential to successful stormwater management.

Settling: Particles remain suspended in stormwater as long as the energy of the moving fluid is greater than the pull of gravity. In a natural stream, the stormwater that overflows the banks slows and is temporarily stored in the floodplain, which allows for sediment settling, and the building of the alluvium soils that comprise this floodplain. As runoff passes through any type of man-made structure, such as a detention basin, the same process takes place, although not as efficiently as in a natural floodplain. Where it is possible to create micro versions of runoff ponds (rain gardens), distributed throughout a site, the same settling effect will result. The major issue with settling processes is that much of the NPS pollutant load is not subject to gravitational settling, as discussed above.

Filtration: Another natural process is physical filtration. Filtration through the soil is by far the most efficient NPS removal process for particulates, provided that care is taken to prevent clogging of the soil. As precipitation conveying NPS pollutants infiltrates through the surface vegetative layer and then percolates down through the soil, larger particles are physically filtered from stormwater. Surface vegetative cover provides a similar type of physical filtering, the denser the better. Runoff that is concentrated, even with well-vegetated surfaces, can overcome the resistance of the standing biomass and exceed its ability to remove particles, resulting in reduced removal. Therefore it is important to minimize concentrated flows, slowing and distributing the runoff over a broad vegetated area.

Although true "sheet flow" is never achieved on a natural landscape, the vegetated surface, ranging from grass blades to underbrush, can effectively to remove larger pollutant particles. Stormwater flow through a relatively narrow natural riparian buffer of trees and herbaceous understory growth has been demonstrated to physically filter surprisingly large proportions of particulate-form stormwater pollutants. Both filter strip and grassed swale BMP's rely very much on this surface filtration process, as discussed in Section 6.

Biological Transformation and Uptake/Utilization: Though grouped here as one process, this category includes an array of different processes that reflect the remarkable complexity of different surface vegetative types, their varying root systems, and their different needs and rates of transformation and utilization of different "pollutants," especially nutrients. An equally vast and complex community of microorganisms exists below the surface within the soil mantle, and though more micro in scale; the myriad natural processes occurring within this soil realm is just as remarkable.

Two nutrients, phosphorus and nitrate, are essential to plant growth and therefore are taken up through the root systems of the various vegetative types, from grasses to shrubs to trees. Nitrogen transformations are quite complex, but the muck bottoms of natural wetlands offer one environment that allows the important process of denitrification to occur, through the action of widely present facultative heterotrophs, which function to facilitate the exchange of ions in the absence of oxygen and ultimately convert nitrates for release in gaseous form. Where nitrates in runoff are conveyed through these systems, they can remove the nitrates from solution. The caution in terms of a wetland or similar surface BMP is that if the vegetation dies at the end of a growing season and the detritus is discharged from the wetland, nitrogen compounds are released back into the system. The guidance for BMP applications is that if biological transformation processes are considered, care must be taken to remove and dispose of the biomass produced in the process.

Chemical Processes: For that stormwater which has infiltrated into the soil mantle and then moves vertically toward groundwater aquifers, various chemical processes also occur within the soil. Important processes occurring include adsorption through ion exchange and chemical precipitation. Cation Exchange Capacity (CEC) is a rating given to soil, which relates to the organic content of the soil and its ability to remove pollutants as stormwater infiltrates through the soil. Adsorption will increase as the total surface area of soil particles increases; this surface area increases as soil particles become smaller, tighter, and denser. For example, clay soils have better NPS reduction performance than sandy soils, and their slower permeability rate has a positive effect. CEC values typically range from 2 to 60 milli-equivalents (meq) per 100 grams of soil. Coarse sandy soils have low CEC values and therefore are not especially good stormwater pollutant removers. A value of 10 meq. is often considered necessary to accomplish a reasonable degree of NPS pollutant removal.

NPS pollutant loadings for land surfaces can be estimated by applying average concentrations for the volume of runoff produced. The primary stormwater quality objective is to reduce (or prevent) the transport of NPS pollutants to waterbodies. Careful consideration of how this transport occurs and the initial sources of the various pollutants are essential. One difficulty in defining exactly how much NPS pollution is generated from a watershed during a given period is that most of the NPS transport occurs during the relatively short span of heavy rainfall periods, perhaps a total of 25 to 30 days in a given year. This is especially true for those NPS pollutants that are transported by or associated with particulate transport. If a sufficient database can be developed for a range of runoff events, then annual mass loadings can be developed. However, for individual runoff events, a "flow weighted mean concentration" can be estimated for NPS transport load analysis. That is, if our site analysis estimates the volume of runoff generated for each different portion of the built site (rooftop, parking area, lawn, etc.), a loading can be estimated by storm event or on an annual basis.

Table 2-2 summarizes a set of values of both particulate and soluble pollutants that can be applied as the average concentration in stormwater runoff. Lacking little current data for the chemistry of storm runoff in the surface waters of Pennsylvania, various sources of representative NPS concentrations have been used for this initial water quality analysis. The table summarizes event mean concentrations for stormwater runoff, derived from a number of studies (USEPA, 1981; Cahill et al, 1978, 1984, 1997; Philadelphia Water Department, 2000). These concentrations, expressed in milligrams per liter (mg./l), are considered to reflect the wet weather transport mechanisms discussed earlier, and are intended to estimate mass transport during runoff, based on the volume and this mean concentration value. This data is of greatest interest in evaluating the potential NPS load from future land use conditions. These estimates of how much of a given pollutant will be contained in the runoff from a given land use is a less than perfect calculation, and the values used should be modified as specific site information is gathered in the future.

One of the most challenging technical issues considered in this Manual involves the selection of BMP's that have a high degree of NPS reduction or removal efficiency. In the ideal, a BMP should be selected that has a proven NPS pollutant removal efficiency for all pollutants of importance, especially those that are critical in a specific watershed (as defined by a TMDL or other process). Both Non-Structural BMP's in Section 5 and Structural BMP's in Section 6 are rated in terms of their pollutant removal performance or effectiveness. The initial BMP selection process analyzes the final site plan and estimates the potential NPS load, using Table 2-2 and Appendix A. The required reduction percentage for representative pollutants (such as 85% reduction in TSS and TP load and 50% reduction in the solute load) is achieved by a suitable combination of Non-Structural and Structural BMP's. This process is described in more detail in Section 9.

Table 2-2. Wet Weather Event Mean Concentration, (Derived from EPA, 1981; Cahill et al, 1978, 1984, and 1997; Philadelphia Water Department 2000, and other references - see Appendix A).

LAND COVER CLASSIFICATION	**POLLUTANT**						
	Total Suspended Solids, ***(mg/l)***	**Total Phosphorus,** ***(mg/l)***	**Nitrate,** ***(mg/l as N)***	**Chemical Oxygen Demand,** ***(mg/l)***	**Total Petroleum Hydrocarbons,** ***(mg/l)***	**Lead,** ***(mg/l)***	**Copper,** ***(mg/l)***
Pervious Surfaces							
Forest	39	0.15	0.17	40	0.0	0.0015	0.008
Cleared Woodland	47	0.19	0.30	40	0.0	0.0015	0.008
Fert. Planting Area	55	1.34	0.73	53	0.0	0.0050	0.010
Rough Grass	180	0.40	0.44	53	0.0	0.0050	0.010
Lawn	180	2.22	1.46	60	0.0	0.0050	0.010
Playfield	200	1.07	1.01	65	0.0	0.0050	0.010
Impervious Surfaces							
Rooftops	21	0.13	0.32	1	0.6	0.0027	0.024
Roads & pavements	135	0.43	0.60	85	9.0	0.0110	0.047
Walks & misc.	60	0.46	0.47	50	0.4	0.0090	0.014

2.5 Major Watersheds and Stream Systems

- **Pennsylvania can be divided into major watersheds or basins that provide important planning framework for stormwater management.**
- **The smallest hydrologic drainage areas (1st order streams), are also important for stormwater management and BMP design.**
- **The patterns of surface water flow reflect topography and groundwater flow.**

Pennsylvania includes several major watersheds or basins which are important for stormwater management. Understanding watersheds is an important aspect of the natural hydrologic system and relates to the management of stormwater runoff in important ways. Pennsylvania's 43,600 square miles lie generally within five major basins (Figure 2-19): the Delaware River (6,470 sq. mi), Susquehanna River (20,926 sq. mi), Potomac River (1,582 sq. mi), Ohio River (15,442 sq. mi), and the Great Lakes of Erie and Ontario (603 sq. mi). Almost half (46 percent) of Pennsylvania drains to the Susquehanna River which runs through the center of the state, flowing into the Chesapeake Bay. Pennsylvania comprises almost a third of the total 64,000 square miles tributary to Chesapeake Bay, making it a major contributor of the various pollutants which are so critical to the Bay.

The second largest river basin in the state is the Ohio River Basin, draining over 34 percent of Pennsylvania, flowing south from the Allegheny basin and north from the Monongahela, before flowing west at Pittsburgh to ultimately join the Mississippi River. The Delaware River Basin is the third largest stream system, draining the eastern 14 percent of the state and flowing into the Delaware Estuary (13,000 sq. mi.), also an important ecosystem.

The headwaters of the Potomac River are situated near the south-central border of Pennsylvania, accounting for almost 4 percent of the state, and are also part of the Chesapeake drainage. The remaining land area drains two watersheds of the Great Lakes basin – the Lake Erie Basin and the Genesee River, which ultimately flows to Lake Ontario.

Each major basin is further subdivided into a number of smaller planning sub-watersheds by PADEP (approximately 100) which are also shown in Figure 2-19, each of which can be quite distinct as natural systems. It should also be noted that watershed system designation can and does take different forms, depending upon the program need and application. For example, in Section 1, Figure 1-2 illustrates the system of approximately 350 watersheds, which has been developed by PADEP for use in the Act 167 stormwater management-planning program.

The smallest hydrologic drainage areas (1st order streams) are also important for stormwater management and BMP design. Major watersheds are aggregations of smaller tributary systems. These tributaries, and the relative importance of these sub-drainage areas down to their smallest element, need to be considered in stormwater management. From a variety of perspectives, the most important or functionally valuable stream in a given watershed system is the "1st order stream," defined as that stream where the smallest continuous surface flow occurs (Horton, 1945). These streams, also called headwaters, are often formed from springs and seeps on the wooded hillsides of typical Pennsylvania watersheds, as well as from wetlands and other zones of groundwater discharge. Headwaters are the beginning of the aquatic food chain that evolves and progresses downstream and constitute the beginning of life in the stream system. As a link between groundwater and surface water, headwaters represent a critical intersection between terrestrial and aquatic ecosystems, where detritus (leaves and other organic food sources) is initially broken down by bacteria and processed

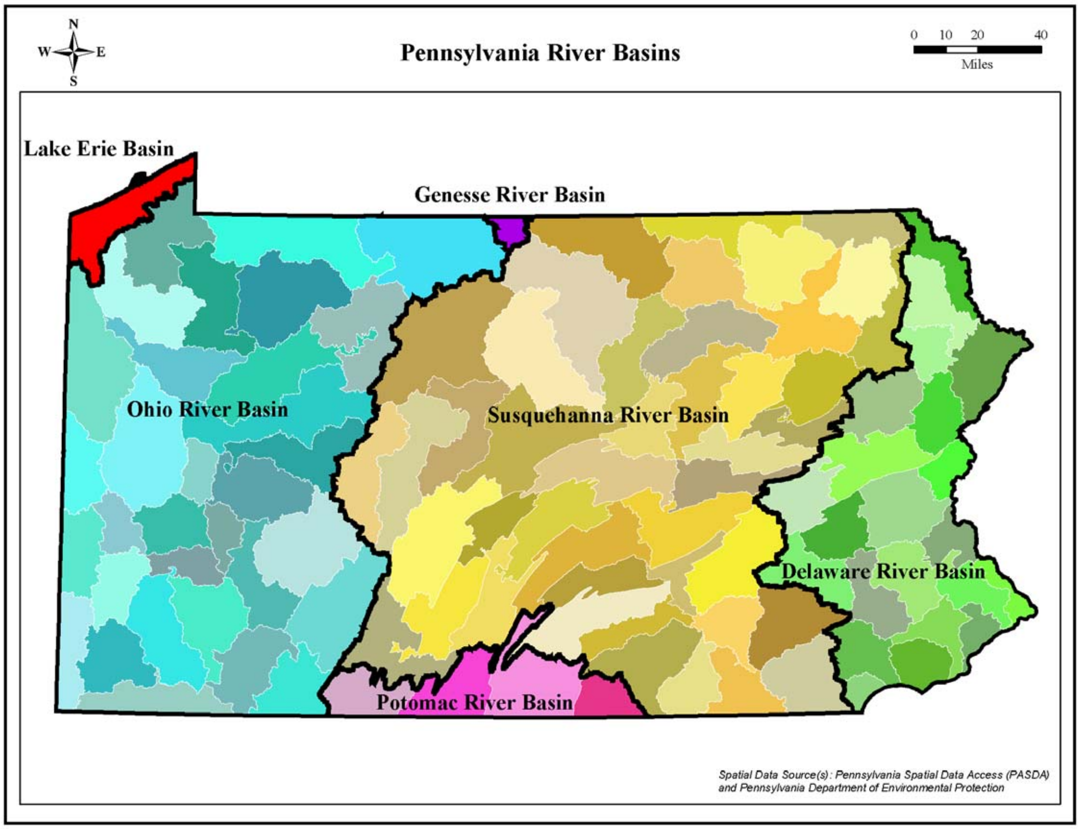

Figure 2-19. Major River Basins and Sub-basins of Pennsylvania

for use by higher organisms in the food chain. Because they combine biologically useful energy from terrestrial and aquatic production, first order streams are especially important energy sources for downstream reaches as well. As the most hydrologically and biologically sensitive elements of the drainage network, headwaters and first order streams warrant special consideration and protection in stormwater management. Their disruption or alteration cannot be fully mitigated with management techniques in the larger river.

The patterns of surface water flow reflect topography and groundwater flow. Throughout most of Pennsylvania, surface hydrology bears a surprising resemblance to sub-surface hydrology. The larger the scale of the analysis, the better the relationship tends to be, although there can be a surprising degree of conformity between surface flows and sub-surface flow even in relatively small watershed units. The relationship is not a perfect one, as demonstrated especially in carbonate bedrock formations where sub-surface pathways may diverge from the surface topography. Also, the orientation (strike) and angle of inclination (dip) of the layers of rock can influence the pathways of sub-surface water movement, so that infiltrating rainfall on one side of a ridge can be discharged on the opposite slope, or watershed area. Such differences notwithstanding, in most of Pennsylvania's watersheds, direct rainfall ultimately remains in the same watershed, either as storm runoff in the surface stream system or emerges as stream base flow after infiltration and groundwater recharge has occurred. Thus one can measure the rainfall into and stream flow out of most watersheds and determine the "water balance" on an annual basis. These relationships contrast rather starkly with patterns found in other parts of the country, where significant groundwater movements may occur, allowing for substantial volumes of water to be moved from one watershed to another.

2.6 Important Natural Systems of Pennsylvania

2.6.1 Geology

- **One of the more important features in the state's geological history involves influence of glaciers in Pennsylvania's northern tier.**
- **Across the state, three basic types of bedrock - sedimentary, igneous, metamorphic - are found, each with different groundwater characteristics.**
- **Groundwater hydrology describes the flow of water through soil and underlying bedrock.**
- **Pennsylvania has a considerable amount of carbonate bedrock (7 percent of total area) that is both a problem and an opportunity in terms of land development and stormwater management.**
- **In carbonate bedrock, stormwater management must replicate the pre-development even distribution of stormwater flow, avoiding flow**

One of the more important features in the state's geological history involves influence of glaciers in Pennsylvania's northern tier. In northern portions of the state, the surface drainage conditions are the result of relatively recent glacial activity. The most recent glacier began receding about 25,000 years ago, after having extended across the northern portion of the state (Figure 2-20). In this area, the land surface is characterized by local soils and drainage systems which were formed by glacial deposition and melting blocks of ice as glaciers receded. The landscape is largely comprised of wet, poorly drained soils with internal surface drainage, and slow recharge of the bedrock

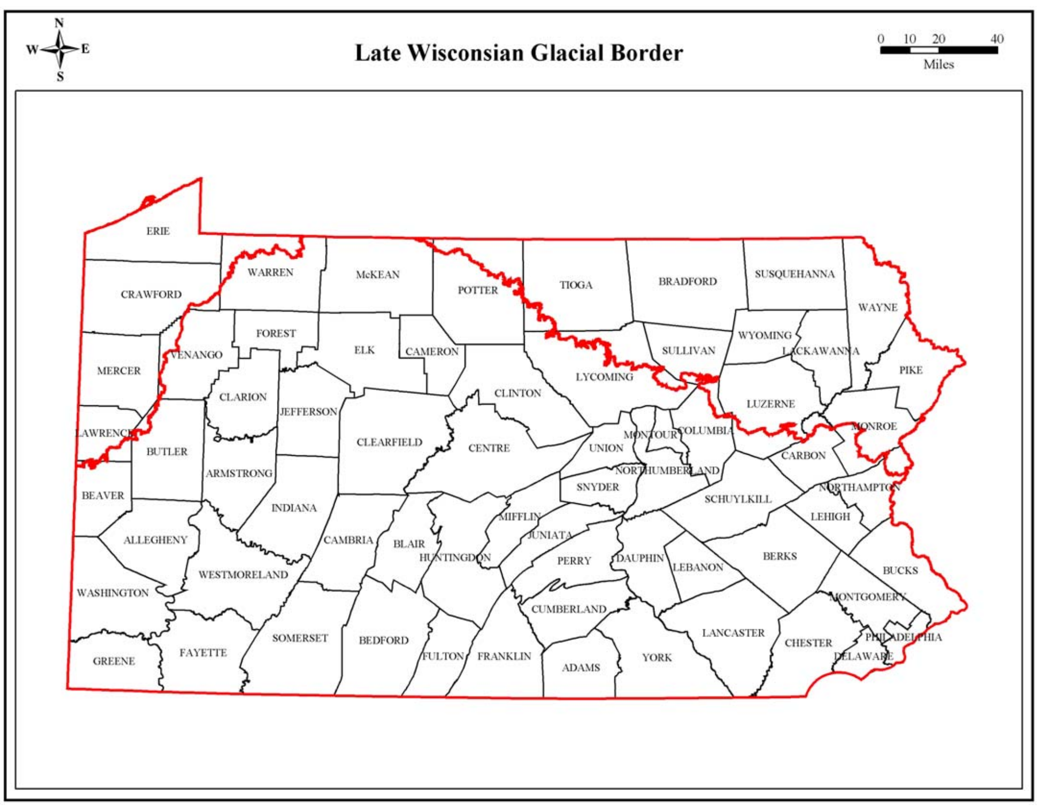

Figure 2-20. Limit of Glacial Activity in Pennsylvania

aquifers. Although the bedrock in these northern glaciated portions has remained unchanged, the geo-hydrology is quite different from the balance of the state and warrants special consideration in terms of stormwater management methods.

Across the state, three basic types of bedrock, sedimentary, igneous, metamorphic, are found, each with different groundwater characteristics. Pennsylvania's diverse and complex natural systems reflect various geologic periods that produced the current land form, with surface bedrock dating from 144 million to 650 million years ago (Figure 2-21). Geologic history is thoroughly described in several references (Socolow, 1976; Barnes and Sevon, 1996; Scotese, 1997). Although all three rock classes, sedimentary, igneous, and metamorphic, are present in Pennsylvania, the majority of the bedrock that lies just below the surface in Pennsylvania is comprised of sedimentary rocks, layered in a succession from oldest to youngest moving from southeast to northwest across the state (PADCNR, 1990). The exceptions to this time progression are rocks formed during the Triassic era (Triassic Basins), as well as rocks formed during the Lower Paleozoic and Precambrian eras, located in the southeast region of the state. The surface hydrology and sub-surface hydrology across the state is influenced in various ways by these bedrock conditions.

Groundwater hydrology describes the flow of water through soil and underlying bedrock. Geology relates directly to the functioning of the water cycle and influences stormwater management as well. Below the surface, infiltrated rainfall not taken up by vegetation generally moves gradually by gravity through the bedrock, the saturated portion of which becomes a water-bearing aquifer. Rate of this

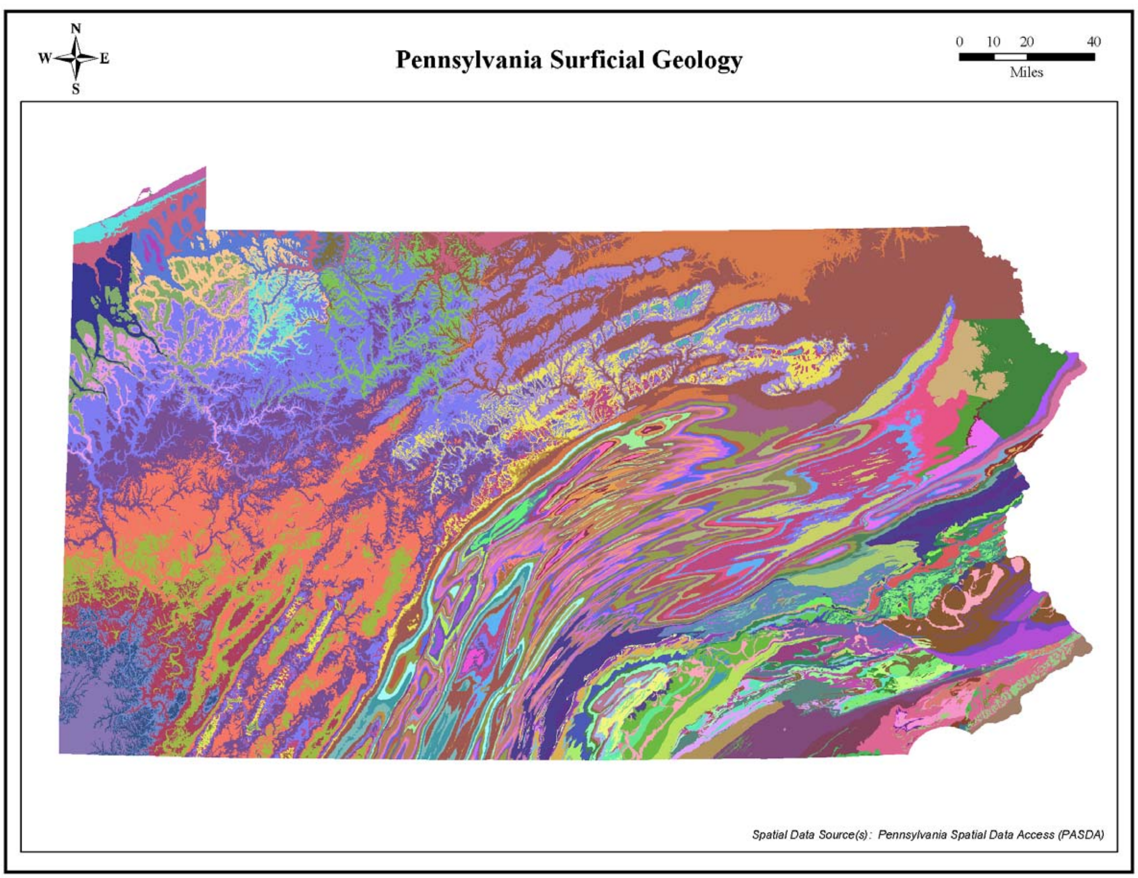

Figure 2-21. Geologic Map of Pennsylvania

movement is quite variable, though typically quite slow, with water moving both vertically and laterally through small and large fractures in the bedrock, through small pores within sandstones and similar materials, or through larger solution channels within carbonate systems that were formed in geologic time. In carbonate watersheds (below), sub-surface water movement usually follows solution channels, but can also occur in fractures. More dense igneous intrusions can also form vertical barriers to water movement in the sub-surface. Bedrock of metamorphic origin tends to have a low permeability, with much reduced groundwater movement. As stated above, this groundwater typically flows out of ground downgradient in the forms of springs, seeps, wetlands, and other zones of groundwater discharge.

Pennsylvania has a considerable amount of carbonate bedrock (7 percent of total area) that is both a problem and an opportunity in terms of land development and stormwater management. Of particular interest in Pennsylvania with respect to stormwater management is the occurrence of carbonate bedrock (also referred to as "karst" or, more simply as "limestone") formations throughout the central and southeastern portions of the state (Figure 2-22). Positively, the soils that are formed in carbonate valleys are generally well drained and have provided some of the best land for cultivation in the state, as well as for any number of land developments; carbonate rock tends to yield an excellent aquifer. Negatively, carbonate bedrock formations have frequently experienced subsidence problems and sinkhole formation (Kochanov, 1987; 1997; 1999), in some cases worsened by the increased runoff volumes and decreased evapotranspiration resulting from conversion of extensive natural woodlands to a cultivated landscape. Sinkholes have occurred during both roadway construction and land

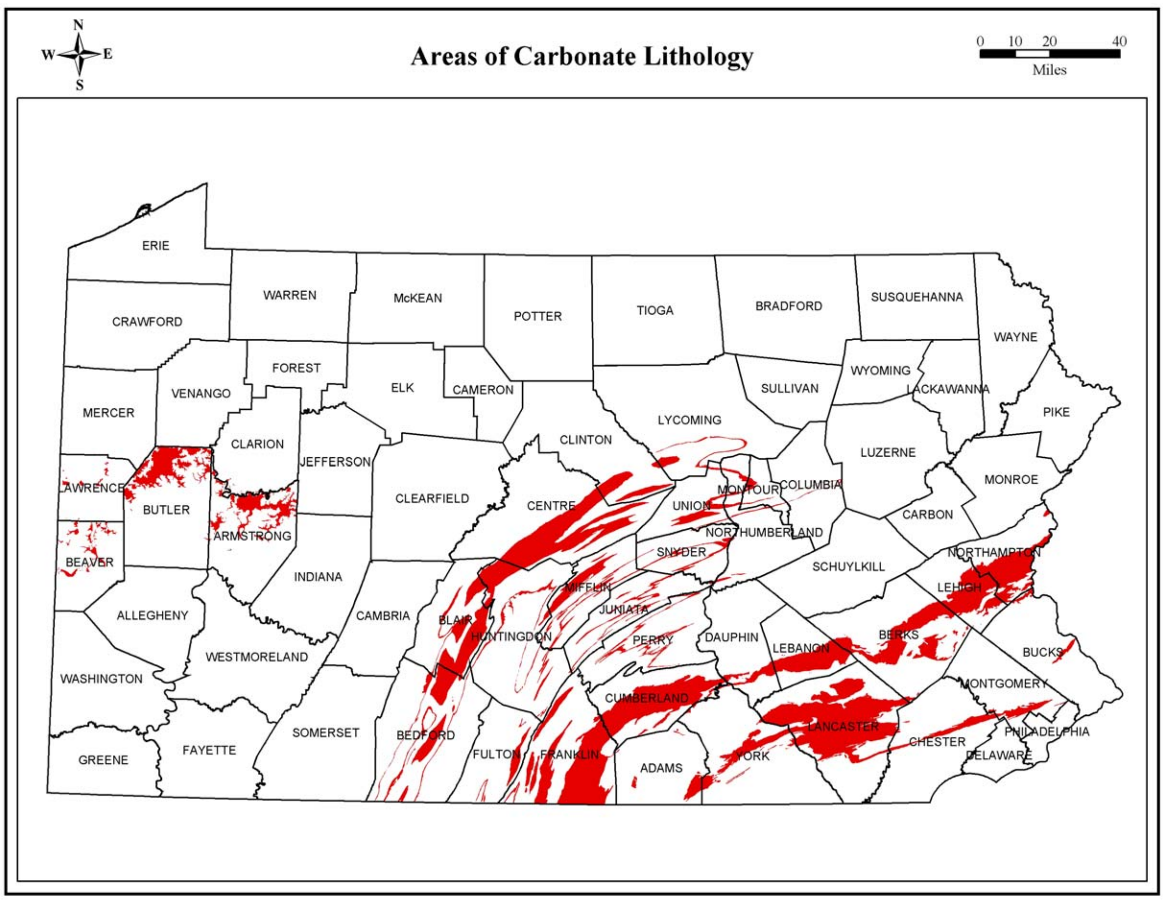

Figure 2-22. Carbonate Geologic Formations in Pennsylvania, (Source: PADCNR)

development, often as the result of concentrating surface runoff during site grading and the land development process (Figure 2-23) into solution channels and rapidly accelerating the otherwise natural subsidence processes. In response to sinkhole fears, stormwater management basins have sometimes been built with impermeable liners to eliminate any infiltration of runoff into the soil. Where evidence of subsidence or sinkholes is encountered in the grading or excavation process, the common practice has been to excavate the soil mantle above the opening in the bedrock and plug the rock with concrete, backfilling with clay soils to reduce subsequent flows. These sinkhole mitigating practices have proven to be difficult and expensive, with subsidence problems sometimes emerging despite best efforts.

In carbonate bedrock, stormwater management must strive to replicate the pre-development broad and even distribution of stormwater flow, avoiding flow concentration. The infiltration of rainfall into and through the natural soil mantle that overlies carbonate formations has taken place for the millions of years that the bedrock has been weathering in the current location and orientation. Insofar as the land development process greatly increases the volume of rainfall that is directed onto the soil surface in a limited location, the potential exists for additional sinkhole development to occur. On the other hand, if natural hydrology - including groundwater hydrology - can be kept close to balance through the broad and even distribution of stormwater management, such that infiltration and resultant recharge is maintained but excessive concentration and "loading" of stormwater flow is avoided, subsidence problems including sinkhole creation can be minimized, if not eliminated.

Therefore extra care in the design and application of BMP's must be taken. Some of the earliest stormwater infiltration/recharge systems, put in place over 20 years ago and still fully operational, have been built over carbonate bedrock (Cahill, 1989; Adams, 2003), using these design principles of highly distributed infiltration/recharge. Use of BMP's that utilize vegetation to promote volume control through increased ET also should be promoted. This successful experience contrasts starkly with documented problems of subsidence, stemming from the conventional collection of runoff from large areas of new impervious cover into concentrated collection and detention facilities, where increased runoff washes the soil into and through sub-surface openings in the bedrock, with increased sub-surface erosion, subsidence, and sinkhole problems. The potential for NPS pollutants, especially solutes such as nitrate, to move rapidly into the carbonate aquifers is an additional issue to be evaluated in the BMP selection program, and is discussed in subsequent sections.

Figure 2-23. New cover collapse sinkhole in a stormwater detention basin in the Ephrata area, Lancaster County, Pennsylvania (Courtesy of William E. Kochanov)

2.6.2 Soils

- **Soil is formed from the weathering of bedrock and may also be deposited by water or wind, and is the medium of rainfall infiltration.**
- **Soils are described BY Soil Series and can be grouped by hydrologic properties, based on soil permeability and site conditions.**
- **All soils are permeable to some extent.**
- **Soils can be measured by cation exchange capacity (CEC) as an indication of NPS pollutant removal.**
- **The land development process results in the compaction of soils, increasing the "bulk density" and reducing permeability.**

Soil is formed from the weathering of bedrock and may also be deposited by water or wind, and is the medium of rainfall infiltration. Although underlying bedrock geology is important to the water cycle, the natural and undisturbed soil is also essential to the water cycle and is especially vulnerable when the land surface is developed. As soils are removed, disturbed, and/or compacted during the land development process, the water cycle no longer functions naturally. Stormwater runoff quantity and quality is affected.

Soils are generally formed by the weathering and eroding of parent rock (mineral material), with the gradual addition of organic matter generated by the natural landscape accumulating on the surface. Soils typically are described in terms of their mix of particle sizes (sand, silt, clay) and the physical processes by which they are formed and transported, such as wind and flood. The soil layer is dynamic, with new soil being formed at the interface of the weathering rock, and with older top layers constantly eroded and transported, even as additional organic matter is added.

Soils are described by Soil Series and can be grouped by hydrologic properties, based on soil permeability and site conditions. An elaborate nomenclature has evolved to describe soils, generally based on where soils are first identified, with each major soil group classified as a "soil series." The NRCS (formerly the Soil Conservation Service, or SCS) has prepared detailed "Soil Surveys" for all Pennsylvania counties, wherein soils are mapped by Soil Series, including data on slope, permeability by horizon and other identifying characteristics. Originally intended to guide farmers in cultivation practices and opportunities, this county-based soils data has also served as a guide for land development. Each soil series has an estimated infiltration capacity, by horizon or depth, which provides initial guidance as to the drainage suitability of a soil for on-site wastewater treatment (e.g., septic systems), as well as drainage suitability for stormwater infiltration BMP's and placement of structures. Although soil series names differ in the different counties across the state, many soil series are quite similar with respect to drainage. Soil series have been assigned a Hydrologic Soil Group (HSG) rating, A through D, which describes the physical drainage and textural properties of each soil type and is useful for stormwater, wastewater, and other applications. This HSG rating usually is based on a range of permeability, as well as certain physical constraints such as soil texture, depth to bedrock, and seasonal high water table (SHWT). Soil types assigned an HSG Group A classification are very well drained and highly permeable (sand, loamy sand, sandy loam); Group D soils (clay loam, silty clay loam, sandy clay, silty clay, clay) are poorly drained and generally situated in a valley bottom or floodplain. HSG-rated B and C soils offer good (B; silt loam, loam) to fair (C; sandy clay loam) drainage characteristics (USDA-SCS, 1986).

All soils are permeable to some extent. Most soils drain to some degree, unless they are saturated by hydrologic conditions, such as hydric soils within a wetland. The wetter D soils have a little or no infiltration potential during rainfall and produce much greater surface runoff, with seasonal variability. Most soils in Pennsylvania are classified with a HSG rating of C or B, with B's usually being very good for the application of many stormwater management systems, as well as on-site septic systems and other infiltration applications. Available data for Pennsylvania indicates that in the eastern two thirds of the state, 51 percent of the area is classified as C, 32 percent as B, 10 percent as D, and 6 percent as A (Figure 2-24).

B and C soils are present throughout the state and throughout the state's different physiographic provinces. Rather poorly draining C soils, if not compacted and manipulated by the construction process, can provide reasonable drainage for use in stormwater management systems, especially if vegetation with existing root systems is left undisturbed. As a general rule, stormwater infiltration measures should be designed with a minimum permeability rate of 0.5 inches per hour, although BMP's can be used successfully in soils with permeability as low as 0.25 inches per hour. It should be noted that the permeability ranges listed for the HSG ratings are based on the "minimum rate of infiltration obtained for bare soil after prolonged wetting" (USDA SCS, 1986). A vegetative cover will increase these rates 3 to 7 times (Linsley et al., 1992).

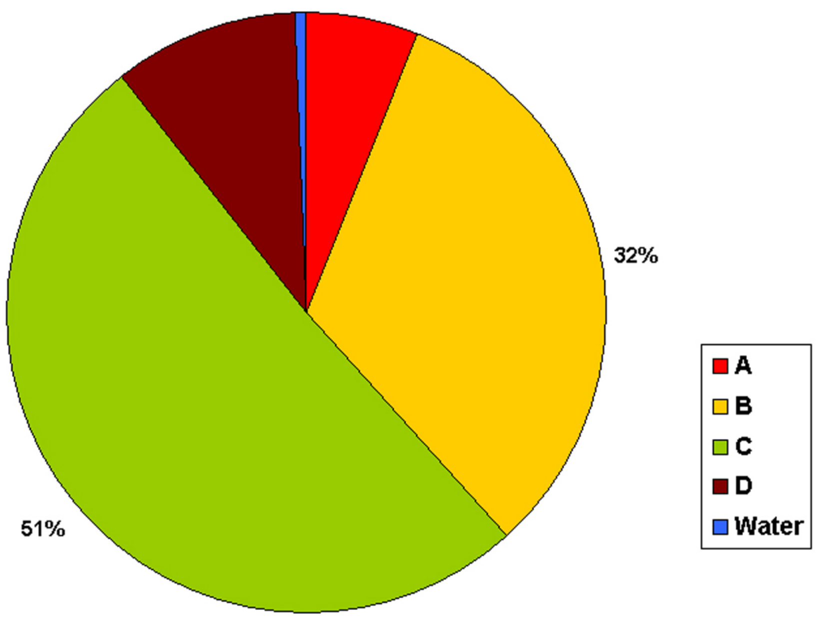

Figure 2-24. Hydrologic Soil Group percentages for the Eastern two-thirds of Pennsylvania, created using STATSGO-derived HSG categories, (CA, 2004).

Soils can be measured by the cation exchange capacity (CEC) as an indication of NPS pollutant removal. The soil provides the medium for organic decomposition of all organic material that evolves on the land surface. Soil is the habitat for a vast spectrum of micro- and macro-organisms that form a natural recycling system. The processed nutrients that result are in turn used by the vegetative systems that develop on the soil mantle. When precipitation is infiltrated, pollutants from our various surface activities move into this soil treatment system, which effectively and efficiently breaks down most non-point source pollutants (biologically), removes them from the stormwater by cation exchange (chemically), and/or physically filters them through soil particles.

One important measure of chemical pollutant removal potential is the Cation Exchange Capacity (CEC), which is closely related to the organic content in the soil. Soils with a CEC of 10 milli-equivalents per 100 grams of soil are very efficient as a treatment medium, and offer the best opportunity to reduce or completely remove most of the pollutants, such as metals and hydrocarbons, which are transported in stormwater runoff. The soil beneath an infiltration bed is the most important part of the pollutant removal process in the stormwater BMP. Non-point source pollutants that are solutes, such as highly solubilized nitrate, are the exception. Nitrates move with the infiltrating rainfall and do not undergo significant reduction or transformation, unless an anaerobic environment is encountered.

For effective stormwater management, the infiltration capacity of the soil mantle should be protected. As part of the initial design process, the soil should be carefully evaluated by soil testing techniques, as set forth in Section 6. After Non-Structural BMP's (Section 5) are applied to reduce total site disturbance and protect natural infiltration potential, Structural BMP's (Section 6) must be selected that utilize the natural properties of the site soil, in terms of infiltration, vegetative support, and pollutant removal potential. When BMP's are considered for development and redevelopment in older urban areas where compaction may already have occurred, the restoration of the soil itself can become a critical part of the stormwater management design program (Section 7). A number of different techniques can be applied to reduce adverse compaction impacts and partially restore the natural bulk density of soil (Table 2-3).

Table 2-3. Bulk Density of Soil after Compaction (Source: Friedman, D.B.)

LAND USE	BULK DENSITY (g/cc)
Undisturbed Lands, Forests, & Woodlands	1.03
Residential Neighborhoods, Golf Courses, Parks, & Athletic Fields	1.69 - 1.97
Concrete	2.2

2.6.3 Vegetation

- **Vegetation decreases the volume and rate of runoff by increasing infiltration and evaoporation.**
- **Vegetation facilitates evapotranspiration (ET) and is a vital part of the water cycle.**
- **Vegetation reduces NPS pollutant loads through both mitigative and preventive functions.**
- **Vegetation can be integrated effectively into a variety of Non-Structural and Structural BMP's.**

Vegetation decreases the volume and rate of runoff by increasing infiltration. In most undisturbed "native" Pennsylvania landscapes, natural vegetation is defined as woodlands, including wetland forests. Pennsylvania's original (pre-European settlement) canopy of oak, hickory, chestnut, hemlock, and pine has been substantially altered, but Pennsylvania's remaining woodlands (Figure 2-25) still provide essential water cycle functions. Removal of vegetation and conversion to impervious surfaces greatly impacts these functions. A variety of studies have documented that different types and densities of vegetative cover – from forest to lawns – generate significantly different volumes of stormwater runoff and different volumes of infiltration. For example, relatively undisturbed woodlands produce less volume of runoff and more infiltration than maintained lawn areas (USDA-SCS, 1978). The relatively short-rooted grasses that commonly occur in maintained lawns, combined with the compaction of the soil that occurs during the land development process, reduce the ability of new lawn to infiltrate to the same extent as in the undisturbed woodland.

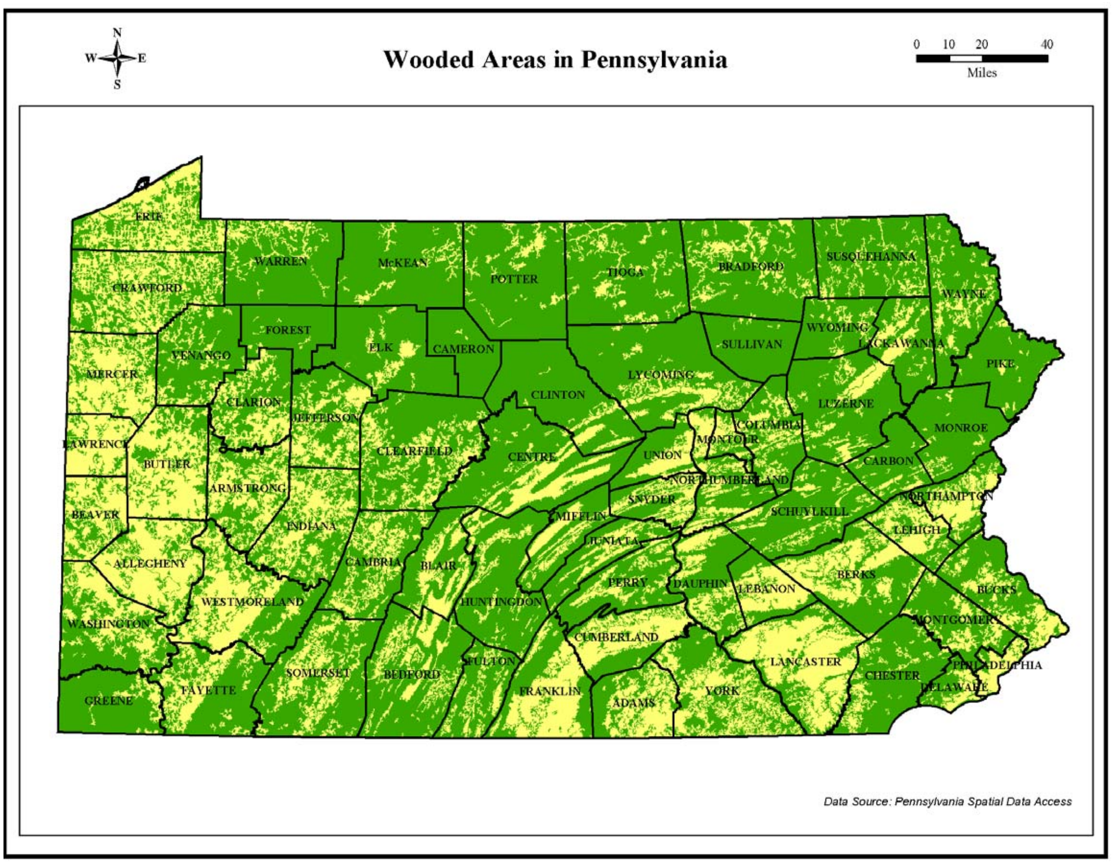

Figure 2-25. Wooded Areas in Pennsylvania

In native woodlands, there is little surface runoff and much infiltration. This runoff has been quantified empirically and is the basis for Curve Number development in the Soil Cover Complex method, among others. Furthermore, surface runoff moves slowly across the land surface, so that the amount of time required for a given area to produce a critical accumulation of runoff downgradient is relatively long. This lengthy Time of Concentration (TOC) is an important variable in stormwater engineering calculations and usually makes anticipated stormwater impacts less severe when natural woodlands can be kept in place.

Vegetation facilitates evapotranspiration (ET) and is a vital part of the water cycle. Once infiltration of precipitation has occurred into the soil, the root system subsequently takes up and removes a portion of this moisture from the soil. Thereafter, the surface areas of plants and trees provide the opportunity for both evaporation and transpiration of this precipitation, generally referred to as evapotranspiration. Vegetation, especially a dense closed forest canopy, intercepts precipitation - up to 25 percent of total annual precipitation (Viessman and Lewis, 2003) - reducing its erosive energy and ultimately its flow, which then is minimized further through increased retention by the increased absorbency of forest soils. ET continues over the days and weeks following precipitation events, occurring more rapidly during the growing season of the specific vegetative system and increasing with ambient temperatures. On an annual basis, vegetation can remove over two thirds of the infiltrating rainfall. In fact, the combination of evaporation and transpiration account for about half of the total average annual rainfall in most of the Commonwealth. In sum, vegetation has a pivotal role in the natural water cycle in Pennsylvania's watersheds, and must be understood if a program of comprehensive stormwater management is to be successful.

In addition to the stormwater management benefits provided by woodlands, these vegetative systems play a larger role by consuming carbon dioxide, producing oxygen, cooling the atmosphere, building the soil mantle and constantly replenishing itself, not to mention the diverse habitat, aesthetic, and other important functions that are provided. Trees themselves are the single BEST stormwater management practice.

Vegetation, properly managed, reduces non-point source water quality pollutant loads through both mitigative and preventive functions. Vegetation provided in riparian buffers offers a range of very important water quality functions, including the physical filtering of particulate pollutants (total suspended solids, phosphorus, other NPS pollutants) from increased stormwater in the form of increased sheet flows, as well as uptake of nutrients such as forms of nitrogen via root zone absorption. Vegetation in Structural BMP's such as rain gardens and constructed wetlands provides for non-point source pollutant removal through a variety of physical, chemical, and even biological removal mechanisms. Preventively, Non-Structural BMP's, as presented in Section 5, work to promote water quality and reduce non-point impacts through source control - by eliminating or preventing the application of nutrients such as fertilizers and pesticides and herbicides through minimizing creation of the maintained landscape which encourages such chemical applications. In fact, pollution prevention through vegetative-based strategies, such as minimum disturbance/minimum maintenance, is probably the most effective approach to stormwater management. This especially true when dealing with pollutants such as Nitrate, where removal after entrainment becomes extremely difficult. In watersheds such as the Susquehanna and Potomac, where Nitrate is a significant water quality problem, preventive Non-Structural BMP's become especially important.

Vegetation can be integrated effectively into a variety of Non-Structural and Structural BMP's. Sections 5 and 6 present an array of Non-Structural and Structural BMP's, which utilize the natural functions of existing vegetation for successful stormwater management. First and foremost is maximizing the practice of minimum disturbance/minimum maintenance in site designs for new land development, avoiding removal and disturbance of existing vegetation whenever possible. In addition to other Non-Structural BMP's, many of the Structural BMP's described in Section 6 rely on existing vegetation and/or additional landscaped species and their natural functions. American Forests (http://www.americanforests.org/resources/rea/), the oldest nonprofit conservation organization focusing on protection and enhancement of the nation's forests, has applied its innovative CITYGREEN program to portions of Pennsylvania. CITYGREEN inventories and analyzes the benefits provided by woodland plantings in developed areas and has demonstrated substantial reduction in stormwater impacts as woodlands are maximized, specifically through reduction in runoff quantities being generated, as well as an increase in the time of concentration.

2.6.4 Physiography

- **Pennsylvania's physiography varies across the state, with the major regions being the Coastal Plain (and Lake Erie Plain), Piedmont Plateau, Blue Ridge, Ridge and Valley, and Allegheny (or Appalachian) Plateau.**
- **Although PA's physiographic provinces are defined in terms of variation in geology, soil, climate, vegetation, and other natural features, their common elements, in terms of stormwater, far outweigh their differences.**

Pennsylvania's physiography varies across the state, with the major regions being the Coastal Plain (and Lake Erie Plain), Piedmont Plateau, Blue Ridge, Ridge and Valley, and Allegheny Plateau (Figure 2-26). In the extreme southeast is the **Coastal Plain Province**, a strip of land about 10 miles by 50 miles along the Delaware River (including the City of Philadelphia), which consists of a long, flat, tidal estuary. Soils here contain "soft" sediments that were deposited by water and glacial erosion. At the opposite corner of the state, bordering Lake Erie, is a relatively narrow (3 to 4 miles in width) strip of land about 40 miles in length, which is called the **Lake Erie Plain**, with fine alluvial soils, rich in agricultural productivity. In some ways this area is similar to the Coastal Plain, although Lake Erie Plain soils tend to be more productive and better drained than those in the Coastal Plain.

Although PA's physiographic provinces are defined in terms of variation in geology, soil, climate, vegetation, and other natural features, their common elements, in terms of stormwater, far outweigh their differences. Pennsylvania's landforms, or physiographic provinces, relate to variations in the state's geologic processes, soil, climate, and vegetative patterns. Some physiographic provinces are comprised of soils that provide more or less infiltration, groundwater recharge, stream base flow, and runoff. A wide range of geological, soil, and vegetative factors is typically found within each physiographic province and from site to site, which can be expected to affect selection of stormwater management BMP's. Whatever the variation might be, such physiographic variability does not alter the basic set of assumptions at the core of this stormwater management program, including applicability of the Recommended Site Control Guidelines for stormwater management set forth in Section 3.

Situated to the west of the Coastal Plain is the **Piedmont Plateau** province, covering much of the southeastern portion of the state. The Piedmont Plateau extends from the border of New Jersey with New York to the central portions of Alabama, and is characterized by gently rolling topography with low hills, fertile valleys, and well-drained soils, with elevations generally ranging from 100 to 500 feet (Fenneman, 1932). The point to the east where the Piedmont meets the Coastal Plain has been called the "fall line," and is marked by waterfalls and rapids that form where the hard rock of the upland Piedmont region meets the unconsolidated layers of the Coastal Plain. Bedrock in the Piedmont typically includes very old crystalline rocks, such as granite, deformed and metamorphosed, with large sheets that are thrust westward along low angle fault lines, representing the "roots" of the old Appalachian Mountains. Carbonate formations also are found.

The **Blue Ridge** forms the next physiographic province to the west, but is a relatively minor element in PA. West of the Blue Ridge is the **Ridge and Valley**, where forested ridges alternate with fertile and highly productive agricultural valleys. The Ridge and Valley is about 80 to 100 miles in width, with parallel ridges and valleys running in an arc from northeast to southwest. Ridges range from about 1,300 to 1,600 feet in elevation with about 600 to 700 feet of local relief. Ridge and Valley consists mostly of sedimentary rock with small scatterings of igneous rock, further characterized by parallel anticlines and synclines with numerous deep thrust faults as well. Ridge and Valley includes the Great Valley (called the Lehigh Valley in Pennsylvania), which blends to the Cumberland Valley and Shenandoah Valley to the south. Carbonate formations are also found within the Ridge and Valley.

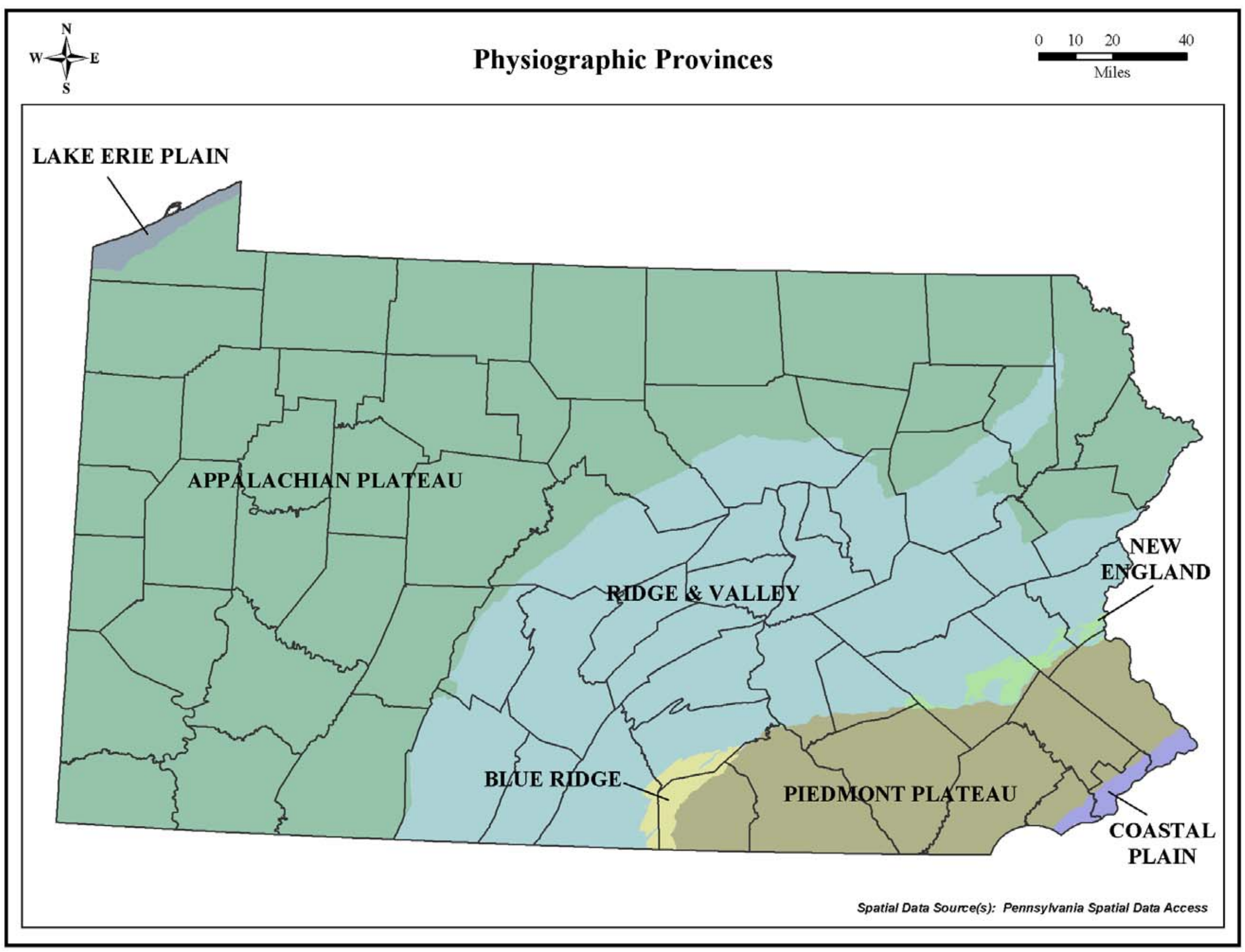

Figure 2-26. Physiographic Provinces in Pennsylvania

Beyond Ridge and Valley is the **Allegheny Plateau** (or Appalachian Plateau), underlain by sedimentary rocks younger than those of the Ridge and Valley. This large area has several sub-sections, including the Allegheny Mountain sub-section on the western side of the Plateau, which is more gently folded. The Plateau tends to range between 1,000 and 2,000 feet in elevation, although some peaks extend to 3,000 feet. The area tends to be wooded and is the most rugged topography in the state, with numerous lakes and swamps with deep narrow valleys, punctuating this once glaciated and highly scenic landscape.

Certainly different BMP's recommended in this Manual in Section 5 and 6 will vary in their applicability and suitability for different physiographic regions of the Commonwealth. Given the wide range in site variability, even within different physiographic provinces, use of all of the different BMP's in a physiographic province is a virtual certainly. For example, large and shallow infiltration basins may be much more practicable in the Piedmont's gently rolling terrain with its often well-drained soils, as found in southeast and south central portions of the state, than on the steeply sloping hillsides of Pittsburgh or the glacially impacted mountains in the northern tier of counties. However, the need to control total runoff volumes, peak rates of runoff, and non-point source water quality loadings, is uniformly important throughout the state. In the Allegheny Plateau and Ridge and Valley provinces, where tremendous damage has been caused by mismanaged runoff and flooding, the full spectrum of BMPs should be considered and applied. Some of the most outstanding Special Protection Waters designated streams (High Quality and Exceptional Value) in the state are located in these physiographic provinces, and as new land development occurs, stormwater management must comply with the most effective BMP's in order to protect these valuable resources.

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