

Chapter 4

WHY STORMWATER MATTERS

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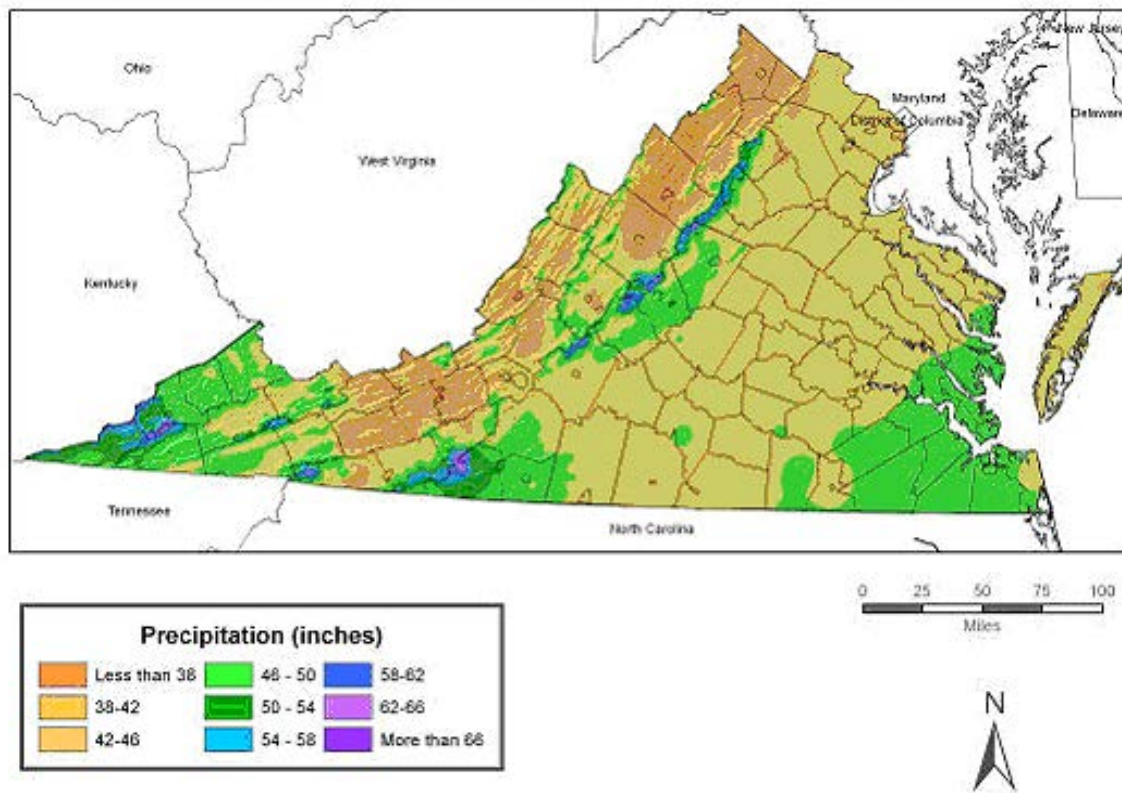
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4.0 INTRODUCTION

When a city takes a bath, what happens to the dirty water?

Stormwater runoff is overland flow from precipitation that accumulates in and flows through natural or man-made conveyance systems during and immediately after a rainfall event or from snowmelt. Average annual rainfall varies across most of Virginia from about 42 to 48 inches per year, with averages in isolated areas of less than 38 inches or more than 66 inches (**Figure 4.1**). Virginia has a number of major rivers that flow from the mountains through the state to the coast. In some areas of Virginia, the underlying geology allows water to infiltrate to underground aquifers. These aquifers provide a significant amount of drinking water to Virginia citizens.



Map copyright (c) 2006 by the PRISM Group and Oregon Climate Service, Oregon State University.

Figure 4.1. Average Virginia Annual Precipitation, 1971-2000

Source: Oregon Climate Service

Stormwater runoff has traditionally been viewed as a nuisance to be disposed of as quickly as possible. However, we must learn to view stormwater as a valuable resource and manage it more carefully than in the past. There are two key reasons for this: (1) only a fraction of the earth's total water is available as fresh water; and (2) the availability of fresh water is critical for human health and survival. Although water availability has not been a serious, continual issue in Virginia, projected population increases and changes in precipitation patterns could alter this reality. To really grasp the value of effectively managing stormwater, we first need to understand how water circulates throughout our world.

4.1 THE HYDROLOGIC CYCLE

It is one of nature's wonders that we never run out of water. Scientists estimate the earth is about four and a half billion years old. After all that time, we continue to have water available for our use because of a natural process called the hydrologic cycle. The sun provides the energy that powers this remarkable process. Our water is constantly being exchanged between the earth and the atmosphere (**Figure 4.2**) in a natural form of recycling. The sun's energy, in the form of light and heat, evaporates water from oceans, rivers, lakes and even mud puddles. Water is also transpired by plants and animals and evaporated from the soil. In combination, these processes are known as evapotranspiration.

Rising air currents lift the water vapor up into the atmosphere. When the water vapor reaches the cooler layers of the atmosphere, it condenses to form clouds. As clouds grow larger and move around, eventually the water droplets grow larger and heavier, falling to the earth's surface as precipitation (rain, snow, sleet or hail). Very little of our local rainfall is due to local evaporation and transpiration. Local rain is moisture that has been transported by clouds from elsewhere.

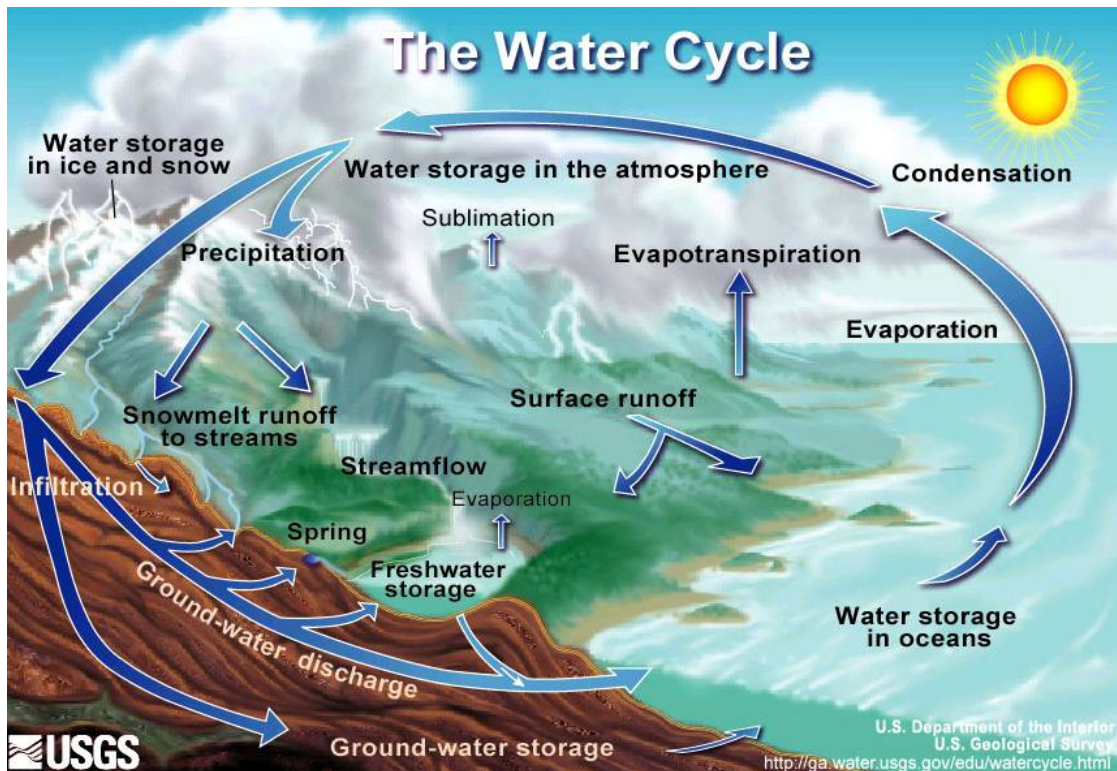


Figure 4.2. The Hydrologic Cycle (Source: USGS web site)

Once the precipitation reaches the ground, several things can happen to it. The water may evaporate, be absorbed by the ground and taken up by plant roots, or infiltrate through the soil and become groundwater, one of the world's largest storehouses of water. The rest becomes *surface runoff* or *stormwater runoff* that drains into streams, rivers, and other surface waters. While depicting the general concept, this representation of the hydrologic cycle over-simplifies a very complex process and does not reflect the impact of man's actions.

4.2 DISTRIBUTION OF THE EARTH'S WATER – THE WATER BUDGET

Water covers approximately 70% of the earth's surface, but we only see a small portion of it. Many people do not understand that most of the earth's water is *not* available for man's use (**Figure 4.3**). Almost 94% of the planet's water is chemically bound up in the rocks and minerals of the earth's crust. The oceans comprise about 97% of the available water, but ocean water is not significantly useable for human consumption due to its salt content.

Allocation of the Earth's Water

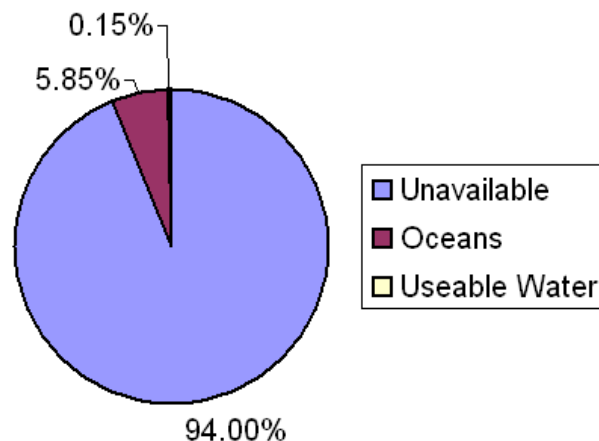


Figure 4.3. Overall Global Water Budget
Source: Adapted from Day and Crafton (1978)

We may consider the remaining water – less than 1/4 % of all the earth's water, or 2.5% of the available water– to be useable for our basic needs (**Figure 4.4** below). Of this useable water, almost over 30% is stored in aquifers, and nearly 69% is found in polar glacial ice masses. The remainder – about one eighth of one percent (0.125 %) – is composed of circulating ground water, inland waterways, and atmospheric moisture.

There is about 100 times as much water circulating in the ground as there is fresh flowing water on the earth's surface in lakes, rivers, streams and wetlands; and there is about eight times as much fresh flowing surface water as there is moisture in the atmosphere.

It is important to understand that all of the world's available water has been, for many years, subject to pollution from man's activities. Smokestacks spew air pollutants into the atmosphere, which become bound up in the water particles in clouds and subsequently drop to the earth as rain. Pipes from industrial and sewage treatment plants and stormwater conveyance systems carry pollution into our streams and rivers. Water that filters into the soil can carry pollutants into the groundwater tables that provide base flow for our streams, or even into deep aquifers that are often tapped for domestic water supply. Since the water we see and use each day is such a small part of the total, we should consider it *all* to be a valuable resource and not view any of it, including stormwater, as disposable.

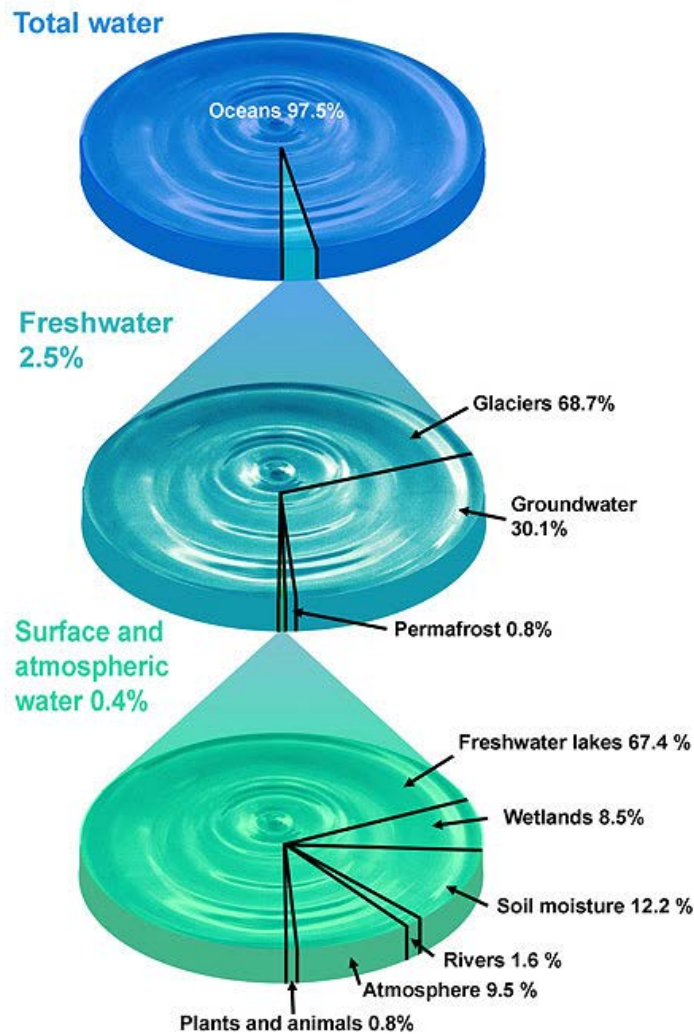


Figure 4.4. Available Water Budget
Source: GreenFact.Org (2011)

4.3 CHANGING PRECIPITATION PATTERNS

The magnitude and frequency of stormwater discharges and the mobilization and transport of pollutants are not just determined by rainfall. They reflect a combination of storm and inter-storm drainage area characteristics, land use, the natural and built drainage system, and any stormwater control measures that have been implemented. Therefore, information on the frequency distribution and characteristics of storm events is relevant to understand how pollutant concentrations and loads are distributed in stormwater discharges.

Any given storm is characterized by the storm's total rainfall depth, duration, and intensity. Because storm magnitudes and frequencies vary by climatic region, it is reasonable to expect them to change during recurring climate events (e.g., El Niño) or over the long term by climate change. Evidence exists that precipitation regimes are shifting systematically toward an increase in more intense rainfall events, consistent with modeled projections of global climate change.

The data indicate that climate is changing, as evidenced by warming air, ocean and land temperatures; melting glaciers and ice caps; rising sea levels; shifting precipitation patterns; and countless changes in natural ecosystems. (IPCC, 2007a and 2007b; UCS-ESA, 2005; NWF, 2009)

More pertinent, the data show a clear increase in heavy rainfall in the U.S. over the past few decades. The most intense rainfall events have been increasing at a rate of 20 percent per 100 years, with more prolonged periods of higher-than-normal precipitation. Scientists at the National Climatic Data Center (NCDC) have concluded that most of the observed increase in storms with heavy and very heavy precipitation has occurred in the last three decades. These storm events vary in character from high-intensity rainfall cells accompanying weather fronts to tropical storms that inundate coastal areas before moving inland to continue dumping large volumes of rain or snow (e.g., hurricanes Isabel and Gaston).

Virginia has seen a 25 percent increase in the frequency of extreme precipitation events since 1948. This is the greatest such increase among all states in the South Atlantic region (Maryland to Florida). An increase in the number of downpours does not necessarily mean more water will be available. The intensity and duration of drought periods is also increasing in Virginia (e.g., Lake Chesdin in the summer of 2007 and 2010), with soil moisture being depleted, annual groundwater recharge decreasing, and runoff from hardened dry soil surfaces increasing.

More surface runoff means there is less infiltration of water into the soil. This translates during the year into decreased stream base flow, since less water is stored in the shallow groundwater zone that feeds the baseflow. Less infiltration will also mean less groundwater recharge. The combination of extreme events and droughts means that water level fluctuations are likely to be commonplace as storage areas (ponds, wetlands, floodplains) change very quickly from dry, exposed conditions to flooded, high-water conditions that typically follow large storm events.

If less water infiltrates into the ground and runoff increases, more frequent and severe flooding is possible. During the 20th century, floods have caused more property damage and loss of life in the United States than any other type of natural disaster.(Madsen and Figdor, 2007).

Another ramification of climate change is a rise in sea level. Combined with the impacts of tropical storms, this means that coastal flooding is likely to be more extensive, as indicated in the analysis illustrated in **Figure 4.5** below. This graphic shows the predicted extent of flooding in the Hampton-Poquoson area resulting from a storm of the intensity of Hurricane Isabel if sea level were to remain at its current elevation (red), rise by 20 inches (green), 40 inches (blue) or 60 inches (orange) – possible scenarios over the next 100 years.

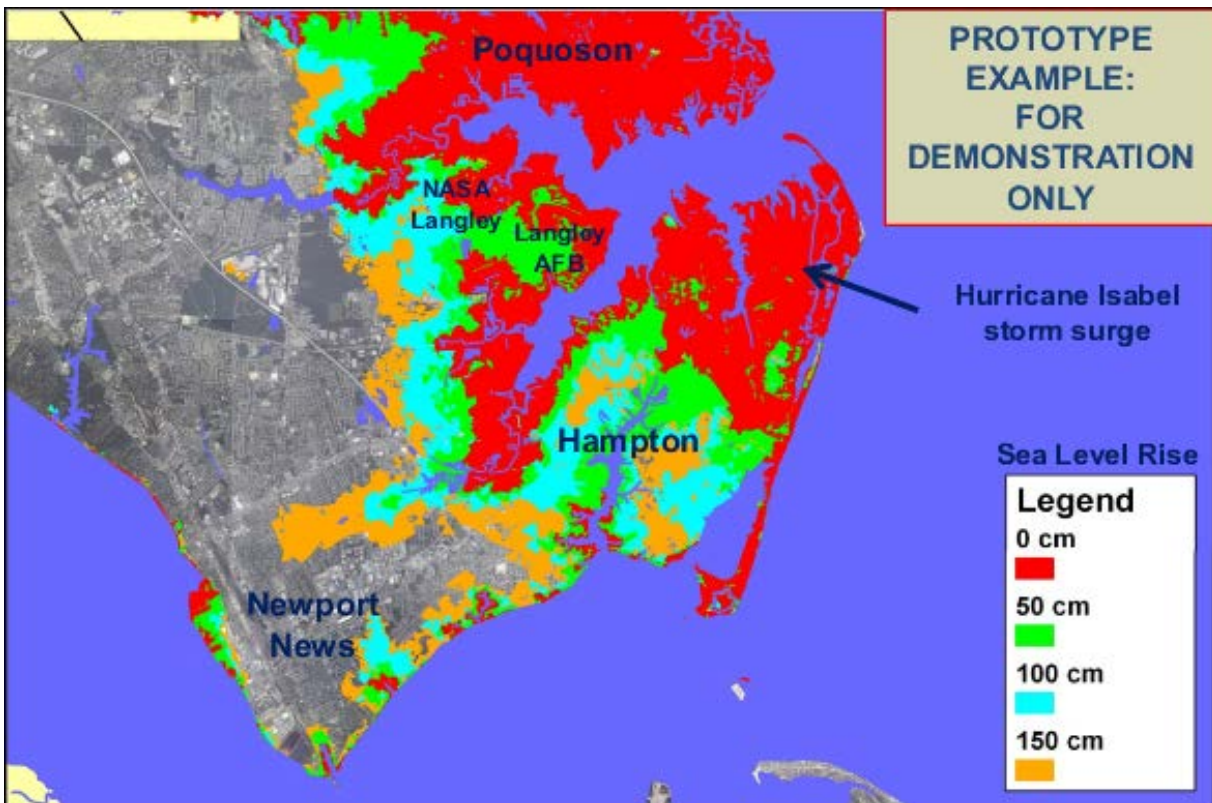


Figure 4.5. Hurricane Flood Prediction Model with Reference to Potential Sea Level Rise

Source: Virginia Institute of Marine Science and Noblis, Inc.

Current climate models project these trends to continue. However, projections are exactly that – projections. Untangling the complex components of our changing atmosphere is no simple task; natural variability in weather patterns, geographical disparities, and climate model limitations are some of the many challenges scientists face.

But, we do know this: *warmer air can hold more water*. The greater water-carrying capacity of a warmer atmosphere means that more water would accumulate there between rainfall events. Then, when it does rain, there is a greater likelihood of a heavy downpour. The consequence of more frequent and intense storms may include flooding, erosion, pollution of waterways with excess runoff, wind damage, crop damage, and other environmental and economic damage. **Table 4.1** below summarizes the potential secondary effects of climate change on precipitation and stormwater runoff.

Predictions for increases in the intensity and frequency of extreme events have significant implications for future stormwater management. First, many of the design standards currently in use will need to be revised, since they are based on historical data.

Table 4.1. Summary of Climate Changes* Leading to Stormwater Impacts

Changing Feature	Primary Impact	Secondary Impact
Precipitation	More mixed winter precipitation; more ice and/or rain-on-snow events	More runoff during winter; increased road salt usage because of more ice
	Less rain during summer season	Drier surface-water bodies for longer periods; increased water-level fluctuations; wetland and floodplain disconnection
	Longer, more severe droughts over larger areas	Soil moisture depletion; more accumulated surface pollution; less available water supply
	More extreme precipitation events	Flooding; erosion; rapid water-level changes
Warmer winters	Less snow accumulation; more and earlier winter runoff; earlier snowmelt	Less water supply saved in snowpack (especially in the west); more winter road salt application; drier streams, wetlands, and floodplains earlier in the year; less groundwater recharge
	Shorter lake ice coverage	Earlier lake turnover in spring, later in fall; greater algal growth; more evaporation during winter; longer lake water stratification period
Warmer summers	Increased temperature of runoff	Less cold-water fishery
	Increased humidity	Greater severity of storms and extreme events like tornadoes
	More suitable vector environment	Increases in the number and type of nuisance and health-related vectors (like mosquitoes in stormwater ponds)
	Less water available in wetlands, lakes, reservoirs and streams	Evapotranspiration-transpiration increases result in volume loss; groundwater recharge decreases, affecting stream base flow
	Gradual warming of the oceans	Increased tropical storm frequency and severity; sea level rise
	Lower water levels	Some perennial streams become intermittent; hydrologic connections to riparian zone decrease
* Variations will occur in different parts of North America		

Source: Adapted in part from IPCC 2007a, IPCC 2007b, and UCS-ESA 2005

For example, intensity-duration-frequency (I-D-F) curves used for design storm data will need to be updated, because the magnitudes of the various design storms appear to be continually changing. Even with revised design standards, in light of future uncertainty, new BMPs will need to be designed conservatively to allow for additional storage that will be necessary for regions with predicted trends of increasing precipitation. In addition, existing BMP designs based on old standards may prove to be undersized in the future. Implementation of a monitoring program to

check existing BMP inflows against original design inflows may be prudent to aid in judging whether retrofit of existing facilities or additional stormwater infrastructure is needed.

Some localities have started to account for climate change in their floodplain management programs. However, one barrier to doing this is that floodplain maps and other planning tools are largely based on historical climate conditions. With more accurate climate projections now available on a regional basis, it is prudent to update these maps and planning efforts (Cunningham, 2009).

States and communities should take steps to educate those living in the floodplain about their current risk, how changing conditions might affect that risk, and steps they can take to prepare for potential floods. The risks to people living behind and below dams should be a priority; government officials should consider strengthening land-use and building codes in these locations. New development in flood-prone areas should be discouraged, and the natural systems that help buffer against floods should be protected, taking advantage of the natural water storage capacity of the floodplain.

Finally, increasing population in Virginia and elsewhere will place continual pressure on our water supplies. Competition for water will also increase as drier conditions translate into increased irrigation demand for crops and lawns. Stormwater managers will be on the front lines in trying to cope with these changes and continue to maintain the quality of life the public has come to expect.

4.4 STORMWATER AS A VALUABLE RESOURCE FOR HUMAN USE: RAINWATER HARVESTING

As changing precipitation patterns alter the hydrologic cycle, it is more important than ever to make smart, conscientious use of water supplies. Stormwater reuse presents a tremendous opportunity to do just that. This is becoming even more important as populations increase. A recent report by Credit Suisse (Garthwaite, 2007) indicates 18 countries will experience water demand beyond supply capabilities by 2025.

Worldwide water consumption is rising at double the rate of population growth (Garthwaite, 2007). Similarly, Virginia's water consumption is continually increasing (**Figure 4.6** below). Due to the increasing demand for public and domestic water supplies, groundwater levels are declining and municipal treatment plants are struggling to supply current demands. Unfortunately, we have continued to treat runoff as a waste product, moving it off developed land as fast as possible.

Virginia's growing population places increasing demands on water supplies. As a result, planners, county and state officials, residents, and developers must begin to seek alternative water sources to supply the demands. Rainwater harvesting offers an affordable, simple, sustainable and reliable alternative source of non-potable water. Not only can rainwater harvesting supply water for indoor and outdoor use, it can protect the environment from detrimental nonpoint source pollution by reducing the delivery of site runoff to nearby streams and rivers. Also, the water can be treated (e.g., reverse osmosis, etc.) for potable uses.

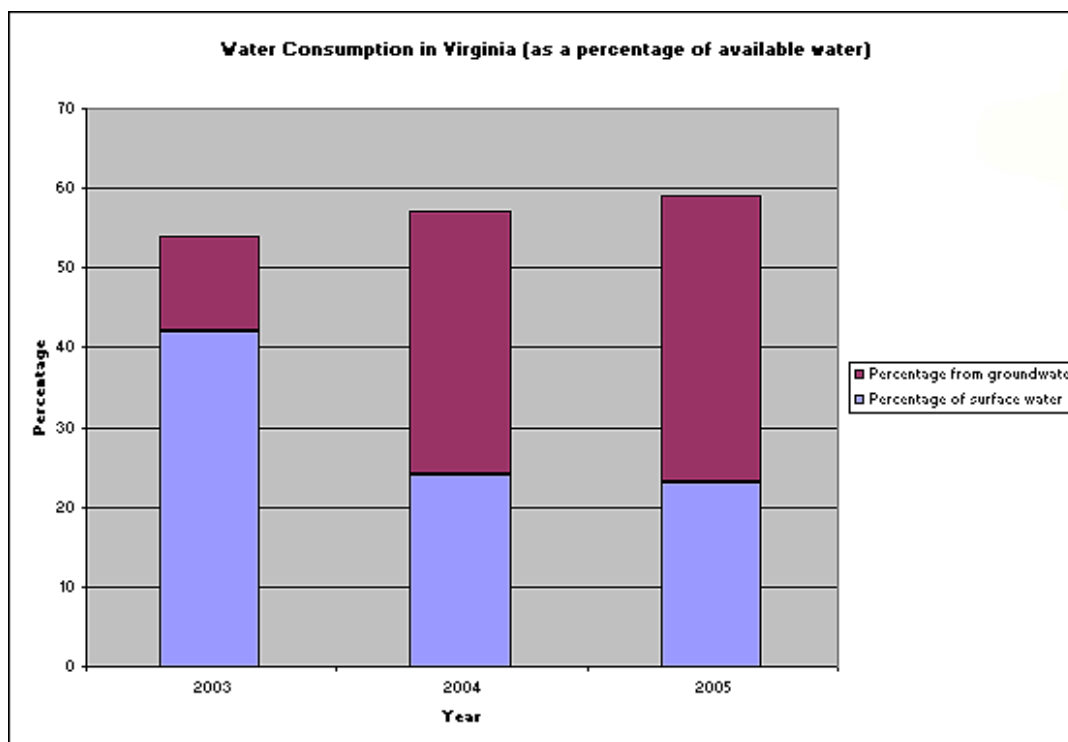


Figure 4.6. Percentage of Available Water Consumed Annually in Virginia (2003-2005)

Source: Virginia DEQ (2004, 2005 and 2006)

Rainwater harvesting is ideal for large retail and industrial buildings (**Figure 4.7** below). Rainwater can be diverted from the flat roof to either an on-site storage tank(s) or a pond. Then stored water can be diverted both indoors and outdoors to be used for toilet flushing, linen washing, facility cleaning, fire suppression, cooling towers, industrial processes, and landscape irrigation. Most of these uses do not require that the water be treated. Not only the owners and tenants save on water consumption costs, but harvesting rainwater also reduces the amount of stormwater runoff that must be treated prior to leaving the site.

Rainwater harvesting can also be cost-effective for homeowners (**Figure 4.8** below). Rainwater is typically cleaner than the municipal water supply, even considering airborne particulates, and the water is typically softer. Soft water requires less laundry detergent than hard water. Use of free rainwater to flush toilets, do laundry, fill swimming pools, wash vehicles and power-wash the home, and irrigate lawns, borders and gardens is much more sensible and cost-effective than paying for municipally treated water to accomplish those same functions. Furthermore, as a growing population places more demands on municipally treated water, the cost of that water supply will rise. Therefore, the economics of rainwater harvesting will pay greater dividends in the future.

Consider the following calculation provided by professional engineer Dr. John Hayes, of Clemson University, and Jeffrey Herr, of Brown and Caldwell. The City of Orlando, Florida, needs 36,000 acre-feet of water to meet residents' annual demand. On average, 48 inches of rain falls each year over the city's 70,400 acres. (NOTE: This is about the same amount of rain that

falls annually on Virginia’s Hampton Roads communities.) Ultimately, the difference between Orlando’s annual pre- and post-development runoff volumes is 56,000 acre-feet, or 1.55 times its yearly water demand.

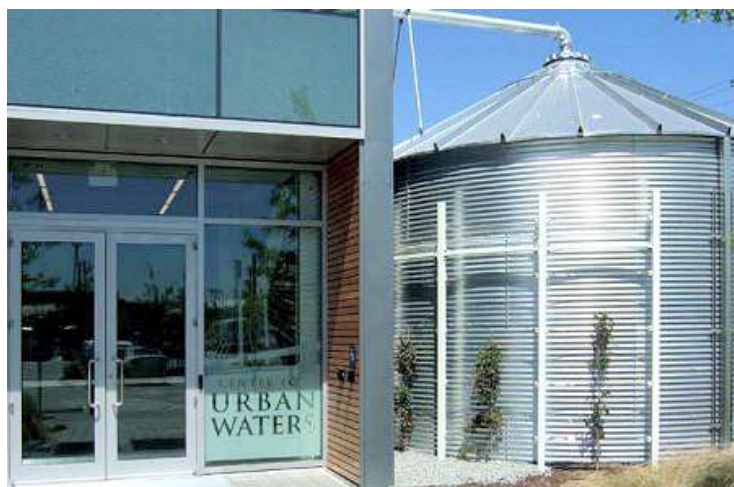


Figure 4.7. Tacoma WA Environmental Services Building – Large Scale Use



Figure 4.8. Rain Barrel – Residential Scale

More and more states and municipalities, including Virginia, are now requiring that stormwater runoff be reduced in new developments through the use of low impact development (LID) practices. Rainwater harvesting is a sustainable approach for accomplishing this, while providing an alternative water source at the same time.

Virginia’s building code and health regulations are currently being reviewed with the intention of enabling more extensive use of rainwater harvesting options. Being proactive to protect the environment and conserve resources is beneficial both today and tomorrow. Municipal efforts to make beneficial use of “nuisance” stormwater will help bridge man-made runoff volume gaps and decrease our reliance on progressively stressed groundwater and surface water sources.

The Cabell Brand Center in Salem, Virginia, has produced the *Virginia Rainwater Harvesting Manual* (2009, 2nd Edition), which details the benefits of rainwater harvesting, both economical and environmental (http://www.cabellbrandcenter.org/Downloads/RWH_Manual2009.pdf).

Also, DEQ has a Rainwater Harvesting best management practice design specification (discussed more in **Chapter 8** of this Handbook) and provides a spreadsheet tool for sizing and designing rain storage cisterns, which can be found at the following web URL:

<http://www.vwrrc.vt.edu/swc/NonProprietaryBMPs.html> .

4.5 HOW POPULATION GROWTH AND LAND DEVELOPMENT AFFECT THE HYDROLOGIC CYCLE

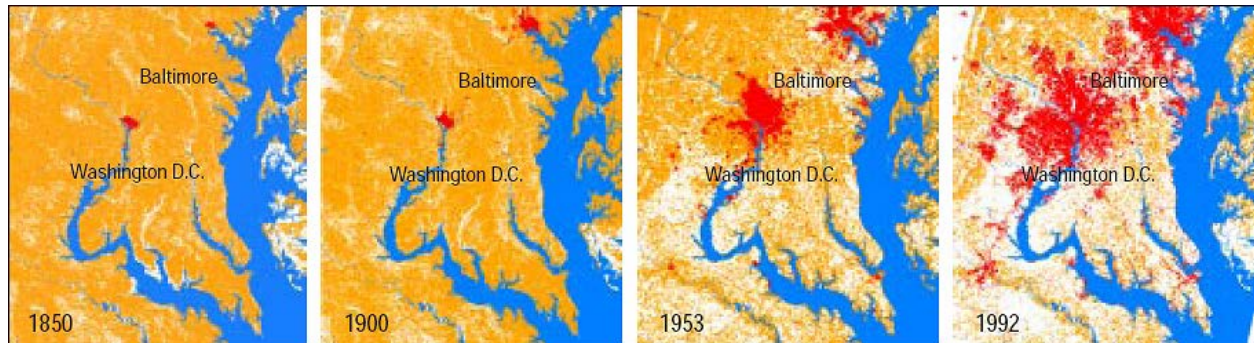


Figure 4.9. Growth Over Time in the Washington, DC-Baltimore Corridor
Source: USGS

For the past three decades the population in the Chesapeake Bay Watershed has grown by more than a million people per decade (**Figure 4.10**). This trend is projected to continue, so that by 2030 nearly 2.5 million additional people are expected to be living within the Chesapeake Bay watershed (extrapolated from USEPA, 2007). Between 1990 and 2000, the watershed population increased by 10.3% while the impervious cover increased by an unsustainable 41% (USEPA, 2010). During this same time, forest cover decreased substantially in most areas of the watershed. During the period from 1990 through 2007, population increased by 18% while impervious cover due *only* to residential development increased by 34% (USEPA, 2010).

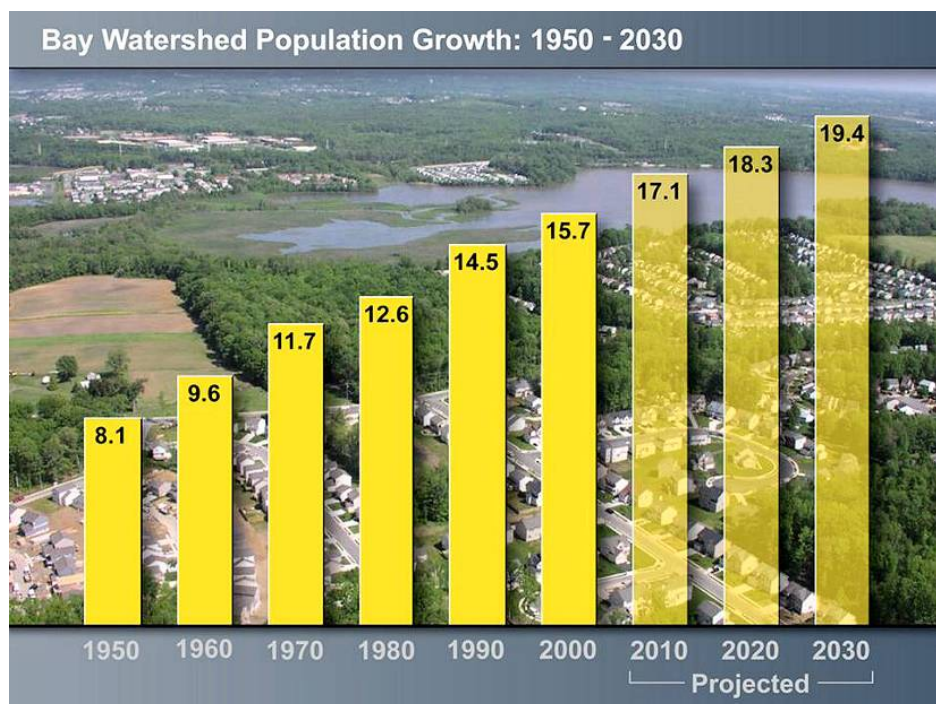


Figure 4.10. Population Growth (Millions) in the Chesapeake Bay Watershed (1950-2030)
Source: Chesapeake Bay Stormwater Training Partnership

That growth in imperviousness does not include new roads, the expansion of existing roads, growth in “big box” commercial and other retail establishments, associated parking areas, industrial plants and warehouses, and institutional expansion. Nor does it address the expansion of turfgrass areas, discussed in more detail below, which have been shown to be effectively impervious due to soil compaction by construction activities and traffic (USEPA, 2010).

This dramatic increase in population, impervious cover, and corresponding loss of tree cover in the watershed has resulted in excessive amounts of stormwater runoff. With the loss of natural vegetation, there is an increasing amount of pollution and a phenomenon referred to as “urban stream syndrome.” Urban stream syndrome is characterized by flash flooding, elevated nutrient and contaminant levels, altered stream morphology, sedimentation from eroded stream banks and loss of biological diversity (Mehan, 2008). These issues demonstrate that water quality and quantity are intertwined as never before. The increased and degraded runoff is destroying local streams, causing damage to infrastructure and properties and polluting our water supply sources.

4.5.1. Hydrologic Impacts from Changes to the Land Surface

Changes to the land surface significantly alter the hydrologic cycle. Inappropriate stormwater management exacerbates the problem. When land is developed, the hydrology (the natural cycle of water) is disrupted and altered. Clearing removes the vegetation that intercepts, slows and returns rainfall to the air through evaporation and transpiration. Grading flattens hilly terrain and fills in natural depressions that would normally slow and provide temporary storage for rainfall. The topsoil (usually required to be replaced) and sponge-like layers of humus are scraped and removed, and the remaining subsoil is compacted. A portion of the rainfall that once seeped into the ground now runs over the surface. The addition of buildings, roadways, parking lots and other surfaces that are impervious to rainfall further reduces infiltration and increases runoff. **Figure 4.11** is an example of the increased imperviousness that take place as an area is developed over time.



Figure 4.11. Typical Changes in Land Surface (1958 – 1999) for a Commercial Area

Source: ARC (2001)

The impacts of development on the hydrologic regime of a site or watershed include the following:

- Loss or change of vegetation, resulting in reduced evapotranspiration and infiltration
- Soil compaction
- Reduced groundwater recharge and stream base flow
- Groundwater pollution or redirected drainage in karst terrain
- Increased imperviousness of the land surface

4.5.1.1. Loss or Change of Vegetation and Reduced Evapotranspiration and Infiltration

In a natural Virginia woodland or meadow, very little rainfall leaves the site as runoff. Runoff will occur from most wooded sites only after more than an inch of rain has fallen. Remember that in the hydrologic cycle, more than half of the annual amount of rainfall returns to the atmosphere through evapotranspiration. Surface vegetation, especially trees, transpires water to the atmosphere (with seasonal variations). Water is also stored in puddles, ponds and lakes on the earth's surface, where some of it will evaporate.

Evapotranspiration varies tremendously with season and with type of vegetative cover. Trees can effectively transpire most of the precipitation that falls in summer rain showers. Evapotranspiration dramatically declines during the winter season, since temperatures are lower and vegetation is dormant. During these periods, more precipitation infiltrates and moves through the root zone, and the groundwater level rises. Removing vegetation or changing the land type from woods and meadow to residential lawns reduces evapotranspiration, reduces infiltration and increases the amount of stormwater runoff.

Significantly, turf grass is now the largest crop grown in the Chesapeake Bay watershed – more than 3.8 million acres covering a staggering 9.5% of the watershed's total land area (**Figures 4.12 and 4.13**, and **Table 4.2** below). Overall, the amount of turf cover in the watershed appears to have tripled in the last three decades. About 75% of all turf grass in the watershed is devoted to home lawns.

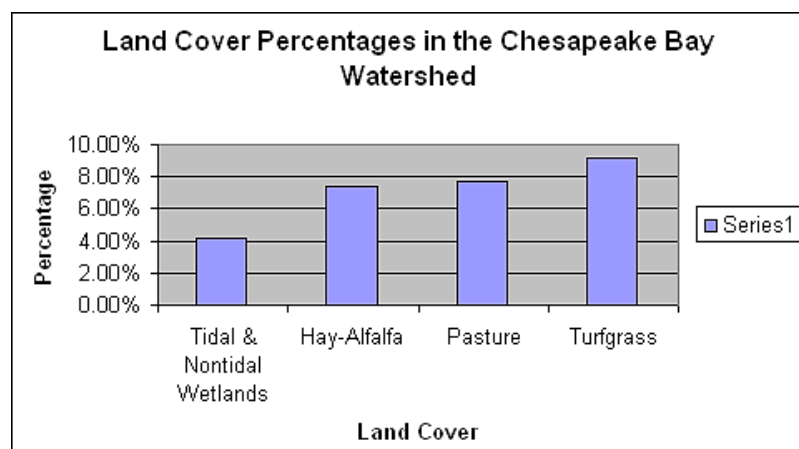


Figure 4.12. Comparative Land Coverages in the Chesapeake Bay Watershed (as a percent of total land area). Source: Schueler (2009a)

Table 4.2. Year 2001 Turf Cover Estimate Using a GIS and Satellite Data

State	Land Acres in Bay Watershed	Urban ¹ Turf Acres	Exurban ² Turf Acres	Total Turf Acres	Percent Land Area with Turf
MD	5,639,428	1,007,269	298,476	1,305,745	23.15%
VA	13,706,037	988,291	135,792	1,124,083	8.20%
PA	14,345,262	900,803	158,212	1,059,015	7.38%
DC	38,956	16,071	2,320	18,391	47.21%
DE	450,384	31,337	3,948	34,985	7.77%
NY	3,983,079	160,788	32,982	193,770	4.86%
WV	2,288,363	75,515	12,425	87,940	3.84%
Total	40,451,509	3,180,074	643,855	3,823,929	9.45%

¹ Urban area includes impervious and non-forested pervious surfaces in industrial, commercial, and residential areas with lot sizes generally less than 2 acres.

² Exurban areas represent all non-urban lands. The “urban recreational grass” land cover class was solely used to identify turf grass in exurban areas.

Source: Schueler (2009a)

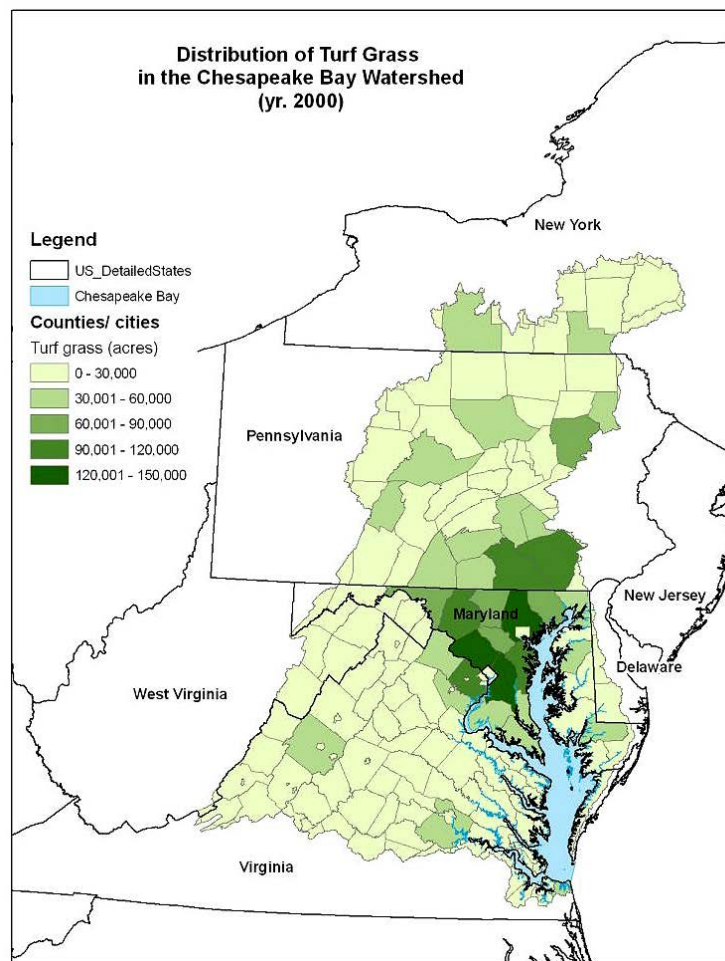


Figure 4.13. Distribution of Counties with High Turf Cover in the Chesapeake Bay Watershed. Source: Schueler (2009a)

Not only does managed turf produce more runoff than natural open space and forestland, but the management of turf involves the application of large amounts of fertilizer and pesticides. These chemicals ultimately find their way into urban runoff and add to the bulk pollution load that must be treated to protect our waterways. Consider the following facts (Schueler, 2009a):

- The annual biomass generated by lawn clippings is equivalent to 272 million bushels of corn.
- An estimated \$600 million annually is spent on lawn fertilizer and pesticides across the Bay watershed.
- The best estimate of nitrogen fertilizer applied to lawns in the Bay watershed is nearly 215 million pounds per year – enough to grow nearly 2 million acres of corn.
- About 19 million pounds of pesticide active ingredients are used each year (mostly herbicides to kill weeds). These pesticides are reaching local streams and rivers. According to USGS monitoring data, one or more pesticides were detected in 99% of urban streams, and one out of every five samples exceeded water quality standards, endangering aquatic life.
- Summer lawn irrigation is calculated to use nearly 7,875 cubic feet per second (cfs) of equivalent river flow to Bay during the summer months. To put this amount of water consumption in perspective, it is roughly five times the *combined* summer flow of the Choptank, James, Monocacy, Pataspsco, Pamunkey, Patuxent and Rappahannock rivers in an average year.
- Our compacted lawns are roughly calculated to produce an extra storm runoff flow of 1,244 cfs *each day* to the Chesapeake Bay.

Vegetation also intercepts and slows rainfall, reducing its erosive energy, reducing overland flow, and allowing infiltration to occur. The root systems of plants provide pathways for downward movement of water into the soil. Water that percolates through the soil either moves vertically or laterally (**Figure 4.14**). The vertical flow eventually reaches the zone of saturation (water table or aquifer) and is stored in the soil or rock. The lateral flow through the soil often emerges as springs or seeps, providing base flow for streams.

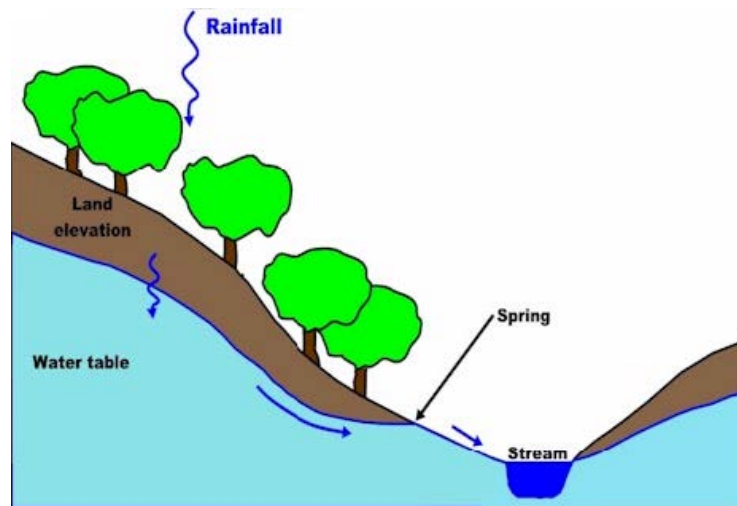


Figure 4.14. Relationship of infiltration to groundwater storage and stream base flow

Source: PA DEP (2006)

4.5.1.2. Soil Compaction

Soils form over time in response to their landscape position, climate, presence of organisms and as the geologic parent materials (rock) break down and mix with organic matter. Freezing, thawing, drying, biological activity, etc., crack and dissolve the parent material and give the soil a texture (based on the distribution of particles of various sizes – sand, silt and clay) and structure. Texture and structure usually vary with depth through a typical soil profile with A, B and C horizons (layers) above bedrock.

The ability of water to move into a soil (infiltrate) and down through the soil (percolate) is a function of soil texture or structure, which determines the amount of pore space (porosity) between the soil particles. Porosity is increased by channels form in the soil by plant roots, worms, etc. A good measure of a soil's porosity is the bulk density, or the weight per unit volume of soil. Lower bulk density reflects higher porosity and therefore easier movement of water.

When soil is disturbed by grading, stockpiling, and heavy equipment traffic, the soil becomes compacted, structure is lost and porosity decreases. When this happens, the soil's ability to take in water (permeability) is substantially reduced and surface runoff increases. Even if topsoil is stripped, stockpiled and reapplied following construction (a practice DEQ strongly recommends), the resultant loss of structure reduces the permeability of the topsoil. The loss of structure in the topsoil, together with compaction of the subsoil by construction equipment, is so profound that the bulk density of a lawn soil can approach that of concrete (**Figure 4.15** and **Table 4.3** below). The result is a surface that is *functionally impervious* because the soil's permeability is so greatly reduced.



Figure 4.15. Compacted Soil (Source: Center for Watershed Protection)

Table 4.3. Common Bulk Density Measurements

Land Surface/Use	Bulk Density
Undisturbed Lands Forest & Woodlands	1.03 g/cc
Residential Neighborhoods	1.69 to 1.97 g/cc
Golf Courses - Parks Athletic Fields	1.69 to 1.97 g/cc
Concrete	2.2 g/cc

The other chief factor that determines a soil's permeability is the soil's effective depth, as determined by the depth to bedrock, a natural or man-made dense soil layer, or the water table. These various factors have been used to group soils into hydrologic soil groups, based on their ability to infiltrate and percolate water (**Table 4.4**). It's an unfortunate fact that those soils most suitable for construction are often the soils with the highest permeability, a characteristic that is typically reduced or eliminated by the construction process.

Table 4.4. USDA-NRCS Estimates of Annual Groundwater Recharge Rates, Based on Soil Type

Hydrologic Soil Group (HSG)	Recharge Rate
Hydrologic Soil Group A	18 inches/year
Hydrologic Soil Group B	12 inches/year
Hydrologic Soil Group C	6 inches/year
Hydrologic Soil Group D	3 inches/year
NOTE: Average annual rainfall varies from approximately 42 - 48 inches across Virginia	

There is often a discontinuity of soil-water movement at the interface between soils of different textures or structures or in the presence of restrictive soil layers, including clay lenses, fragipans (commonly found in colluvial and glacial soils), and plow pans (compressed layers of soil formed by the repeated traversing by moldboard plows on farmland). In general, any interface between soil layers can slow the downward movement of water through a soil profile and promote lateral flow. This is especially true in sloping landscapes typical of the Piedmont and Ridge-Valley provinces of Virginia.

All of these factors have some effect on how water will move through the soil. It is important to understand these factors when designing an appropriate stormwater system at a particular location. These factors are especially critical when considering BMPs that rely on infiltration to remove runoff volume or pollutants.

4.5.1.3. Reduced Groundwater Recharge and Reduced Stream Base Flow

As shown in **Figure 4.14** above, eventually the groundwater table intersects the land surface and forms springs, first order streams and wetlands. Perennial streams receive continuous baseflow from this groundwater discharge, during both wet and dry periods. Much of the time, all of the natural flow in a stream is from groundwater discharge. In this sense, groundwater discharge can be seen as the "life" of streams, supporting all water-dependent uses and aquatic habitat. First-

order streams (**Figure 4.16**) are defined as “that stream where the smallest continuous surface flow occurs” (Horton, 1945), and are the beginning of the aquatic food chain that evolves and progresses downstream.



Figure 4.16. In headwater streams, leaves and organic matter are initially broken down by bacteria and processed into food for higher organisms downstream

Source: Chesapeake Bay Stormwater Training Partnership

During periods of wet weather, the water table may rise to near the ground surface in the vicinity of the stream. As a result, this area saturates quickly during rain events; and the larger the rain event, the more extensive the area of saturation may be. A significant amount of the surface runoff observed in streams during precipitation events is generated from the saturated areas surrounding streams (Chorley, 1978; Hewlett and Hibbert, 1967), referred to as *saturation overland flow*.

When stormwater runoff is allowed to drain away rather than recharge the groundwater, it alters the hydrologic balance of the watershed. As a consequence, stream base flow is deprived of constant groundwater discharge, and the flow may diminish or even cease. A perennial stream may develop intermittent flow, which could become an ephemeral channel, which could transition into a wetland area, which could eventually become so dry that it becomes upland habitat.

Wetlands and first order streams reflect changes in groundwater levels most profoundly, and the reduced flow can stress or even eliminate the aquatic community. 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 planning. As the link

between groundwater and surface water, headwaters represent the critical intersection between terrestrial and aquatic ecosystems.

During a drought, reduced stream base flow may also significantly affect the water quality in a stream. As the amount of water in the stream decreases, the oxygen content of the water often falls, affecting the fish and macroinvertebrates that live there. Reduced oxygen content can also create chemical reactions that release pollutants previously bound up in bottom sediments.

4.5.1.4 The Effects of Development on Drainage in Karst Terrain

The valleys of western Virginia are underlain largely by soluble limestone and dolomite geologic deposits, which slowly dissolved over the millennia to form karst hydrologic systems. The effects of urbanization are exacerbated in this setting, where groundwater flows rapidly through caves to aquifers and springs that supply drinking water and support the base flow of local streams. Prior to urbanization, much runoff reaches the epikarst (the zone of weathering at the upper surface of a limestone stratum) by diffuse infiltration through fractured bedrock. This water is released slowly into the underlying network of caves. After development, this runoff is typically routed overland to surface streams or discharged to karst features (e.g., sinkholes) that bypass the epikarst. This increases flood pulses in cave streams and associated springs. In either case, the base flow of springs and ambient groundwater levels are reduced and sinkholes can develop.

4.5.1.5 Increased Imperviousness of the Land Surface

Impervious cover has emerged as a measurable, integrating concept used to describe the overall health or, conversely, degradation of a watershed. Research has established that when impervious cover in a watershed reaches between 10 and 25 percent (**Figure 4.17**), ecological stress becomes apparent (Schueler et al., 2009). Beyond 25 percent impervious cover, stream stability is reduced, habitat is lost, water quality is degraded, and biological diversity is diminished.

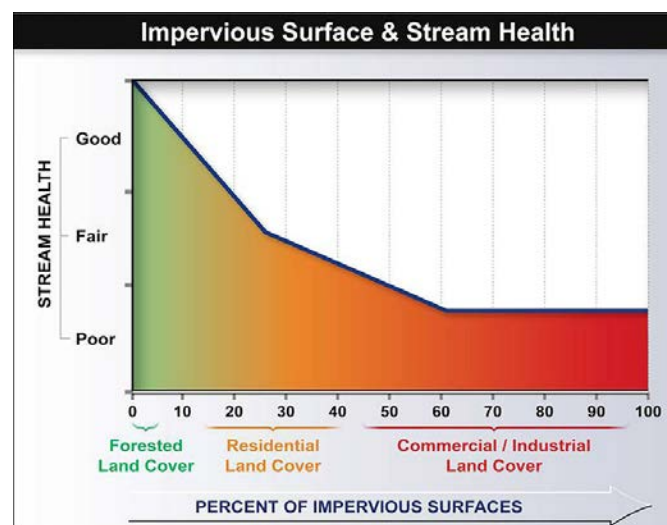


Figure 4.17. The Impervious Cover Model: How Imperviousness Impacts Stream Health. Source: Chesapeake Bay Stormwater Training Partnership

To put these thresholds into perspective, total imperviousness in typical single-family home residential neighborhoods ranges from 15 to 60 percent. **Table 4.5** below indicates typical percentages of site impervious cover for various land uses in the Northeastern United States. It is important to note that these tabulated values reflect impervious coverage within individual land uses, but they do not reflect overall watershed imperviousness, to which the ecological stress thresholds apply. However, in developed watersheds with significant residential, commercial, and industrial development, overall watershed imperviousness often exceeds the ecological stress thresholds.

Table 4.5. Typical Site Impervious Coverage of Land Uses in the Northeast U.S.

Land Use	% Impervious Cover
Commercial and Business District	65-100
Industrial	70-80
High Density Residential	45-60
Medium Density Residential	35-45
Low Density Residential	20-40
Open (Natural Areas)	0-10

Source: MADEP, 1997; Kauffman and Brant, 2000; Arnold and Gibbons, 1996; Natural Resource Conservation Service, 1975

4.5.1.6 Collective Impact of Development on the Hydrologic Cycle

Although the total amount of rainfall varies somewhat in different regions of the state, the basic average hydrologic cycle holds true (**Figure 4.18** below). Under natural woodland and meadow conditions, only a small portion of the annual rainfall becomes stormwater runoff.

Altering one component of the water cycle affects all other elements of the cycle. Roads, buildings, parking areas and other impervious surfaces prevent rainfall from infiltrating into the soil and significantly increase the amount of runoff. As natural vegetation is replaced with impervious surfaces, natural drainage patterns are altered; the amount of evapotranspiration and infiltration decreases, and runoff increases substantially.

Depending on the magnitude of changes to the land surface, the total runoff volume can increase dramatically. These changes not only increase the total volume of runoff, but also accelerate the rate at which runoff flows across the land. This effect is further exacerbated by drainage systems such as gutters, storm sewers (**Figures 4.19 and 20** below) and smooth-lined channels that are designed to quickly carry runoff to rivers and streams. Impervious surfaces also reduce the amount of water infiltrated into the soil and groundwater, thus reducing the amount of water that can recharge aquifers and feed streamflow during periods of dry weather.

The overarching conclusion of many studies is that the impact of urbanization on the hydrologic cycle is dramatic. Increased impervious area and drainage connectedness decreases stormwater travel times, increases flow rates and volumes, and increases the erosive potential of streams. The flooding caused by increased flows can be life-threatening and damaging to property. As described in the following sections, changes to the hydrologic flow regime also can have harmful effects on the geomorphic form of stream channels and the stability of aquatic ecosystems. Although these impacts are commonly ignored in efforts to improve “water quality,” they are

inextricably linked to measured changes in water chemistry and must be part of any attempt to recover beneficial uses that have been lost to upstream urbanization.

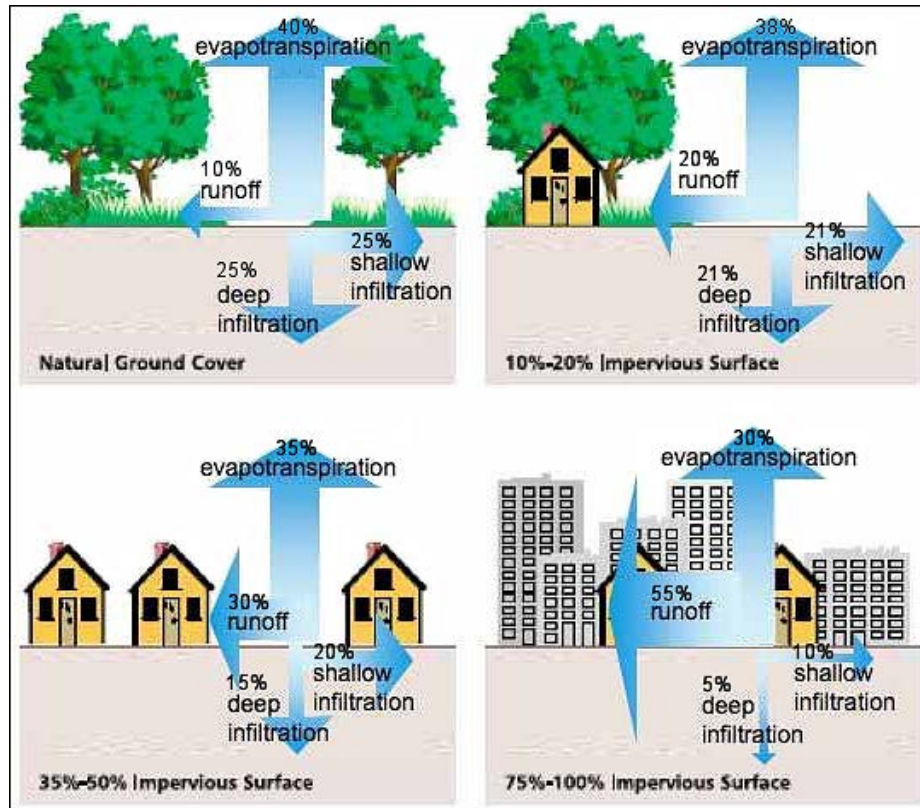


Figure 4.18. Relationship Between Impervious Cover and Surface Runoff.
Source: Federal Interagency SWRG (1998)



Figure 4.19. Impervious Cover Increases Stormwater Runoff and Pollutants.
Source: ARC (2001)



Figure 4.20. Constructed Storm Drainage System Components. Source: Chesapeake Bay Stormwater Training Partnership

4.5.2. Stream Channel and Floodplain Impacts

Increased peak discharges for a developed watershed can be two to five times higher than those for an undisturbed watershed. As runoff velocities increase, it takes less time for water to run off the land and reach a stream or other water body (time of concentration). Streams in developed areas are often characterized as very "flashy" or "spiky" because of their response to these altered runoff characteristics. This characterization translates into the sharp peak and increased size of the postdevelopment hydrograph as seen in **Figure 4.21** below, which depict typical pre-development and post-development streamflow hydrographs for a developed watershed. The combination of greater volumes of runoff more often and at higher flow rates can create altered stream flows, localized flooding, stream channel degradation and property damage, even in small storm events.

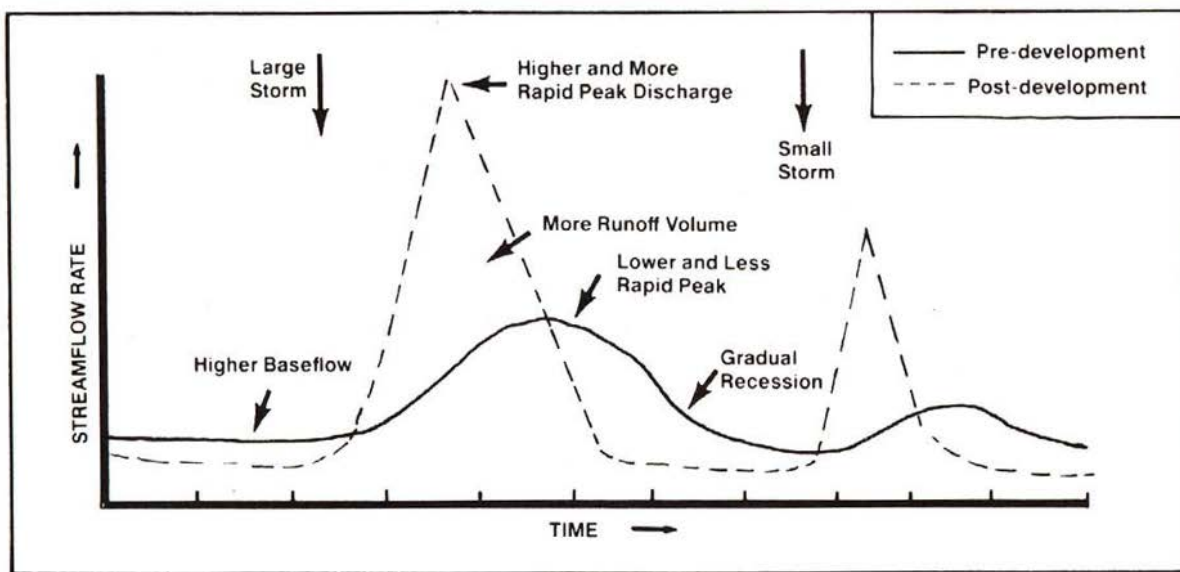


Figure 4.21. Pre- and Post-Development Stormwater Runoff Hydrographs

The impacts of altered stormwater runoff characteristics on stream channels and floodplains include the following:

- Altered stream flow
- Channel erosion, widening and downcutting
- Increased frequency of bank-full and over-bank floods
- Floodplain expansion

4.5.2.1. Altered Stream Flow

A comprehensive nationwide study by the United States Geological Survey (Carlisle et al., 2010) found that water flowing in streams and rivers has been significantly altered in nearly 90 percent of waters that were assessed (**Figure 4.22** below). Flow alterations are considered to be the primary contributor to degraded river ecosystems and loss of native species. The USGS

considers this assessment to provide the most geographically extensive analysis to date of stream flow alteration.

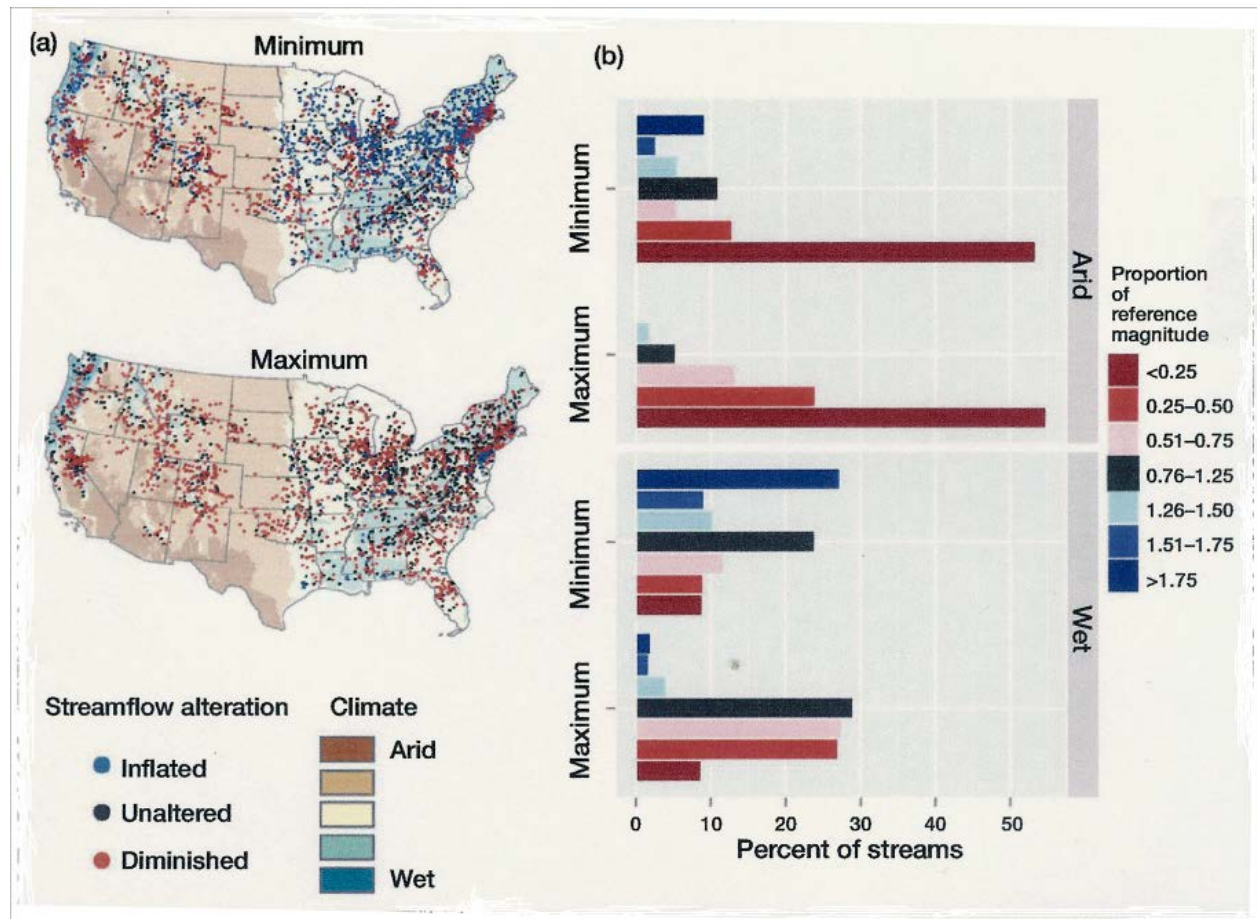


Figure 4.22. USGS Study Sites and Severity of Streamflow Alteration

Source: Carlisle et al (2010)

Annual and seasonal cycles of water flows – particularly the low and high flows – shape ecological processes in rivers and streams. An adequate minimum flow is important to maintain suitable water conditions and habitat for fish and other aquatic life. High flows are important because they replenish floodplains and flush out accumulated sediment that can degrade habitat. Flows are altered by a variety of land- and water-management activities, including reservoirs, diversions, subsurface tile drains, groundwater withdrawals, wastewater inputs, and impervious surfaces, such as parking lots, sidewalks and roads. In wet climates, like that in Virginia, watershed management is typically focused on flood control, which can result in lower maximum flows and higher minimum flows.

The USEPA's Wadeable Streams Assessment, a biological assessment of 1,392 randomly selected wadeable stream sites within the conterminous United States, estimated that 42% of the nation's wadeable stream length is in poor biological condition relative to existing reference site conditions (USEPA, 2006). Altered flow affects stream biota as much or more than pollution does.

As an area is urbanized, lower-order stream channels are typically re-routed or encased in pipes and paved over, resulting in a highly altered drainage pattern. The buried stream system is augmented by an extensive system of storm drains and pipes, providing enhanced drainage density (total lengths of pipes and channels divided by drainage area) compared to the natural system. **Figure 4.23** below shows how the drainage density of Baltimore, MD, today compares to the natural watershed before the modern stormwater system was fully developed. The artificial drainage system occupies a greater percentage of the landscape compared to natural conditions, *permanently altering the terrestrial component of the hydrologic cycle.*

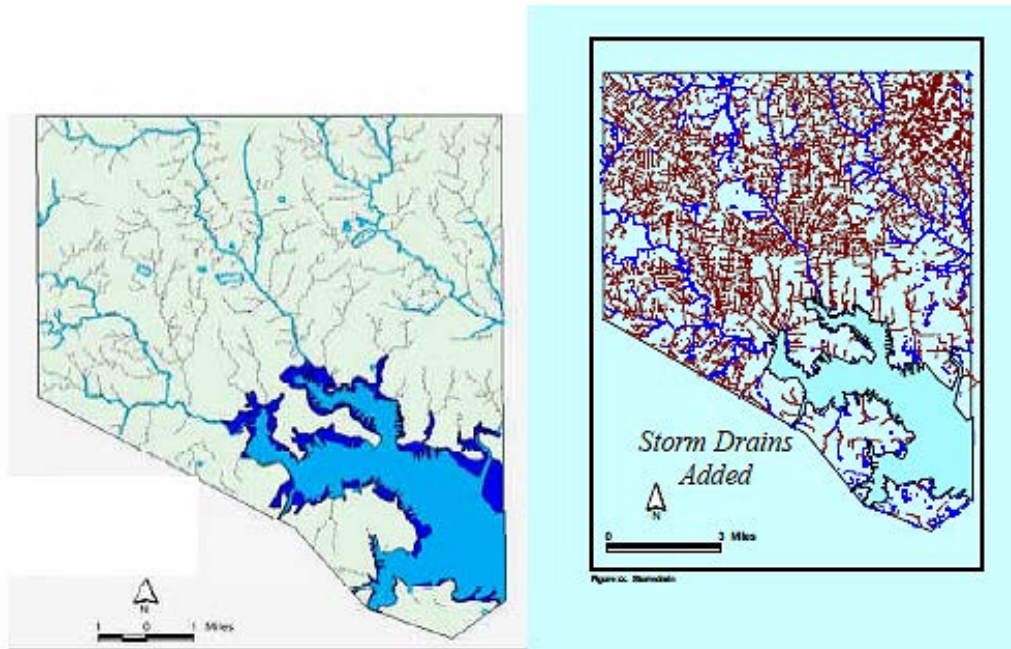


Figure 4.23. Baltimore City before and after development of its stormwater system. The left-hand panel shows first- and second-order streams lost to development. The right-hand panel shows the increase in drainage density resulting from construction of the modern storm-drain network.

SOURCE: Courtesy of William Stack, Baltimore Department of Public Works.

4.5.2.2. Channel Erosion, Widening, and Downcutting

Numerous studies have documented the link between altered stream channels and land development. Notably, the Center for Watershed Protection contends that land development influences both the morphology and stability of stream channels, causing downstream channels to enlarge through widening and stream bank erosion (CWP, 1999). Increased stormwater runoff volume can turn small meandering streams into highly eroded and deeply incised stream channels (**Figure 4.24**).

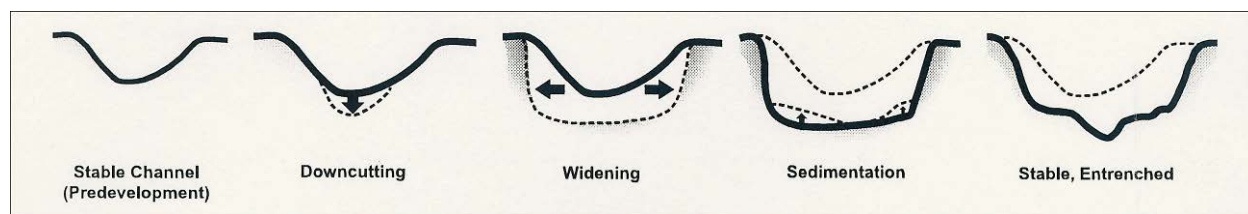


Figure 4.24. Typical Changes to a Stream's Physical Character Due to Watershed Development

Stream meander and the resulting erosion and sedimentation are natural processes, and all channels are in a constant process of incremental alteration. However, as the runoff volume from each storm is increased, natural stream channels experience more frequent bank-full or nearly bank-full conditions. As a result, streams change their natural shape and form. The majority of this stream channel devastation is intensified during the frequently occurring small-to-moderate rainfall events, rather than major flooding events.

Stream channels widen to accommodate and convey the increased runoff and higher stream flows from developed areas. More frequent small and moderate runoff events undercut and scour the lower parts of the streambank, causing the steeper banks to slump and collapse during larger storms. Higher flow velocities further increase streambank erosion rates.

Rainfall events, or *storms*, are typified by their total rainfall, time span, and average and peak intensity. Storms are ranked in terms of the statistical frequency of their return interval (NRC 2008). For example, a storm that has a 50% chance of occurring in any given year is termed a “2-year” storm (i.e., it is statistically likely to occur once every two years).

Traditionally, the 2-year storm was believed to represent the typical bankfull flow of a stream channel, because earlier research had indicated that most natural stream channels in the Commonwealth have just enough capacity to carry the 2-year flow without spilling out of the stream's banks. In Virginia, a 2-year storm produces from 2.5 to 5.2 inches of rain in a 24-hour period. Less annual rainfall occurs in the ridge and valley province, with more in the Piedmont. Southeastern Virginia and the eastern slopes of the Blue Ridge typically experience the most annual rainfall. The majority of the state experiences from 3.2 to 3.6 inches of rain from a two-year 24-hour storm (NOAA Atlas 14). This rainfall depth is called the 2-year design storm.

In recent years, scientists have conducted much research on stream channels to improve their understanding of how channels are formed naturally and how degraded channels can be restored to their natural equilibrium. The research indicates that channel forming flows vary, depending upon the channel's setting in the landscape. Stream channels in urban areas may be formed by flows as little as the 0.9-year storm, whereas channels in rural areas are typically formed by the 1.5-year to 1.7-year storm (i.e., a storm that is statistically likely to occur once every 18 to 21 months).

However, the channel-forming storm varies with each stream channel, depending on a number of physical characteristics. Fortunately, scientists have determined methods for determining the channel-forming storm level for any particular stream section. For regulatory purposes, most states have begun to establish the 1-year 24-hour storm event as the average channel-forming

storm. In Virginia, a 1-year storm produces from approximately 1.9 to 3.2 inches of rain in a 24-hour period. However, the majority of the state experiences from 2.6 to 3.0 inches of rain from a 1-year 24-hour storm (NOAA Atlas 14). This rainfall depth is called the 1-year design storm.

Similarly, a storm that has a 10% chance of occurring in any given year is termed a 10-year storm. In Virginia, a 10-year storm produces from approximately 3.5 to 8 inches of rain in a 24-hour period. However, the majority of the state experiences from 4.8 to 5.5 inches of rain from a 10-year 24-hour storm (NOAA Atlas 14). Under traditional engineering practice, most channels and storm drains in Virginia are designed with enough capacity to safely pass the peak discharge from a 10-year design storm.

The Committee on Reducing Stormwater Discharge Contributions to Water Pollution and common sense indicate that accurate and well-maintained long-term records of precipitation are “vital and nontrivial” to stormwater regulation. For a network of precipitation gauge data, visit the National Climatic Data Center online at <http://www.ncdc.noaa.gov/oa/ncdc.html> or the Cooperative Weather Observer Program at <http://www.nws.noaa.gov/om/coop/>. Additionally, the National Weather Service offers a service that estimates the return period for a range of depth-duration events. It can be found at <http://www.nws.noaa.gov/om/coop/>. Considering the implications of changing precipitation patterns, as discussed above, it is paramount to update applicable I-D-F curves in order to guarantee stormwater management facilities will be able to accommodate more intense precipitation.

The shape of a stream channel (i.e., 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. The stream channel’s physical shape and character (morphology) is determined by the energy of typical stream flows ranging from “low flow” to “bankfull”. The flow depths determine the energy of the water in the stream channel, and this energy shapes the channel itself. During bankfull flows, the speed (velocity) of the water flow is typically at its maximum. If these high-velocity flows last long enough or occur often enough, they can generate enough energy to scour soil from streambanks and transport sediment and rocks from the stream bottom. During larger flood events, the flow overtops the stream banks and flows into the floodplain. As the flow spreads out, velocity is reduced, resulting in much less impact on the shape of the stream channel itself.

In a developing watershed, bankfull flows occur more often. The volume and flow rate of stormwater runoff increase during small storm events and the stream channel changes to accommodate the greater flows. Greater flows occurring more often and for longer periods of time will erode the stream banks and cut down the channel bottom, configuring the stream channel geometry for these larger flows. A stream can become many times wider than its original size due to post-development runoff (**Figure 4.25** below). As streambanks are gradually undercut and slump into the channel, trees that had protected the banks are exposed at the roots. This leaves them more likely to be uprooted during major storms, further weakening bank structure.



Figure 4.25. Stream Channel Widening

Source: Center for Watershed Protection

Another way that streams accommodate higher flows is by downcutting their streambed (**Figure 4.26**). This causes instability in the stream profile, or elevation along a stream's flow path, which increases velocity and triggers further channel erosion both upstream and downstream.



Figure 4.26. Stream Channel Downcutting

Source: ARC (2001)

Shoreline and bank erosion diminish property values. In fact, many urban governments find themselves engineering degraded stream channels, straightening them and lining them with concrete, in order to prevent further erosion and speed the stormwater through their jurisdiction. Unfortunately, sooner or later that concrete channel ends, and the higher-volume, higher-velocity flows are released into a natural stream channel further downstream. This merely transfers the

damage into another part of the stream at someone else's property and, perhaps, in another jurisdiction.

Traditionally, stormwater managers have used detention basins to capture (detain) excess stormwater runoff and slowly release it over a period of days into the receiving stream channel. However, the release rate of flow from the basin typically mimics the bankfull flow. Stormwater rules have attempted to assure that runoff from development sites should not exceed the capacity of the receiving stream channel.

In Virginia, this requirement has been translated into not exceeding a 2-year 24-hour design storm, originally considered to be the bankfull storm. Virginia has required that the peak rate of discharge from the 2-year storm applied to the post-development site conditions be reduced to the pre-development rate of discharge. The problem is that, unlike a normal "flashy" rainstorm, after which runoff flow recedes rather quickly, the outflow from a detention basin often exposes the channel to a longer *duration* of erosive flows than it would have otherwise received. Thus, in order to prevent flooding, the stream bed and banks stay wet and subject to high-velocity flows for a longer period of time, which makes them more susceptible to erosion. Therefore, channel deterioration is often most pronounced downstream of detention basins or where similar stormwater management practices are placed as a result of land development.

These physical changes, in turn, degrade stream habitat and produce substantial increases in sediment loads resulting from accelerated channel erosion. The typical stream bed structure of pools, riffles and meanders disappears. Sediments are deposited in the stream as sandbars and other features, covering the channel bed, or substrate.

4.5.2.3. More Frequent Bankfull and Flooding Events

Flows that exceed the capacity of the stream channel spill over onto adjacent floodplains. These are termed *overbank* or *out-of-bank* floods. They can damage property and downstream drainage structures. In many watersheds throughout the state, flooding problems have increased over time due to the changes in land use and ineffective stormwater management. As noted above, this increase in stormwater volume is the direct result of more extensive impervious surface areas, combined with substantial tracts of natural landscape being converted to lawns on highly compacted soil. Increased runoff volumes and peak flows increase the frequency and duration of smaller bankfull and near bankfull events (**Figure 4.27** below), which are the primary channel forming events.



Figure 4.27. More Frequent Bankfull and Near Bankfull Flows

Source: ARC (2001)

While some overbank flooding is inevitable and even desirable, the historical goal of drainage design in most of Virginia has been to maintain pre-development peak discharge rates for both the two- and ten-year frequency storms after development, aiming to keep the level of overbank flooding the same over time, thus preventing or limiting costly damage or maintenance for culverts, drainage structures, and swales, as well as damage to personal property. This design method reduces runoff volumes and peak flows but increases the frequency, duration and severity of out-of-bank flooding, as shown in **Figure 4.28** below. Flooding accounts for larger annual property losses than any other single geophysical hazard (Riley, 1985).



Figure 4.28. Out-of-Bank Flooding Endangers Human Life and Property

Source: ARC (2001)

4.5.2.4. Floodplain Expansion

The level areas bordering streams and rivers are known as floodplains. Operationally, the floodplain is usually defined as the land area within the limits of the water elevation of the 100-year storm flow. The 100-year storm has a 1% chance of occurring in any given year. The 100-year storm typically serves as the basis for controlling development and establishing insurance rates by the Federal Emergency Management Agency (FEMA). In most of Virginia, a 100-year storm results in approximately 8 to 9 inches of rainfall in a 24-hour period. Floods of this scale can be very destructive and can pose a threat to human life. Floodplains are natural storage areas that help to attenuate downstream flooding.

Floodplains are very important habitat areas, encompassing riparian forests, wetlands, and wildlife corridors. Consequently, all local jurisdictions in Virginia restrict or even prohibit new development within the 100-year floodplain, to prevent flood hazards and conserve habitats. Nevertheless, prior development that has occurred in the floodplain remains subject to periodic flooding during these storms.

Development sharply increases the peak discharge rate associated with the 100-year design storm. As a consequence, the elevation of a stream's 100-year flood crest and floodplain becomes higher and the boundaries of its floodplain expand laterally (see **Figure 4.29** below). This problem is compounded by building and filling in floodplain areas, which cause flood heights to rise even further. In some instances, property and structures that had not previously been subject to flooding become at risk. Additionally, such a shift in a floodplain's hydrology can degrade wetlands and forest habitats.

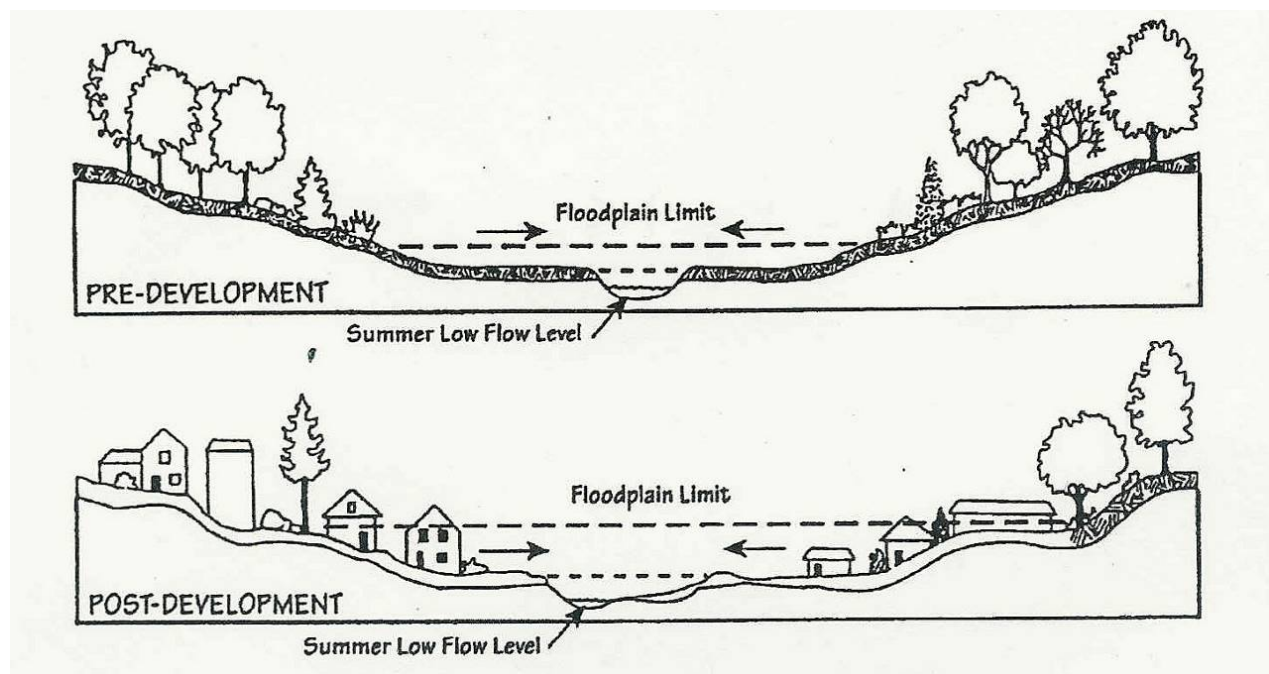


Figure 4.29. Response of Stream Geometry to Land Development

4.5.3. Habitat and Ecological Impacts

As the shape of the stream channel changes to accommodate more runoff, aquatic habitat is often lost or altered, and aquatic species decline. Destruction of freshwater wetlands, riparian buffers, and springs often occurs as a result of land development. 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.

4.5.3.1. Degradation of Habitat Structure

Higher and faster flows due to development can scour channels and wash away entire biological communities. 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 stream banks are eroded and this material is deposited along the stream bottom, burying the substrate material of the stream bed, which is habitat for many benthic organisms.

4.5.3.2. Loss of Pool-Riffle Structure

Streams draining undeveloped watersheds often contain pools of deeper, more slowly flowing water that alternate with "riffles" or shoals of shallower, faster flowing water. These pools and riffles provide valuable habitat for fish and aquatic insects. As a result of the increased flows and sediment loads from urban watersheds, the pools and riffles disappear and are replaced with wider, more uniform streambeds that provide less varied aquatic habitat. Because the channels are so much larger, low flows become much shallower. As a result, the number of fish and aquatic insects diminishes and the species change.

4.5.3.3. Reduced Baseflows

As noted above, reduced baseflows – due to increased impervious cover in a watershed and the loss of rainfall infiltration into the soil and water table – adversely affect in-stream habitats, especially during periods of drought.

4.5.3.4. Increased Stream Temperature

Runoff from warm impervious areas, storage in impoundments, loss of shading as riparian trees and shrubs topple or are removed, and shallower channels can all cause an increase in the water temperature in urban streams. Increased temperatures can reduce dissolved oxygen levels and disrupt the food chain. Certain aquatic species can only survive within a narrow temperature range. Thermal problems are especially critical for many Piedmont streams which straddle the borderline between cold water and warm water stream conditions. This issue is discussed further, in the context of water quality degradation, in **Section 4.5.4.11** below

4.5.3.5. Shift in Aquatic Food Sources

A shift takes place from external food sources (leaf matter) for the aquatic species to internal stream production (algal organic matter). This also results in diminished biomass.

4.5.3.6. Decline in Abundance, Richness and Biodiversity of the Stream Community (aquatic insects, fish, amphibians, etc.)

Just as weeds can invade and overwhelm preferable vegetation when conditions provide the opportunity, less desirable species begin to replace desirable species in degraded streams when there is a reduction in various habitats and habitat quality. Both the number and the variety (diversity) of organisms (wetland plants, fish, macroinvertebrates, etc.) are reduced. Sensitive fish species and other life forms disappear and are replaced by those organisms that are better adapted to the poorer conditions. For example, in streams with severely diminished flow, native trout, a popular sport fish that requires cold, fast-flowing streams with gravel bottoms, are replaced by less desirable non-native species, such as carp. The diversity and composition of the benthic, or streambed, community have frequently been used to evaluate the quality of urban streams.

Aquatic insects are a useful environmental indicator, since they form the base of the stream food chain. **Table 4.6** summarizes trends in macroinvertebrate and fish traits at sites with various forms of altered streamflow magnitudes. Understanding the ecological effects of these flow alterations can help water managers develop effective strategies to ensure that water remains sufficiently clean and abundant to support fisheries and recreation opportunities, while simultaneously supporting economic development.

Table 4.6. Summary of Trends in Macroinvertebrate and Fish Traits at Sites – with Various Forms of Altered Streamflow Magnitudes—Across the Conterminus U.S.

Source: Carlisle et al (2010)

Trait	Community	Diminished Minimum	Diminished Maximum	Inflated Minimum
Reproductive strategy	Fish	Nest guards replace simple nesters	Broadcast spawners replace simple nesters	Broadcast spawners replace simple nesters
Morphology / locomotion	Fish	Active swimmers replace benthic and streamlined forms	Active swimmers replace benthics	None observed
	Macro-invertebrates	Active swimmers replace taxa with slow crawling rates	Active swimmers replace taxa with slow crawling rates	None observed
Exit ability	Macro-invertebrates	Increased taxa with exit ability	Increased taxa with exit ability	None observed
Geomorphic and substrate preference	Fish and macro-invertebrates	Pool taxa preferring fine-grained substrates replace riffle taxa preferring coarse substrates	Pool taxa preferring fine-grained substrates replace riffle taxa preferring coarse substrates	Increased taxa preferring riffles (macro-invertebrates only)

4.5.3.7. Creation of barriers to fish migration

Structures such as dams inhibit fish from migrating to their upstream spawning grounds, resulting in declines of certain fish species. In recent years across the Chesapeake Bay watershed, states and communities have engaged in the construction of fish ladders (e.g., the Boshier Dam on the James River in Henrico County) and, in a number of cases, the breaching of dams in order to restore fish migration patterns to Bay watershed rivers. For example, in February 2004 the Embury Dam on the Rappahannock River in Fredericksburg was breached, reopening 71 miles on the main stem of the Rappahannock River and 35 miles of the Rapidan River to migratory shad and herring for spawning and rearing habitat.

4.5.3.8. Water Quality Impacts on Aquatic Species

Fish and other aquatic organisms are impacted not only by the habitat changes brought on by increased stormwater runoff quantity, but are often also adversely affected by water quality changes due to development and resultant land use activities in a watershed (**Figure 4.30**). These impacts are discussed more specifically in the next section (**Section 4.5.4**) of this chapter.

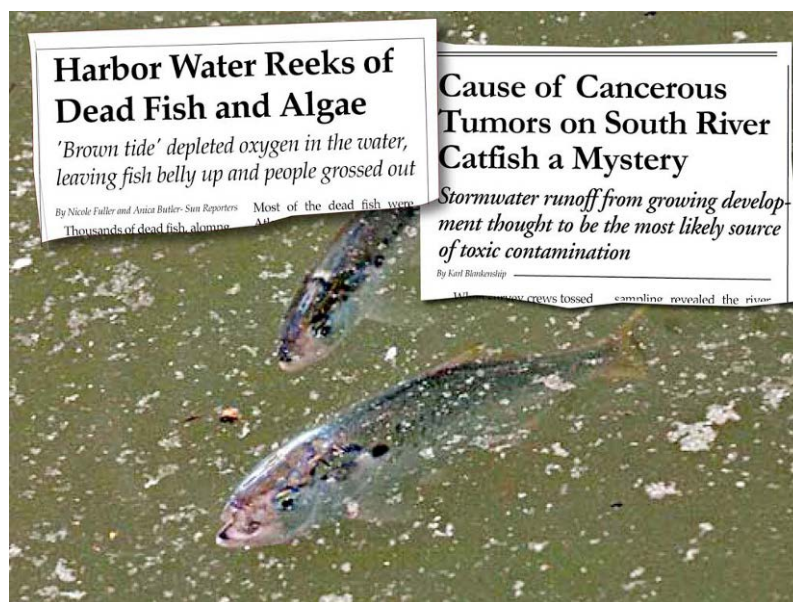


Figure 4.30. Fish Kills. Source: Chesapeake Bay NEMO Program

4.5.4. Water Quality Impacts

Point and nonpoint source water pollution from pipes, streets, rooftops, and parking lots swell downstream waterways every time it rains. Since the natural vegetation and soils that could absorb it have been paved over, stormwater becomes a high-speed, high-volume conduit for pollution into streams, rivers, lakes and coastal waters (**Figure 4.31** below).

Distribution of Impaired* Waters in Virginia's Watersheds

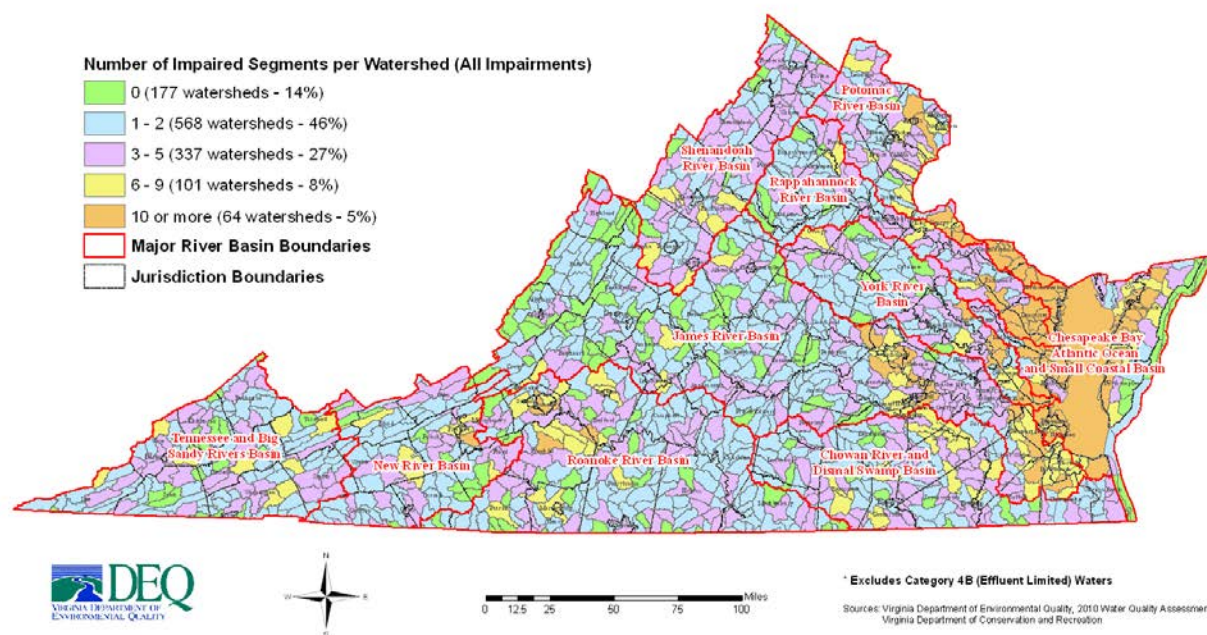


Figure 4.31. Impaired Waters in Virginia

Source: Virginia DEQ (2010)

Urban stormwater runoff can be considered both a point source and a nonpoint source of pollution. Stormwater runoff that flows into a conveyance system and is discharged through a pipe, ditch, channel, or other structure is considered a *point source* because it discharges from a discrete location (point on a map). Stormwater runoff that flows across the land surface and is not concentrated in a defined channel or pipe is considered *nonpoint source (NPS)* pollution, which is the primary cause of polluted stormwater runoff and water quality impairment.

NPS pollution comes from many diffuse or scattered sources, many of which are the result of human activities within a watershed. Development concentrates and increases the amount of these nonpoint source pollutants. As stormwater runoff moves across the land surface, it picks up and carries away both natural and human-made pollutants, depositing them into Virginia's streams, rivers, lakes, wetlands, coastal waters and marshes, and underground aquifers.

In most cases stormwater runoff begins as a nonpoint source and becomes a point source discharge. Both point and nonpoint sources of urban stormwater runoff have been shown to be significant causes of water quality impairment to rivers and streams. Urban runoff is also reported as a contributor to excessive nutrient enrichment in numerous lakes and ponds throughout the state, as well as a continued threat to estuarine waters and the Chesapeake Bay.

Most Virginia cities have separate stormwater sewer systems through which stormwater discharges directly into waterways. These storm flows often cause streambank erosion and carry pollutants directly into waterways. However, in older cities such as Richmond and Lynchburg, some stormwater flows into the same pipes as sewage. This sometimes results in combined sewer overflows (CSOs), dumping untreated human, commercial, and industrial waste into

waterways. Contaminated stormwater from CSOs is required to be controlled under the Clean Water Act and Virginia laws and regulations. However, progress is slow because the problems are large and multi-faceted, and the solutions are very expensive and time-consuming to accomplish.

The USEPA has ranked stormwater runoff as the second most prevalent source of water quality impairment in the nation's estuaries (agriculture is currently ranked as number one). At least in the Chesapeake Bay watershed, urban stormwater runoff appears to be the only pollution source that continues to increase. With the large projected increase in population expected in Virginia, urban stormwater issues will likely become much more significant in the near future and could rival agriculture as the number one impact to water quality. This is especially true since large areas of agricultural lands are expected to be developed for urban and suburban uses (**Figure 4.32**).



Figure 4.32. Conversion of Agricultural Land to Residential Development

Source: AECOM

Water quality degradation in urbanizing watersheds starts when the land development process begins. Erosion from construction sites and other disturbed areas (**Figure 4.33** below) can potentially contribute large amounts of sediment to streams. As construction and development proceed, impervious surfaces replace the natural land cover and pollutants from human activities begin to accumulate on these surfaces. During storm events, these pollutants are then washed off into the streams. Stormwater also causes discharges from sewer overflows and leaching from failing septic drainfields. There are a number of other causes of NPS pollution in urban areas that are not specifically related to wet weather events, including leaking sewer pipes, sanitary sewage spills, fluid leaks from vehicles, residue from tire wear, and illicit discharge of commercial/industrial wastewater and wash waters to storm drains.



Figure 4.33 Construction Site Erosion

Source: Chesapeake Bay Stormwater Training Partnership

Structural stormwater collection and conveyance systems allow stormwater pollutants to quickly wash off and concentrate during rainfall or snowmelt events and discharge to downstream receiving waters. By contrast, in undeveloped areas, natural processes such as infiltration, interception, depression storage, filtration by vegetation, and evaporation can reduce the quantity of stormwater runoff and remove pollutants. Impervious areas decrease the natural stormwater purification functions of watersheds and increase the potential for water quality impacts in receiving waters.

Many areas assumed to be pervious, such as lawns and landscaped areas, also add significantly to the pollutant load, especially where these pervious areas drain to impervious surfaces and storm sewers. As noted above, compacted soils at many land development sites result in vegetated surfaces that are, in many instances, nearly impervious and produce far more runoff than the natural (pre-development) soil did. These new lawn surfaces are often loaded with fertilizers that result in polluted runoff that degrades receiving streams, ponds, and lakes.

Urban land uses and activities can also degrade groundwater quality if stormwater with high pollutant loads is directed into the soil without adequate treatment. Certain land uses and activities, referred to as stormwater “hotspots” (e.g., commercial parking lots, vehicle service and maintenance facilities, fuel stations, etc.), are known to produce higher loads of pollutants such as trace metals, petroleum hydrocarbons and toxic chemicals (**Figure 4.34** below). Soluble pollutants from hotspot sites can migrate into groundwater and potentially contaminate wells in groundwater supply areas (aquifers). The potential for groundwater pollution from stormwater is even greater in regions of karst geologic formations, where seams and channels dissolved in the limestone base material can quickly transport pollutants into perched groundwater and deeper aquifers.



Figure 4.34. Fueling Stations Can Be Stormwater Hotspots
Source: Chesapeake Bay Stormwater Training Partnership

Many older studies of pollutant transport in stormwater have documented that pollutant concentrations showed a distinct increase at the beginning of a flow hydrograph referred to as the “*first flush*” (typically considered the first 1/2-inch of runoff from impervious surfaces during the first half-hour of a storm). In fact, the particulate-associated pollutants that are initially scoured from the land surface and suspended in the runoff are generally observed in a stream or river *before* the runoff peak occurs. This pattern has helped to stimulate the concept of a first flush of stormwater pollutants. These pollutants include sediment, phosphorus that is moving with colloids (clay particles), metals, petroleum products, and organic particles and litter. Capturing the first flush pollutant load was the focus of the quality control criteria of Virginia’s earlier stormwater management regulations.

However, more recently, researchers have found that the actual transport process of stormwater pollutants is somewhat more complex than the first flush would indicate. This has been the subject of numerous technical papers (Cahill et al, 1974: 1975; 1976; 1980; Pitt, 1985, 2002). Some studies have shown that the first flush makes up only about 20% of the annual runoff pollution load and rainfall volumes of 1-inch or more must be treated to capture the majority of the load. Other research indicates that dissolved pollutants, although still contributing to total load, may actually decrease in concentration during heavy runoff, but their total load may continue to increase throughout a storm (Hager, 2001). These include nitrate, salts and some synthetic organic compounds applied to the land for a variety of purposes. Therefore, capturing the first flush does not necessarily ensure effective treatment of the majority of pollution in runoff.

Due to the magnitude of the problem, it is important to understand the nature and sources of urban stormwater pollution. **Table 4.7** below lists the main pollutants found in urban stormwater runoff, typical pollutant sources, related impacts to receiving waters, and factors that promote pollutant removal. The Table also identifies the pollutants that commonly occur in dissolved or soluble form, which has important implications for the selection and design of stormwater treatment practices. Concentrations of pollutants in stormwater runoff vary considerably between sites and storm events. More detailed descriptions of those pollutant categories follow.

Table 4.7. Summary of Urban Stormwater Pollutants

Stormwater Pollutant	Potential Sources	Receiving Water Impacts	Removal Promoted by ¹
Excess Nutrients Nitrate, Nitrite, Ammonia, Organic Nitrogen, Phosphate, Total Phosphorus	Animal waste, fertilizers, failing septic systems, landfills, atmospheric deposition, erosion and sedimentation, illicit sanitary connections	Algal growth, nuisance plants, ammonia and nitrate toxicity, reduced clarity, oxygen deficit (hypoxia), pollutant recycling from sediments, decrease in submerged aquatic vegetation (SAV), eutrophication, loss of recreation and aesthetic value	Phosphorus: Filtering/settling sediment, high soil exchangeable aluminum and/or iron content, vegetation and aquatic plants, alum in pond Nitrogen: Aeration, alternating aerobic and anaerobic conditions, maintaining near neutral pH (7)
Sediments Suspended, dissolved, sorbed pollutants, turbidity	Construction sites, stream bank erosion, washoff from impervious surfaces	Increased turbidity, lower dissolved oxygen, deposition of sediments, aquatic habitat alteration, sediment and benthic toxicity, contaminant transport, filling of lakes and reservoirs, loss of recreation and aesthetic value	Low turbulence, increased residence time
Pathogens Total and Fecal Coliforms, Fecal Streptococci, Viruses, E. Coli, Enterocci	Animal waste, failing septic systems, illicit sanitary connections	Human health risk via drinking water supplies, contaminated swimming beaches, and contaminated shellfish consumption	High light (ultraviolet radiation), increased residence time, media/soil filtration, disinfection
Organic Materials Vegetation, sewage, other oxygen demanding materials (BOD/COD)	leaves, grass clippings, brush, failing septic systems	Dissolved oxygen depletion, odors, fish kills, algal growth, reduced clarity	Aerobic conditions, high light (ultraviolet radiation), high soil organic content, maintaining near neutral pH
Hydrocarbons Oil and grease	Industrial processes, commercial processes, automobile wear, emissions, and fluid leaks, improper oil disposal	Toxicity of water column and sediments, bioaccumulation in food chain organisms	Low turbulence, increased residence time, physical separation or capture technique, volatilization
Metals Copper, lead, zinc, mercury, cadmium, chromium, nickel, aluminum (soluble)	Industrial processes, normal wear of automobile brake linings and tires, automobile emissions and fluid leaks, metal roofs and pipes	Toxicity of water column and sediments, bioaccumulation in food chain organisms	High soil organic content, high soil cation exchange capacity, maintaining near neutral pH (7), controlling sludge applications
Synthetic Organic Chemicals Pesticides, VOCs, SVOCs, PCBs, PAHs (soluble)	Residential, commercial, and industrial application of herbicides, insecticides, fungicides, rodenticides, industrial processes, commercial processes	Toxicity of water column and sediments, bioaccumulation in food chain organisms	Aerobic conditions, high light (ultraviolet radiation), high soil organic content, low levels of toxicants, near neutral pH (7), high temp. and air movement for volatilization of VOCs
Deicing Constituents Sodium chloride, calcium chloride, potassium chloride, ethylene glycol, other pollutants (soluble)	Road salting and uncovered salt storage, snowmelt runoff from snow piles in parking lots and along roads during the spring snowmelt season or during winter rain and snow events	Toxicity of water column and sediments, contamination of drinking water, harmful to salt-intolerant plants; concentrated loadings of other pollutants as a result of snowmelt	Aerobic conditions, high light (ultraviolet radiation), high soil organic content, low levels of toxicants, near neutral pH (7)
Trash and Debris	Litter washed through the storm drain networks	Degradation of aesthetics, threat to wildlife, potential clogging of storm drainage	Low turbulence, physical straining/capture
Thermal Impacts	Runoff with elevated temperatures from contact with impervious surfaces (asphalt)	Dissolved oxygen depletion, adverse impacts to aquatic organisms that require cold and cool water conditions	Use of wetland plants and trees for shading, increased pool depths
Freshwater Impacts to Saltwater	Stormwater discharges to tidal wetlands and estuarine environments	Dilution of the high marsh salinity and encouragement of the invasion of brackish or upland wetland species, such as Phragmites	Stormwater retention and volume reductions

¹ Factors that promote removal of most stormwater pollutants include: (1) Increasing hydraulic residence time; (2) Low turbulence; (3) Fine, dense, herbaceous plants; and (4) Medium-fine textured soil

Source: Adapted from Connecticut DEP, 1995, Metropolitan Council, 2001; Watershed Management Institute, Inc., 1997

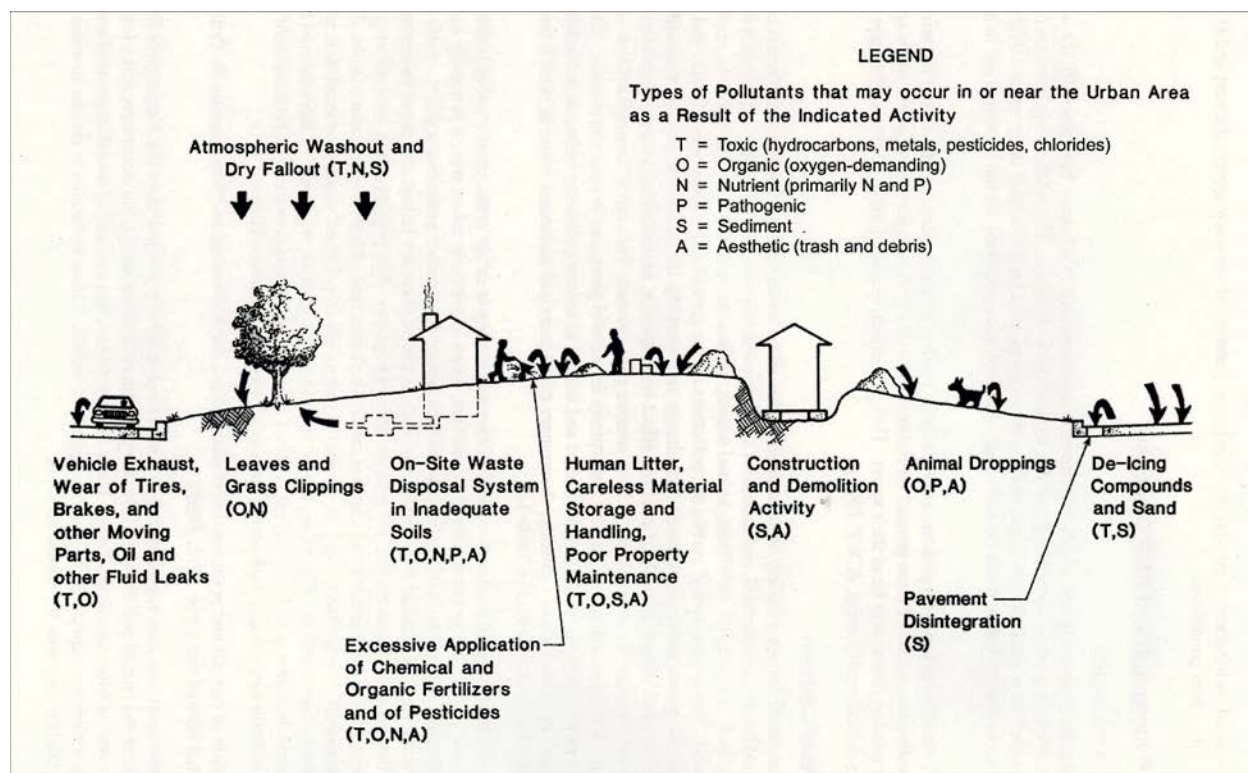


Figure 4.35. Availability of Potential Pollutants on the Land Surface

Source: Walesh (1989)

4.5.4.1. Particulates and Solutes

One very important distinction for stormwater pollutants is the extent to which the pollutants exist in a solid (*particulate*) form, or are dissolved in the runoff (as *solutes*). The best example of this comparison is the two common fertilizer components: phosphate ($\text{PO}_4\text{-P}$) and nitrate ($\text{NO}_3\text{-N}$). Phosphorus is usually bound to colloidal soil particles, so stormwater management practices that rely on physical filtering and/or settling of sediment particles can be quite successful at removing phosphorus. In stark contrast, nitrate tends to occur in highly soluble forms, and is unaffected by many of the structural BMPs designed to eliminate suspended pollutants. As a consequence, stormwater management BMPs for nitrate may be quite different than those used for phosphorous removal. Non-structural (typically vegetative) treatment practices may in fact be the best at removing nitrate from runoff.

Particulates: Stormwater pollutants that move in association with or attached to solid particles include total suspended solids (TSS), total phosphorus (TP), most organic matter (as estimated by Chemical Oxygen Demand, or COD), metals, and some herbicides and pesticides. Kinetic energy keeps particulates in suspension; clays and fine silts settle much more slowly and tend to stay suspended. These suspended particles result in turbidity that can extend for many miles in streams or keep ponds and lakes looking muddy for a long time after a storm. For this reason, 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 fine clay particles that may take longer to settle out.

Because most of the particulate-associated pollutants are transported with the smallest particles (or *colloids*), their removal by stormwater control measures is especially difficult. These colloids are so small that they do not settle out in a quiescent pool or basin, but remain in suspension for days at a time, passing through detention basins with the outlet discharge. It is possible to add chemicals (e.g., alum, PAM) to a detention basin to coagulate these colloids to promote settling. However, these chemicals turn a natural stream channel or pond into a treatment unit, and subsequent removal of sludge is required. A variety of manufactured stormwater control measures 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 quickly become clogged, especially during major storm events. Of course, one could argue that if the filter systems become clogged, they are performing efficiently at removing particulate material from the runoff. However, this means that substantial maintenance is required for all filtering (and to some extent settling) measures. The more numerous and distributed these control measures are within the built conveyance system, the greater the removal efficiency, but also the greater the cost for operation and maintenance.

Solutes: Dissolved stormwater pollutants generally do not exhibit any increase during storm event runoff, and in fact may exhibit a slight dilution over a given storm hydrograph. Dissolved stormwater pollutants 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 some watersheds, the stormwater transport of soluble pollutants can represent a major portion of the total annual load for a given pollutant, even though the absolute concentration remains relatively constant.

Some dissolved stormwater 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 – Nitrogen Oxide (NOX) and Sulfer Dioxide (SOX). Chesapeake Bay scientists have measured rainfall with Nitrate (NO₃) concentrations of 1 to 2 mg/L, which could comprise a significant fraction of the total input to the Bay. Studies by the NOAA and the USGS have resulted in similar conclusions. Impervious pavements can transport nitrates, reflecting a mix of deposited sediment, vegetation, animal wastes, etc.

4.5.4.2. Excess Nutrients

Nutrients are a major source of degradation in many of Virginia’s water bodies. Urban stormwater runoff typically contains elevated concentrations of nitrogen and phosphorus compounds that are most commonly derived from lawn fertilizer, detergents, animal waste, atmospheric deposition, organic matter, sewer overflows and leaks, and improperly installed or failing septic systems. Elevated nutrient concentrations in stormwater runoff can result in

excessive growth of vegetation or algae in streams, lakes, reservoirs, and estuaries (**Figure 4.36** below), a process known as accelerated eutrophication. Nitrates can contaminate groundwater supplies.



Figure 4.36. Algae Bloom in the James River

Source: Richmond Times-Dispatch

Excessive nitrogen loadings have led to hypoxia, a condition of low dissolved oxygen, in the Chesapeake Bay and the lower reaches of some of Virginia's major rivers. Phosphorus in runoff has impacted the quality of many of Virginia's lakes and ponds, which are susceptible to eutrophication from phosphorus loadings. Nutrients are also detrimental to submerged aquatic vegetation (SAV). Nutrient enrichment can favor the growth of epiphytes (small plants that grow attached to other things, such as blades of eelgrass) and increase amounts of phytoplankton and zooplankton in the water column, thereby decreasing available light for the SAV. Excess nutrients can also favor the growth of macroalgae, which can dominate and displace eelgrass beds and dramatically change the food web (Deegan et al., 2002).

Phosphorus is typically the growth-limiting nutrient in freshwater systems, while nitrogen is growth-limiting in estuarine and marine (saltwater) systems. This means that in marine waters algal growth usually responds to the level of nitrogen in the water, and in fresh waters algal growth is usually stimulated by the level of available (soluble) phosphorus (Connecticut DEP, 1995). Urban runoff has been defined as a key and controllable source of nutrients by the USEPA Chesapeake Bay Program. Virginia has committed to reducing tributary loadings of phosphorus, nitrogen and sediment from developing consistent with the most current iteration of the Commonwealth's Chesapeake Bay Watershed Implementation Plan (WIP-2, 2012).

4.5.4.3. Sediments/Suspended Solids

Sediment loading to water bodies occurs from washoff of particles that are deposited on impervious surfaces such as roads and parking lots, soil erosion associated with land disturbance activities, and streambank erosion. Although some erosion and sedimentation is natural, excessive sediment loads can be detrimental to aquatic life including phytoplankton, algae,

benthic invertebrates, and fish, by interfering with photosynthesis, respiration, growth, and reproduction. Solids can either remain in suspension or settle to the bottom of the water body. Suspended solids can make the water cloudy or turbid (**Figure 4.37**), detract from the aesthetic and recreational value of a water body, and harm SAV, finfish, and shellfish. Sediment transported in stormwater runoff can be deposited in a stream or other water body or wetland and can adversely impact fish and wildlife habitat by smothering bottom dwelling aquatic life and changing the bottom substrate.



Figure 4.37. A Sediment Plume Entering a River

Source: ARC (2001)

Sediment deposition in water bodies can reduce the capacity of reservoirs and lakes and result in the loss of deep-water habitat, affecting navigation and often necessitating dredging. As noted above, sediment transported in stormwater runoff can also carry other pollutants such as nutrients, metals, pathogens, and hydrocarbons. High turbidity due to sediment increases the cost of treating drinking water and reduces the value of surface waters for industrial and recreational use. Sediment also fills ditches and small streams and clogs storm sewers and pipes, causing flooding and property damage.

4.5.4.4. Pathogens

Pathogens are bacteria, viruses, and other microbes that can cause disease in humans. The presence of bacteria, such as fecal coliform or enterococci, is used as an indicator of pathogens and of potential risk to human health (Connecticut DEP, 1995). Pathogen concentrations in urban runoff routinely exceed public health standards for water contact recreation and shellfish harvesting. High pathogen levels also increase the cost of treating drinking water. Sources of pathogens in stormwater runoff include animal waste from pets, wildlife, and waterfowl;

combined sewer overflows; failing septic systems; and illegal sanitary sewer cross-connections. High levels of indicator bacteria in stormwater have commonly led to the closure of beaches and shellfish beds along coastal areas of Virginia.

4.5.4.5. Organic Materials

Oxygen-demanding organic substances, such as grass clippings, leaves, animal waste, and street litter, are commonly found in stormwater. As with excess nutrients, the decomposition of such substances in water bodies can fuel bacterial and algal growth, depleting oxygen from the water. Organic matter is of primary concern in water bodies where oxygen is not easily replenished, such as slower moving streams, lakes, and estuaries. It is a particular concern in the Chesapeake Bay because the Bay's average depth is unusually shallow. An additional concern for unfiltered water supplies is the formation of trihalomethane (THM), a carcinogenic disinfection byproduct generated by the mixing of chlorine with water high in organic carbon (New York DEC, 2001).

4.5.4.6. Hydrocarbons

Oils, greases and gasoline contain a wide array of hydrocarbon compounds. Some of these have proven to cause tumors, cancer and mutations in certain species of fish, even at low concentrations (Woodward- Clyde, 1990). In large quantities, oil can impact drinking water supplies and affect recreational use of waters. Oils and other hydrocarbons are washed off roads and parking lots, primarily due to engine leakage from vehicles, the primary source of hydrocarbons in urban runoff. Other sources include the improper disposal of motor oil in storm drains and streams, spills at fueling stations, and restaurant grease traps. Source areas with high concentrations of hydrocarbons in stormwater runoff include roads, parking lots, gas stations, vehicle service stations, residential parking areas, and bulk petroleum storage facilities.

4.5.4.7. Trace Metals

Metals such as copper, lead, zinc, mercury, aluminum, chromium, nickel and cadmium are commonly found in urban stormwater runoff. The following are the primary sources of these metals in stormwater:

- Industrial and commercial sites, including marinas
- Urban surfaces such as rooftops and painted areas
- Residue from vehicle anti-freeze, exhaust systems, brakes and tires
- Fossil fuel combustion
- Corrosion of galvanized and chrome-plated products
- The application of deicing agents
- Improperly disposed of household chemicals
- Landfills
- Hazardous waste sites
- Atmospheric deposition

Antifreeze from automobiles is a source of phosphates, chromium, copper, nickel, and cadmium. Architectural copper associated with building roofs, flashing, gutters, and downspouts has been shown to be a source of copper in stormwater runoff (Barron, 2000; Tobiason, 2001). Marinas

have also been identified as a source of copper and aquatic toxicity to inland and marine waters (Sailer Environmental, Inc. 2000). Washing or sandblasting of boat hulls to remove salt and barnacles also removes some of the bottom paint, which contains copper and zinc additives to protect hulls from deterioration. Discharge of metals to surface waters is of particular concern. Metals can be toxic to aquatic habitat and organisms and can contaminate drinking water supplies and impair human health.

Although metals generally attach themselves to the solids in stormwater runoff or receiving waters, recent studies have demonstrated that dissolved metals – particularly lead, copper, cadmium and zinc – are the primary toxicants in stormwater runoff from industrial facilities (Mas et al., 2001; New England Bioassay, Inc., 2001). Additionally, stormwater runoff can contribute to elevated metals in aquatic sediments. The metals can become bio-available where the bottom sediment is anaerobic (without oxygen), such as in a lake or estuary, and they can bioaccumulate in the food chain. Metal accumulation in sediments has resulted in more difficult maintenance dredging operations in estuaries, where the contaminated sediments require special handling.

4.5.4.8. Pesticides/Synthetic Organic Chemicals

Synthetic organic chemicals can also be present at low concentrations in urban stormwater. Pesticides, phenols, polychlorinated biphenyls (PCBs), and polynuclear or polycyclic aromatic hydrocarbons (PAHs) are the organic compounds most frequently found in stormwater runoff. Such chemicals can exert varying degrees of toxicity to aquatic organisms and can bioaccumulate in fish and shellfish. Toxic organic pollutants are most commonly found in stormwater runoff from industrial areas. Pesticides are commonly found in runoff from urban lawns and street or road rights-of-way (New York DEC, 2001). A review of monitoring data on stormwater runoff quality from industrial facilities has shown that PAHs are the most common organic toxicants found in roof runoff, parking area runoff, and vehicle service area runoff (Pitt et al., 1995).

4.5.4.9 Chlorides/Deicing Constituents

Salting of roads, parking lots, driveways, and sidewalks during winter months and snowmelt during the early spring result in the discharge of sodium, chloride, and other deicing compounds to surface waters via stormwater runoff. Excessive amounts of sodium and chloride may have harmful effects on water, soil and vegetation and can also accelerate corrosion of metal surfaces, which results in even more pollution. Drinking water supplies, particularly groundwater wells, may be contaminated by runoff from roadways where deicing compounds have been applied or from transportation agency facilities where salt mixes are improperly stored. In addition, sufficient concentrations of chlorides may prove toxic to certain aquatic species. Excess sodium in drinking water can lead to health problems in infants (“blue baby syndrome”) and individuals on low sodium diets.

Other deicing compounds may contain nitrogen, phosphorus, and oxygen demanding substances. Deicing compounds can cause the release of other pollutants that had been trapped in ice or snow. The pollutant loading during snowmelt can be significant and can vary considerably during the course of the melt event (New York DEC, 2001). For example, a majority of the

hydrocarbon load from snowmelt occurs during the last 10 percent of a winter storm event and towards the end of the snowmelt season (Oberts, 1994). Similarly, PAHs, which are hydrophobic materials, remain in the snowpack until the end of the snowmelt season, resulting in highly concentrated loadings (Metropolitan Council, 2001). Other pollutants such as sediment, nutrients, and hydrocarbons are released from the snowpack during the spring snowmelt season and during winter rain-on-snow events.

4.5.4.10. Trash and Debris

Trash and debris are washed off of the land surface by stormwater runoff and can accumulate in storm drainage systems and receiving waters (**Figures 4.38 and 4.39** below). Litter detracts from the aesthetic value of water bodies and can harm aquatic life and wildlife either directly (by being mistaken for food) or indirectly (by habitat modification). For example, many photos have appeared in various media of animals and birds trapped in a “necklace” of plastic that once held together a six pack of soft drinks. Other animals have been found starved to death because their stomachs were full of plastic materials confused for food.

In smaller streams, debris can cause blockage of the channel, which can result in localized flooding and erosion. Sources of trash and debris in urban stormwater runoff include residential yard waste, commercial parking lots, street refuse, combined sewers, illegal dumping, and industrial refuse. Virginia citizens regularly participate in community river clean-ups focused on removing such debris from our waterways.



Figure 4.38. Trash Accumulated at a Curb Inlet.
Source: Center for Watershed Protection



Figure 4.39. Trash and Debris along a River
Source: ARC (2001)

4.5.4.11. Thermal Impacts

When stream flow is comprised primarily of groundwater discharge, the constant cool temperature of the groundwater buffers variations in stream temperature. As the flow of groundwater decreases and the amount of surface runoff increases, the temperature regime of the stream changes. Water temperatures are increased due to shallow ponds and impoundments

along a watercourse, as well as fewer trees along streams to shade the water. As well, when runoff flows over impervious surfaces, such as asphalt and concrete, it increases in temperature before reaching a stream or pond.

Runoff from impervious surfaces in the summer months can be significantly 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. Temperature changes can severely disrupt certain aquatic species, such as trout and stoneflies, which can survive only within a narrow temperature range.

Since warm water holds less dissolved oxygen than cold water, thermal pollution further reduces oxygen levels in depleted urban streams. Important fungal communities can be lost altogether. It is apparent that increasing impervious areas can lead to significant degradation of surface water by altering the entire aquatic ecosystem.

Land clearing for development can reduce stream surface shading. Direct exposure of sunlight to shallow ponds and impoundments as well as unshaded streams may further elevate water temperatures. Elevated water temperatures can exceed fish and invertebrate tolerance limits, reducing survival and lowering resistance to disease. Coldwater fish such as trout may be eliminated, or the habitat may become marginally supportive of coldwater species when the water temperature rises only a few degrees.

Studies have shown that when stream surface shade is reduced to 35%, trout populations can drop by as much as 85% (CBP, 1998; Galli, 1991). Stream and shoreline buffers also contribute to better water quality, which means better fish habitat and therefore more productive fisheries. Elevated water temperatures also contribute to dissolution of solutes in water bodies.

4.5.4.12. Freshwater Impacts

Discharge of freshwater, including stormwater, into brackish and tidal wetlands can alter the salinity and hydroperiod of these environments, which can result in the incursion of invasive species such as Phragmites.

4.5.5. Impacts on Other Receiving Environments

The majority of research on the ecological impacts of urbanization has focused on streams. However, urban stormwater runoff has also been shown to adversely impact other receiving environments such as karst systems, wetlands, lakes, and estuaries. Development alters the physical, geochemical, and biological characteristics of wetland systems. Lakes, ponds, reservoirs, estuaries, wetlands, and submerged aquatic vegetation are impacted through deposition of sediment and particulate pollutant loads, as well as accelerated eutrophication caused by increased nutrient loadings.

Table 4.8. Effects of Urbanization on Other Receiving Environments

Receiving Environment	Impacts
Wetlands	<ul style="list-style-type: none"> ! Changes in hydrology and hydrogeology ! Increased nutrient and other contaminant loads ! Compaction and destruction of wetland soil ! Changes in wetland vegetation ! Changes in or loss of habitat ! Changes in the community (diversity, richness, and abundance) of organisms ! Loss of particular biota ! Permanent loss of wetlands (e.g., concentrated stormwater can erode a channel to a critical depth and drain a wetland)
Lakes and Ponds	<ul style="list-style-type: none"> ! Impacts to biota on the lake bottom due to sedimentation ! Contamination of lake sediments ! Water column turbidity ! Aesthetic impairment due to floatables and trash ! Increased algal blooms and depleted oxygen levels due to nutrient enrichment, resulting in an aquatic environment with decreased diversity ! Contaminated drinking water supplies
Estuaries	<ul style="list-style-type: none"> ! Sedimentation in estuarial streams and SAV beds ! Altered hydroperiod of brackish and tidal wetlands, which results from larger, more frequent pulses of fresh water and longer exposure to saline waters because of reduced flow ! Hypoxia (oxygen starvation) ! Turbidity ! Bio-accumulation of harmful chemicals ! Loss of SAV due to nutrient enrichment and/or turbidity ! Scour of tidal wetlands and SAV ! Short-term salinity swings in small estuaries caused by the increased volume of runoff which can impact key reproduction areas of aquatic organisms
Karst Systems	<ul style="list-style-type: none"> ! Erosion and underground sediment deposits ! Decreased recharge of the karst aquifer ! Spikes of waterborne pathogens in drinking water supplies following storms ! Deposition of sediment, reducing storage capacity and increasing turbidity within the karst aquifer ! Increased fluctuation in water levels, resulting in land subsidence (i.e., sinkhole formation), both on and off the site ! Increased flashiness and sediment load of down-gradient springs ! Impacts to habitat for globally rare, subterranean obligate fauna, in both aquatic and riparian habitats ! Plugging of karst conduits, due to sedimentation and trash/debris

Source: Adapted from WEF and ASCE, 2998

Lakes and reservoirs do not flush contaminants as quickly as streams. Consequently, they act as sinks for nutrients, metals and sediments. Estuaries experience increased sedimentation and pollutant loads and more extreme variations in salinity caused by increased pulses of runoff and reduced base flow. These rapid pulses or influxes of fresh water from higher in the watershed may be two to ten times greater than normal and may lead to a decrease in the number of aquatic organisms living in the unique estuarine environment. Tidal flows can also effectively trap and

concentrate pollutants. Karst systems are also impacted by deposition of sediment and particulate pollutant loads and can transport chemical, biological and physical contaminants associated with stormwater directly to drinking water supplies and surface springs. **Table 4.8** above summarizes the effects of urbanization on these receiving environments.

4.6 SOCIAL AND ECONOMIC IMPACTS OF STORMWATER ON VIRGINIA COMMUNITIES

The effects of urban stormwater runoff are not only environmental, but also have very real social and economic impacts on Virginia's communities. These include the following, some of which have been mentioned above:

- ***Endangerment of human life from floodwaters.*** Land development changes the hydrology of a watershed such that increased runoff peak flows and volumes can potentially overwhelm under-designed stormwater drainage facilities, structural controls and downstream conveyances, putting human life and property at risk. Floodwaters can cause driving hazards by overtopping roadways and washing out bridges, as well as carrying sediment and debris onto streets and highways.
- ***Property and structural damage due to flooding.*** Due to upstream development, properties that were previously outside the 100-year floodplain may now find themselves subject to flood damage. Areas that previously flooded only once every 10 years may now flood far more frequently and with more severity. Increased property and infrastructure damage can also result from stream channel widening, undersized runoff storage and conveyance facilities, and development in the floodplain.
- ***Loss of Reservoir Capacity.*** As the velocity of storm flows entering large lakes and reservoirs suddenly slows, sediment settles out of the water column. Over time, the volume of sediment fills in the reservoir, displacing water supply volume.
- ***Impairment of Drinking Water Supplies (Surface and Groundwater).*** Water quality degradation from polluted stormwater runoff can contaminate both surface and groundwater drinking water supplies and potentially make them unfit for a community's use.
- ***Increased Cost of Treating Drinking Water.*** Even if a drinking water supply remains viable, heavy concentrations of contaminants such as sediment and bacteria can increase the costs of water treatment to a community and water customers.
- ***Increased Cost of Remediating Pollution and Other Damages.*** Once our water becomes polluted and streams become otherwise degraded – especially if state water quality standards are violated – states and communities must engage in remediation projects. A good example of this is the Chesapeake Bay Program, where hundreds of millions of dollars have been spent over the past 25 years, but we still have a long way to go to having a truly restored Bay.
- ***Loss of Recreational Opportunities on Streams, Lakes, Rivers and Ocean Beaches.*** Turbidity from sediment, odors, floating trash, toxic pollutants and microbial contamination from stormwater runoff all reduce the viability of water bodies for recreational activities such as swimming, boating and fishing. In addition, the aesthetic loss along these waterways also reduces the experience for non-contact recreation such as picnicking, jogging, biking, camping and hunting.
- ***Declining Property Values of Waterfront Homes and Businesses.*** Stormwater pollution affects the appearance or quality of downstream water bodies, influencing the desirability of

working, living, traveling or owning property near the water. For example, shoreline and bank erosion diminish property values. One Maryland study (Van de Verg and Lent, 1994) determined that property values for Chesapeake Bay shoreline homes in Maryland would decline on average \$3,474 *per annual foot of erosion*. That cost would be much higher today.

- ***Loss of Sport and Commercial Fisheries.*** Commercial fisheries are a significant part of Virginia's economy. A number of Virginia waters are *not* safe for fish consumption. A significant part of the problem is attributable to polluted surface water runoff. This income from fisheries can quickly decline when water quality declines. Pollutants can contaminate or suffocate fish, as well as degrade fish habitat. In 1989 the USEPA estimated that stormwater runoff costs the commercial fish and shellfish industries approximately \$17 million to \$31 million per year. High levels of nutrients associated with stormwater runoff have been linked to fish kills caused by the toxic dinoflagellate *pfiesteria piscicida*. According to the Maryland Sea Grant Extension Program, *pfiesteria* cost the Chesapeake Bay seafood industry \$43 million in 1997, and the recreational fishing industry \$4.3 million.
- ***Closure of Shellfish Harvesting Areas.*** Many of Virginia's estuaries are *not* safe for shellfish consumption due to bacterial contamination. A major source of this impairment is stormwater runoff.
- ***Increased Litigation.*** Increased legal action can result against local governments that have not adequately addressed stormwater runoff drainage and water quality problems or against developers or private citizens who do not comply with stormwater management requirements.
- ***Reduction in Quality of Life.*** Stormwater quantity and quality impacts can reduce the overall quality of life in a community and make it a less desirable place to live, work or play.

4.7. THE ECONOMIC BENEFITS OF GOOD STORMWATER MANAGEMENT

The economic value of the Chesapeake Bay is estimated to be nearly \$1 trillion to the economies of Virginia and Maryland through commercial fishing, marine trade, water recreation and tourism, port activities, and land values (Chesapeake Bay Blue Ribbon Finance Panel, 2004; CBF, 2011; CBF, 2012; NOAA, 2008; Senate of Virginia, 2011).

The irony of placing an economic value on water and other natural resources is that, for the most part, the services of these resources are freely available to those who wish to use them. However, poorly managed stormwater runoff from human activity can have negative impacts on water resources. Such consequences also have a negative *economic* impact on the value of these water resources to others who wish to use them. The person creating the negative impact may be transferring at least part of the cost of carrying out his or her activities onto other property owners or the general public, who will end up paying the costs through taxes and user fees. For example, the USEPA (1999) estimated that because of urban runoff pollution, hundreds of millions of dollars are lost each year through added government expenditures, illness, or loss of economic output.

There are two types of economic benefits of implementing sound stormwater management regulations and programs: (1) income generated by economic activities that rely on water and related natural resources; and (2) a reduction in or avoidance of costs which may result from

environmental degradation and consumption of natural resources. These benefits are listed in **Table 4.9** below.

The benefits listed may be direct benefits, indirect benefits, or diversionary benefits. Direct benefits of water quality improvement include enhanced recreational water activities and reduced exposure to contaminants. Indirect benefits include enhancement of near-stream recreational activities, or the quality of residing, working, or traveling near water. Diversionary benefits include avoided water storage replacement costs and water treatment costs.

Table 4.9. Economic Benefits of Sound Stormwater Management

Watershed Protection Tool	Economic Benefit
Open Space Protection – forest conservation, wetland protection, preservation of parkland and open space	<ul style="list-style-type: none"> • Income from recreation and tourism • Increased property values • Reduction of energy costs, health care costs, flood control and stormwater quality and quantity treatment costs
Aquatic Buffers – Resource Protection Areas, stream buffers	<ul style="list-style-type: none"> • Enhanced aquatic habitat • Income from fishing • Increased property values • Reduction of flood control and stormwater quality and quantity treatment costs • Reduction of stream channel erosion and related degradation • Reduction of stream restoration costs
Environmental Site Design – cluster development, reduction of impervious cover, natural stormwater conveyances	<ul style="list-style-type: none"> • Increased property values • Reduction of construction, maintenance, and infrastructure costs • Reduction of flood control and stormwater quality and quantity treatment costs
Erosion and Sediment Control – channel protection, limiting clearing and grading, construction site erosion and sediment control	<ul style="list-style-type: none"> • Reduction of dredging costs • Improved income from marine and port activities • Reduction of drinking water treatment costs • Increased property values • Reduction of construction costs • Reduction of stream restoration costs
Stormwater Management Practices – stormwater management regulations, floodplain protection, etc.	<ul style="list-style-type: none"> • Increased property values • Reduction of flood damage costs • Reduction of flood control costs • Reduction of stream channel erosion and related degradation • Reduction of stream restoration costs • Improved water quality in our streams and rivers • Protected or improved aquatic habitat • Enhanced recreational opportunities • Lower water supply and laundry supply costs

Source: Adapted from DCR and CWP-2001

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