RESIDENTIAL STORMWATER: METHODS FOR DECREASING RUNOFF AND INCREASING STORMWATER INFILTRATION

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INTRODUCTION

Humans and plants depend on an adequate supply of clean water for numerous reasons, from food production to sustaining terrestrial and aquatic life. The average Virginia resident uses about 47 gallons (178 L) of fresh water daily (VDEQ 2008). While a majority of Virginians are provided water from a centralized, public utility, there are nearly two million Virginia residents who depend on well water as their main source (VDH 2008). Replenishing groundwater withdrawals depends on recharge (water moving from the surface to groundwater) from infiltration of precipitation through permeable surfaces in the environment; an important part of the hydrologic, or water, cycle (VDEQ 2010). Forests and grasslands provide much of the available recharge area due to their high capacities to infiltrate precipitation. However, the urbanization process is rapidly converting forested areas and grasslands to commercial, residential, or industrial developments.

FIGURE 1. Site grading—changing forested sites into suburban developments. (Photo courtesy Stephen Mosberg)

This conversion creates a significant increase in impervious surfaces such as concrete, asphalt, building roofs, and even compacted vegetated sites (U.S. EPA 2003). Impervious surfaces decrease infiltration and groundwater recharge. They also generate increases in stormwater runoff; defined as any precipitation from a rain or snow event that flows off of an impervious surface. As water runs off urban impervious surfaces, it picks up sediment, oils, debris, nutrients, chemicals, and bacteria. The runoff is then

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FIGURE 2. Stream channel erosion from stormwater runoff. (Photo courtesy Stephen Mosberg)

collected in a conveyance system, transported, and discharged to surface waters such as creeks and rivers; most of the time without any type of water quality treatment (U.S. EPA 2003; Paul and Meyer 2001). In addition to carrying pollutants, the runoff is also typically warmer than the receiving surface waters.

The increased volume and velocity of the stormwater runoff erodes soil and stream channels and can lead to stream "blow out." Water quality is degraded and aquatic habitats are adversely altered (Meyer, et al. 2005, Booth and Jackson 1997). Due to the interconnected nature of watersheds, the degraded water travels downstream causing subsequent problems. The effect of increased development is an increase in stormwater runoff and associated pollutants into surface waters and a decrease in infiltration for groundwater recharge and stream base flows.

Traditional practices for mitigating stormwater runoff impacts have targeted the management of peak runoff by using storage facilities such as detention and retention ponds.

Mounting evidence that these methods are inadequate prompted the National Research Council in 2008 to advocate a shift to Low Impact Development (LID) practices to better meet stormwater quality and quantity management goals. LID is based on a set of techniques used in Prince Georges County, Maryland (Prince Georges County 1999). LID seeks to restore the natural hydrology of a site by minimizing the creation of impervious surfaces and increasing infiltration of runoff volume. The ineffectiveness of conventional management approaches and the implementation of the Chesapeake Bay and other critical watershed Total Maximum Daily Loads (TMDLs) caused Virginia to revise its entire process for regulating stormwater. LID and Environmental Site Design (ESD) practices are now used to design sites to meet hydrologic goals and to treat runoff to meet a net site nutrient export standard (Battiata et al. 2010). As of the date of this paper, 15 of these best

FIGURE 3. A detention pond for stormwater runoff from a new commerical development. (Photo courtesy Stephen Mosberg)

management practices, or BMPs, have been approved for use by Virginia (Virginia Stormwater BMP Clearinghouse 2011). Similar approaches are being considered and adopted in other Chesapeake Bay jurisdictions, as well as nationally.

The responsibility of stormwater management can be fragmented between state, local, and municipal government (Roy, et al. 2008), often differing from watershed to watershed. Because LID is decentralized, it changes the management focus from a large, regional scale to a site scale. Changes at the residential lot level can generate much greater infiltration over the watershed. Each homeowner can significantly reduce the stormwater load leaving their property, thereby improving surface water quality and helping to recharge groundwater reserves. From a green building perspective, LID techniques can provide a substantial credit under the LEEDS-ND (Leadership in Energy and Environmental Design-Neighborhood Development) program. The objective of this paper is to provide a relative context for runoff at the site scale, and an overview of the available BMPs that may be applicable.

KEYWORDS

residential stormwater management, low impact development, environmental site design, permeable pavement, rainwater harvesting, rain gardens, green roofs, dry swales, bioretention

JUST HOW MUCH RUNOFF DOES MY SITE CREATE?

We can estimate the average annual runoff from an average single-family residential lot by making a few assumptions, which include: all precipitation which falls on an impervious surface (roof, driveway, or walkway) runs off; and all the runoff leaves the site. These assumptions help provide a better understanding of how much potential runoff water is contributed by a single-family residential site. Average annual precipitation for Virginia is 42.7 inches (108 cm) (Hayden and Michaels 2000). If the roof area of the house is 1600 ft^2 (149 m^2) and the area of the driveway and all walks totals 750 ft^2 (this includes a 12' × 50' driveway and 50 feet of three foot wide walkways around the house), this would mean a total of 2350 ft^2 of impervious surface. A single half-inch rain event would generate 732 gallons of runoff from the site. Based on average rainfall in a year, this impervious area would contribute 62,552 gallons of runoff into the local watershed. Pollutants from this site could include nutrients, sediments, metals, oil, grease, pesticides, and fecal matter. Minimizing even a percentage of this runoff by encouraging infiltration will significantly reduce the amount of stormwater and associated pollutants leaving this residential site and increase groundwater recharge. Ultimately, as the practice is duplicated, water quality throughout the entire watershed would be improved.

Stormwater on residential sites can be managed in numerous ways. The following practices, which can be integrated into new construction and retrofitted into existing residential settings, help manage stormwater. These practices manage stormwater by several methods, including increasing permeability, directing water to more permeable areas, detaining water to allow infiltration, and intercepting and holding rainwater to utilize on site at a later time.

PRACTICES TO MINIMIZE RUNOFF OR IMPROVE INFILTRATION

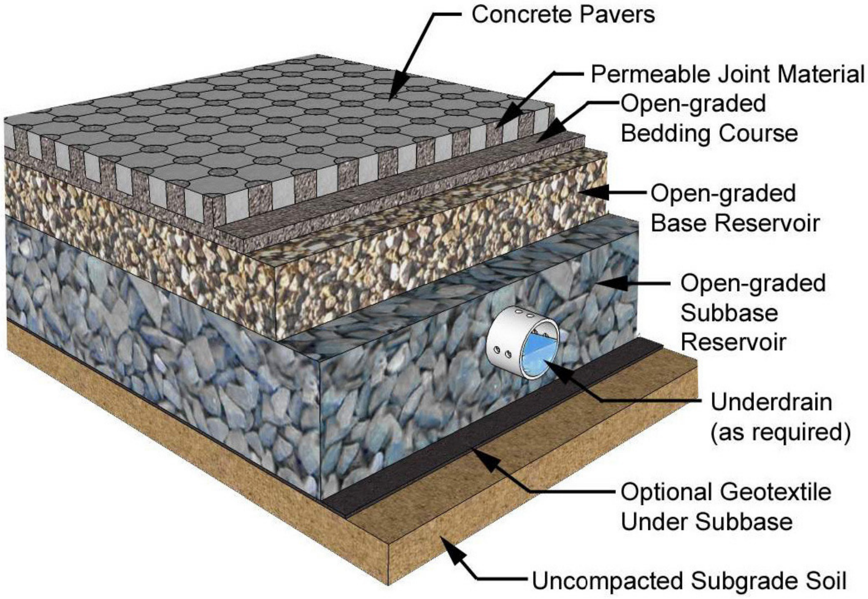
Permeable Pavement

Permeable Pavement (PP) is a modified form of asphalt or concrete whose top layer is pervious to water due to voids intentionally created during mixing or installation. PPs include porous concrete, porous asphalt, grid pavers, and interlocking pavers with joints (Figure 4). These applications are designed to allow water infiltration at a rate of 0.5 to 3 inches per hour, produce nearly zero runoff, and work in low-traffic settings such as residential applications and parking lots. PPs are efficient for removal of sediments, nutrients, and some metals. However, sediment can clog the voids of these systems, leading to failure. Periodic vacuuming of the surface is necessary to remove sediments and maintain the functionality of the system.

Permeable pavement areas can be receiving areas (sinks) for runoff from other areas of the site. By directing water to these areas, significant amounts of runoff can be captured until the underground reservoir capacity is met. This can be as much as a 2:1 ratio between the contributing catchment and the permeable pavement. Permeable surfaces can be retrofitted into existing driveways and walkways, or can be incorporated into new designs. Water flows through the pavement and is then filtered by the sub-base gravel and soil under the pavement before infiltrating into the ground (Figure 5). For more information, consult Sample and Doumar (2011).

FIGURE 4. Examples of permeable pavement applications: grid pavers; pavers; permeable asphalt; and permeable concrete. (Images courtesy Laurie Fox)

FIGURE 5. Profile of typical permeable pavement. (Source: Smith, D., 2006.)



Expected Cost

A preliminary estimate of the average cost of PP to provide treatment of an acre of impervious surface is $45,000 to $100,000 depending on the specific system. The unit cost may be greater when utilized in smaller residential areas. A typical residential driveway is about 75 feet long by 25 feet wide, which is less than 5% of an acre. While unit costs may be higher, an estimated cost for this type of driveway using permeable pavement would be about $8,000 to $15,000, not including any underdrain work that might be needed as an exit for overflow stormwater. The annual maintenance cost depends on the vacuuming frequency, which is based on the individual site conditions and general maintenance practices. Since PP allows land to be used for alternative purposes such as parking, the opportunity cost of land is not included in this estimate.

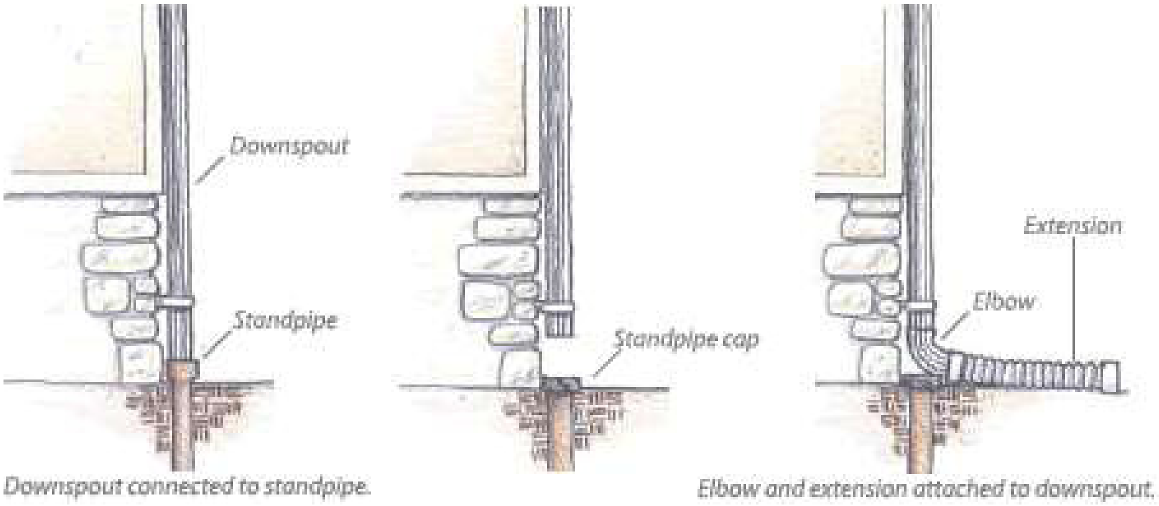
Performance

PPs are effective at removing multiple pollutants from stormwater runoff. A typical PP is expected to reduce Total Phosphorus (TP) and Total Nitrogen (TN) by approximately 60% on a mass-load basis, accounting for the runoff reduction in practice. In advanced designs, the PP has more filtration layers to provide a longer residence time, which is the average amount of time for water to travel through the layers. Advanced PP designs can improve the reduction of TP and TN up to 80% on a mass-load basis accounting for runoff reduction (VDCR No. 7 2011).

Disconnecting Downspouts from Drains

Often downspouts from home gutters connect into underground pipes that run directly into stormwater drains or drain into the street where the runoff flows into a stormwater drain. Rooftop disconnection (RD) is one of the simplest means of reducing stormwater from residential sites. Simply unhooking roof downspouts from the storm drain system can

FIGURE 6. Disconnecting a downspout from underground pipes leading to storm sewers. (Image courtesy of: Mid-America Regional Council (MARC) at http://www.marc.org/Environment/Water/downspout.htm)



significantly reduce the amount of runoff from a site. Redirecting these downspouts away from the house and towards grassy areas or other areas with high permeability provides infiltration of the runoff. (Figure 6). Because RD is passive, easy to maintain, inexpensive, and controls pollutants near their source, it is considered a very sustainable practice. Care should be taken to limit the contributing roof area (roofshed) to a maximum of 1000 ft^2 per downspout to minimize local impacts. To encourage infiltration, the flow path from the end of the downspout to a down slope pervious area should be at least 40 ft. Sloped areas greater than 2% should be avoided to prevent erosion. If turf reinforcement is used, slopes can be as high as 5%. To minimize impacts to basements and foundations, downspout outlets should be located at least 5 feet from any building. For more information, consult Sample (2011).

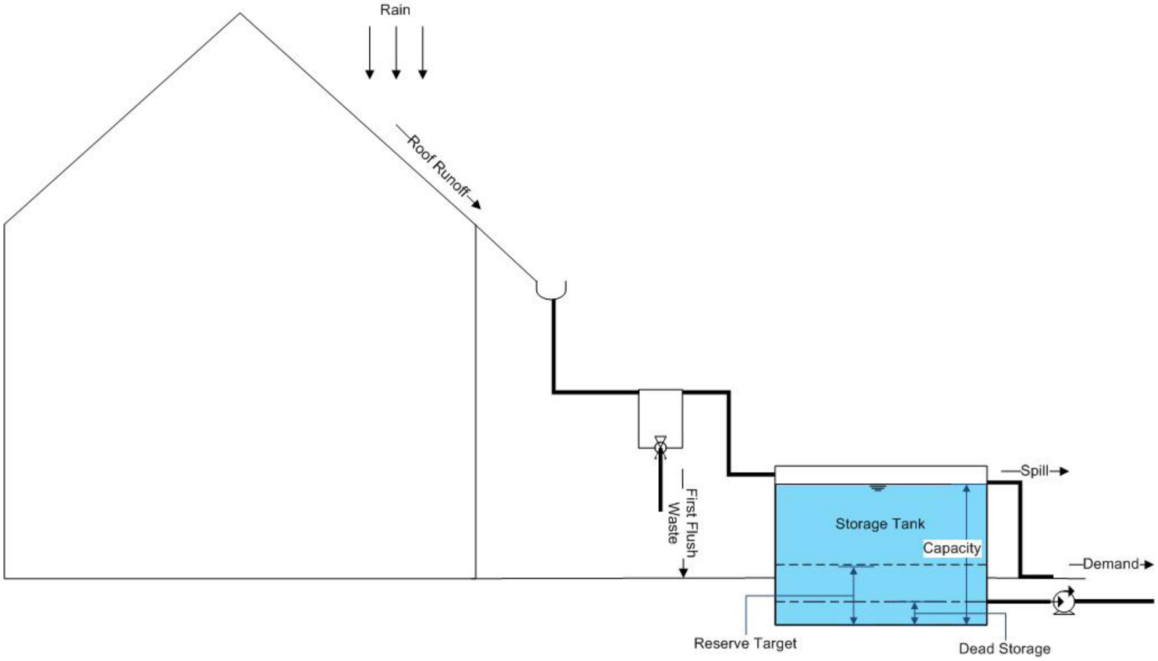
Rainwater Harvesting (Bulk or Rain Barrels)

Rainwater Harvesting (RWH), also known as rainwater harvesting systems or cisterns, are devices that intercept, divert, store, and release collected roof runoff from rainfall for later use as an alternative water supply. Capturing rainwater for re-use can significantly reduce runoff and also provide an alternative "clean" source of water for irrigation and other non-potable water uses. Harvesting runoff from other impervious surfaces such as driveways and parking lots is discouraged due to a much higher potential pollution level.

Collection can be in smaller containers, such as a rain barrels (Figure 7), or in larger storage containers or tanks (Figure 8) that can capture thousands of gallons of rainwater from a single storm. The storage tanks can be above or below ground and are often equipped with a pump to facilitate use of the stored rainwater when needed. Stored rainwater can be used indoors for nonpotable use (such as toilet flushing), or outdoors for irrigation, car washing, or filling water gardens or birdbaths. Harvesting rainwater reduces runoff and also reduces the demand on potable water supplies. For more information, consult Sample and Doumar (2011) and VDCR (No. 6 2011) and Cabell Brand Center (2009).

FIGURE 7. A rain barrel system for rain water harvesting. (Photo courtesy Vision Design Collaborative)

FIGURE 8. Components of an RWH system. (Image from VCE Pub. 426-125)



Expected Cost

RWH is generally an inexpensive stormwater treatment practice when compared to other alternatives. A rain barrel can cost as little as $60. More sophisticated underground tanks with a filtering system and pump could cost several thousand dollars. Cost for each system is based on the size of the roofshed, the local rainfall, the expected demand, and management plan. Larger systems can significantly reduce the need for potable water and can also reduce utility costs. These savings should be included in a total cost comparison. A significant impediment to wider implementation of these systems has been regulation by local health departments and recent revisions to national building codes (International Code Council, 2009), which classify harvested rainwater as greywater, potentially requiring expensive backflow prevention similar to other greywater systems.

Green Roof or Vegetated Roof Applications

Green roofs or vegetated roofs (VR) convert an impervious or non-porous surface into one that can accept and retain precipitation (Figure 9); thus reducing stormwater runoff and pollution. Components of a VR include a waterproofing barrier, drainage system, engineered growing media, and vegetation.

The VR intercepts rainfall and retains it temporarily, reducing runoff volume and velocity. The growing media and vegetation act as filters. Runoff then evaporates or evapo-transpires through the plants back into the atmosphere, is retained in the media, or continues into a storm drain at a reduced rate. During peak growing times, green roofs can retain up to 75% of the precipitation that falls on them; 20 to 40% is retained during the winter. Estimates from Green Roofs for Healthy Cities (www.greenroofs.org) state "a grass roof with a 1.6 to 7.9 inches (4 to 20 cm) layer of growing medium can hold 3.9 to 5.9 inches (10 to 15 cm) of water." Over the course of 12 months, EPA estimates show that 50% of annual precipitation, which would otherwise be runoff, can be retained through green roof applications (Berghage et al. 2009). Additional benefits from VRs include: longer lifespan of roofing materials, sound reduction, and reductions in building heating and cooling costs.

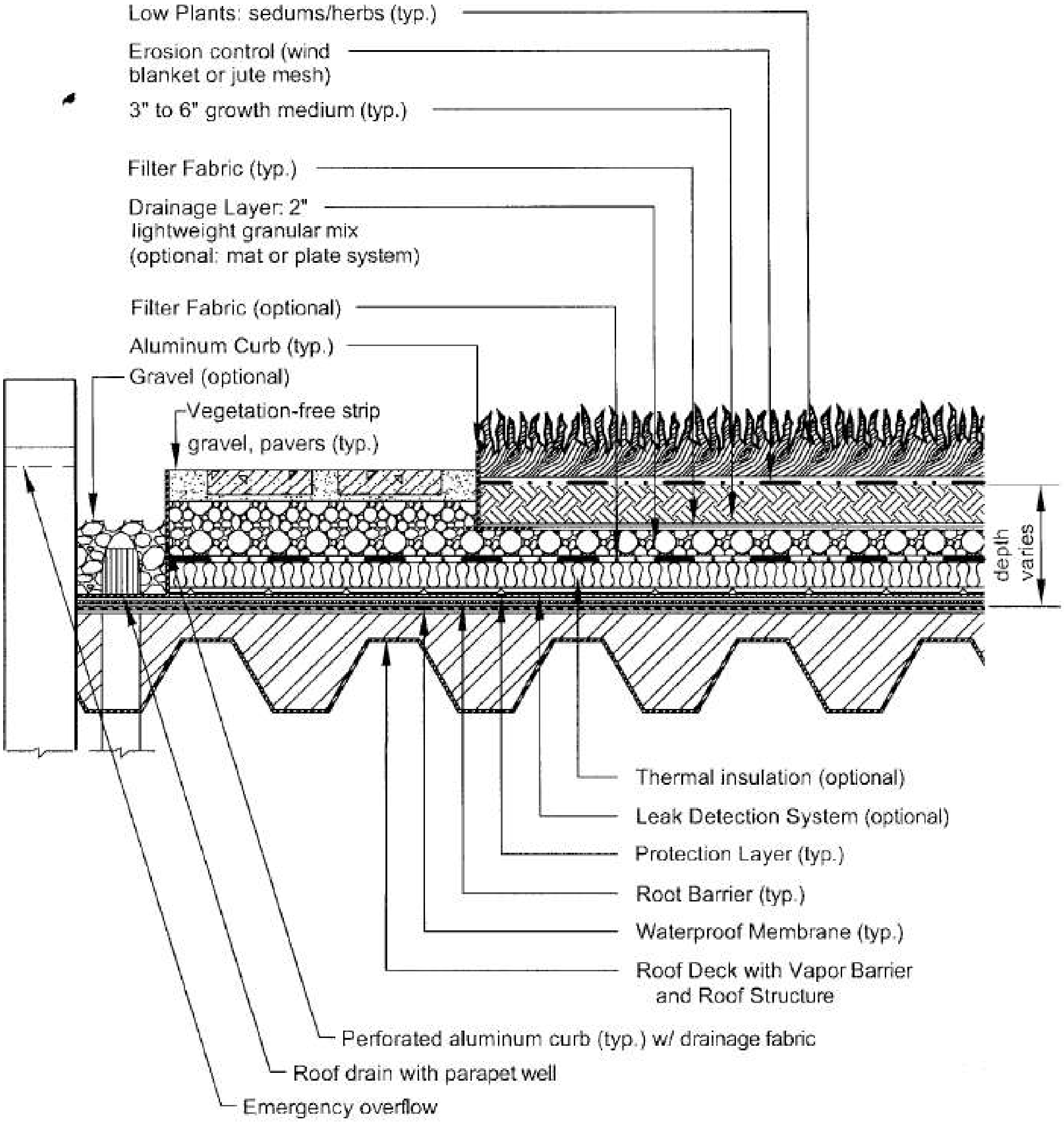
VRs can be used in new building designs where the roof is engineered to support the weight. They can also be used to retrofit an existing roof if that roof can support the additional weight of at least 15–30 lbs./sq. ft. VRs are generally used on flat roofs, but can work on shallow sloped roofs that can withstand the additional weight. VRs are either extensive (most common) with limited human interaction and maintenance or intensive, designed for human interaction and requiring higher maintenance. For more information, see Sample and Doumar (2011).

Performance

VRs are effective at reducing pollutants through reduction of runoff and biological uptake. In large storm events nutrients may actually be exported due to leaching. However, an extensive VR is expected to reduce Total Phosphorus (TP) by 45% and Total Nitrogen (TN) by 45%, which includes mass load reductions from runoff reduction. An intensive system is deeper, which provides a longer residence time. Intensive VR systems can improve the expected reduction of TP up to 60% and of TN to 60% (VDCR No. 5 2011).

FIGURE 9. A green roof application. (Photo courtesy of Dr. Susan Day)

FIGURE 10. Cross section of extensive vegetated roof. (Source: VDCR Stormwater Design Specification Number 5: Vegetated Roof, Version 1.9, 2011.)



Expected Costs

VRs have relatively high initial installation costs when compared to other alternative stormwater BMPs. Initial costs depend on site conditions and accessibility of the roof, the roof surface area, and the type of VR system being installed. The VR industry provides an average cost range from \$9-\$24/ft^2. Maintenance costs can be incorporated into the landscaping budget.

Urban Forestry Applications

Incorporating trees into residential settings provides a number of benefits for managing stormwater runoff (Nowak and Dwyer 2007). A mature deciduous tree has the potential to

FIGURE 11. An example of urban trees. (Photo courtesy of Dr. Susan Day)

intercept 500 to 700 gallons of water per year, mainly via retention on leaves. Additionally, evergreen trees can intercept more than 4,000 gallons per year (Seitz and Escobedo 2008). The intercepted rainfall is often precipitation that would have fallen on an impervious surface and contributed to runoff. Surface runoff is reduced when precipitation is held on foliage until it evaporates into the atmosphere. Water also moves from the tree canopy via stemflow along the branches and down the trunk to the permeable soil areas near the trunk increasing infiltration. Other benefits of urban trees include cooling cost reductions, shading, aesthetics, wildlife habitat and increased real estate value. Tree species vary widely, but can be easily integrated into a residential landscape (Figure 11). Site conditions should also be taken into account when selecting tree species. Virginia Department of Conservation and Recreation's website on Natural Heritage at http://www.dcr.virginia.gov/natural_heritage/nativeplants.shtml contains links with extensive plant listings and preferred growing conditions divided by region. For example, several trees adapted to high moisture sites suited to Virginia's Piedmont region would include river birch (*Betula nigra*), Eastern Redbud (*Cercis Canadensis*), sweetbay (*Magnolia virginiana*), and serviceberry (*Amelanchier Canadensis*). Local Cooperative Extension Offices can provide additional information and assistance.

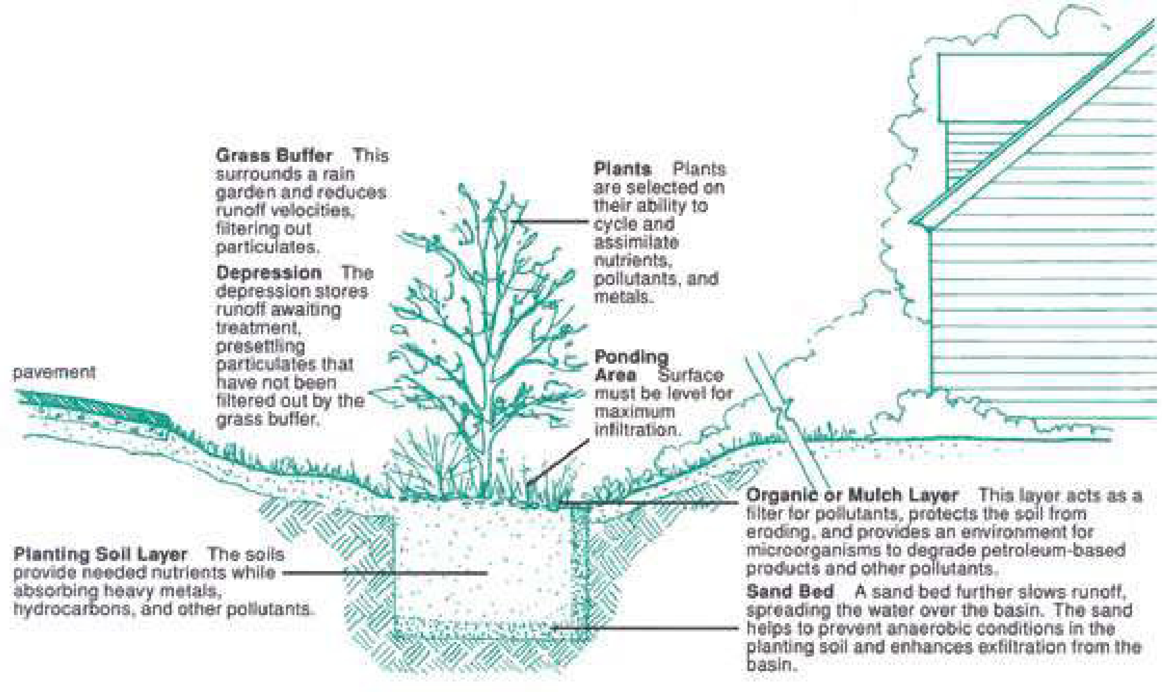
Rain Gardens

Rain gardens are shallow depressions that collect stormwater runoff from nearby impervious surfaces. The runoff is temporarily detained, allowing infiltration, evaporation, or evapotranspiration, much like a puddle (Figure 12). Rain gardens are planted with evergreen and deciduous or herbaceous species that provide pollution filtration, landscape aesthetics, and pollinator and wildlife habitat. Rain gardens are an attractive way to manage a significant volume of runoff, capable of absorbing 30% more rainfall as compared to the same size turf area. Rain garden design and plant selection are very site dependent (Andruczyk, et. al. 2008, VDOF Publication P00127).

Bioretention

A bioretention cell, or basin, is a more advanced type of rain garden that typically is engineered and includes an underdrain. A typical cell consists of a depression with a vegetated layer, a mulch layer, layers of sand and soil, an organic media filter bed, an overflow, and an optional underdrain (Figure 13). A small pretreatment basin known as a forebay traps sediment before it enters the bioretention cell. Within a cell, runoff is treated by a variety of physical, chemical, and biological processes.

FIGURE 12. Cross section of a rain garden with descriptions of each component. (Image from Rain Gardens Technical Guide http://www.dof.virginia.gov/mgt/resources/pub-Rain-Garden-Tech-Guide_2008-05.pdf)



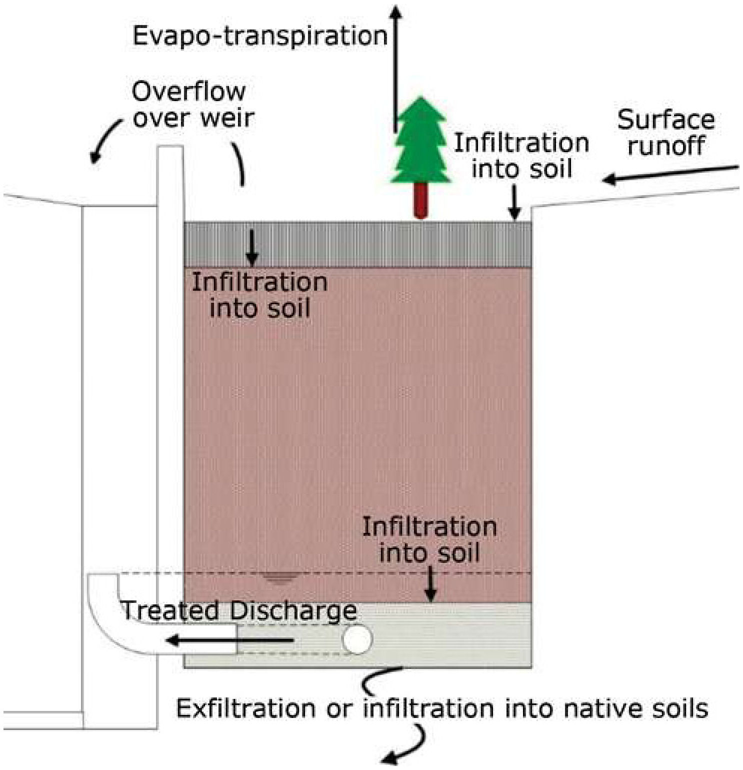


FIGURE 13. Diagram of a biorentetion design, vertical profile exaggerated to show detail. (Image from VCE Pub. 426-128.)

Stormwater storage is provided when water temporarily ponds in the cell. The collected stormwater is filtered through different layers of mulch, media, and compost inside the cell. Media, plants, and microorganisms in the soil treat the pollutants carried by the runoff through physical processes like filtration, infiltration, or adsorption, and through biological processes like biological uptake or microbial decomposition. For more information, consult Sample and Liu, 2011.

An underdrain consists of perforated pipe in a gravel filled trench installed along the bottom of the media filter bed. An upturned outlet promotes periodic anaerobic conditions within a fluctuating water table and facilitates removal of nitrogen. In soils with high infiltration rates, the underdrain can be omitted, thus increasing runoff reduction. Bioretention cells without underdrains should be avoided in commercial and industrial areas to prevent groundwater contamination.

Performance

Bioretention can be very effective at reducing runoff and removing pollutants such as excess nutrients. A typical bioretention cell has a media depth of 1.5 to 2 feet. An annual reduction of 25% for Total Phosphorus (TP), 40% for Total Nitrogen (TN), and 40% for runoff can be expected. Improving the media and its depth to 2 to 3 feet and providing a gravel underdrain and other enhancements can improve the estimated annual reductions to 50% for TNP, 60% for TN, and 80% for runoff (VA-DCR No. 9 2011).

Expected Cost

The installation cost of a bioretention cell is approximately $10,000 for a 900-square-foot cell. The annual maintenance cost is approximately $600; $350 for mulching and debris removal and $250 for vegetation replacement if necessary (Low Impact Development Center 2005).

Dry Swales

A dry swale (DS) is a shallow, gently-sloping channel with broad, vegetated side slopes. A DS provides temporary storage, filtering, and infiltration of stormwater runoff, and is designed to remain dry during periods of no rainfall. A DS is an engineered BMP that is designed to reduce pollution through runoff reduction and pollutant removal, and is part of an overall stormwater treatment system for a site.

DSs are versatile because the area they require is relatively small. A DS can be used in place of curbs, gutters, and sewer systems. It can be thought of as bioretention arranged in a straight line (further described in Sample and Doumar, 2011). A DS is typically installed on a shallow slope so that flow velocities are slowed, thus increasing infiltration and water-quality treatment. Vegetation species can include turf, meadow grasses, shrubs, and in limited quantities, small trees. When compared to open ditches, which mainly channel runoff and contribute to erosion, DSs are an improved method of managing stormwater (see Figure 14).

DSs are always located above the water table to provide drainage capacity. In highly-permeable soils, no underdrains are typically used, while the reverse is true in poorly-drained soils. The purpose of the underdrain is to provide overflow for excess runoff that does not infiltrate. This helps the DS regain capacity quickly for the next rain event. Underdrains are constructed with a perforated pipe fit within a gravel-filled trench at the bottom of the swale and connected to the stormwater conveyance system (Figure 15).

FIGURE 14. Typical dry swale just after construction. (Source: Wetland Studies and Solutions, Inc., Gainesville, VA, 2009.)

FIGURE 15. An example of a grassed dry swale in a residential application. (Photo courtesy Stephen Mosberg)

Performance

Dry swales are effective at removing multiple pollutants from stormwater runoff. A typical DS is expected to reduce Total Phosphorus (TP) by 52% and Total Nitrogen (TN) by 55%. Advanced designs provide for off-line design and multiple treatment cells with dense and diverse vegetation (i.e., not a single turf species) to enhance treatment. Advanced DS designs can improve the expected reduction of TP to 76% and TN to 74% (VA-DCR No. 13 2011).

Expected Cost

Dry swales vary in price depending on the complexity of the design. A preliminary estimate of the cost would be $7,500 for a drainage area of 5 acres according to the Federal Highway Administration (FHWA). This does not include the value of land dedicated to the BMP. A DS is a relatively inexpensive stormwater treatment practice when compared to other alternatives. Maintenance costs are variable and can be reduced if sediment and debris are regularly removed from the DS.

Improving Turf Density and Permeability

Improving soil permeability leads to reduced runoff and greater infiltration. Generally, residential sites have a large percentage of the site in turf. Turfgrass is very effective at filtering out sediment and increasing infiltration, but two issues affect the ability of turf to perform these functions. Compaction makes infiltration slow, allowing for more runoff. Poor management results in thin turf stands, which lead to sediment erosion. In order to reduce compaction and to keep turf density high, core aeration of

FIGURE 16. Fall fertilization based on soil analysis helps to build healthy cool season turf. (Photo courtesy John Freeborn)

the turf and proper mowing height and fertilization practices are recommended based on the turf species and soil tests.

Healthy turf will allow maximum infiltration of precipitation. Recommendations for turf species and management are available at local cooperative extension offices, and a number of publications are available at the Virginia Cooperative Extension Turf website at http://pubs.ext.vt.edu/category/turf.html. The cost of turf establishment and maintenance is very species- and site-specific, but is usually low compared to other BMPs.

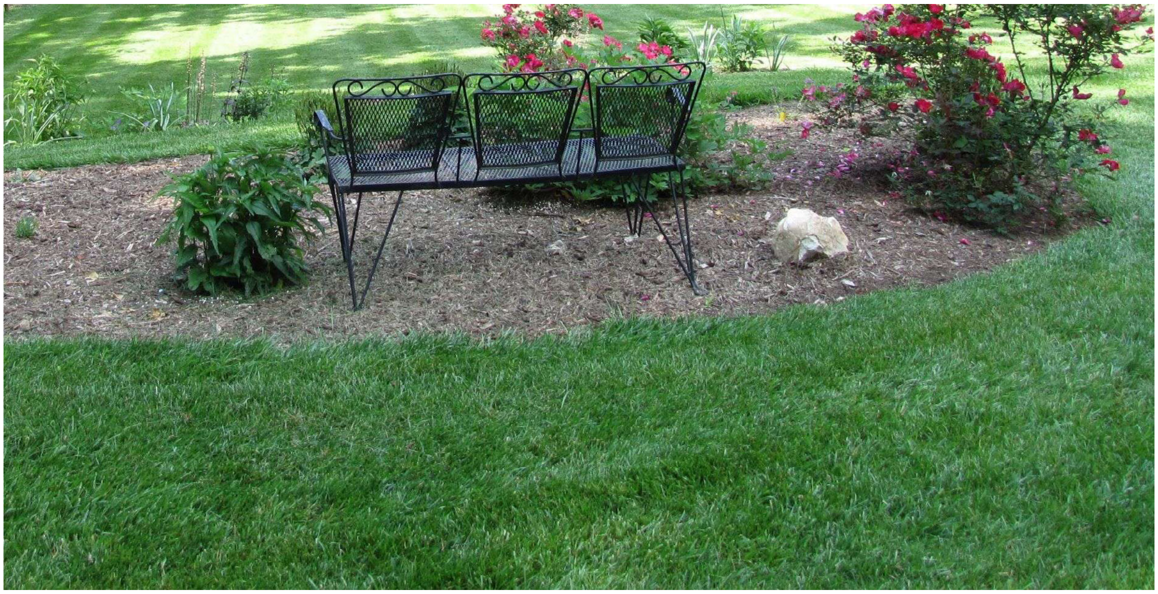
Mulched Areas

The application of organic mulches generates a number of benefits for both plants and soils. Mulch improves precipitation infiltration and soil moisture retention, provides organic matter, and moderates plant root-zone temperatures (Relf 2009). In addition to these benefits, mulch also significantly reduces compaction and erosion. Mulch should be applied at a 3-inch (7.62 cm) depth with subsequent annual applications to maintain that depth. The cost of mulching depends on the type of mulch and application area. Costs for hauling/delivery and spreading should also be added into the overall expense.

Soil Restoration

Soil restoration (SR) is the technique of enhancing compacted soils to improve their porosity and nutrient retention. SR is suitable for areas that have been subjected to compaction or significant removal of topsoil and is most effective in drier soils with slope grades of less than 10%. SR includes biological (worms and insects) and mechanical aeration, mechanical loosening (tilling), planting dense vegetation, and applying Soil Amendments (SA). SA involves the spreading and mixing of mature compost into disturbed and compacted urban soils. For more information, consult Sample and Barlow (2011).

FIGURE 17. High turf density and mulched areas to manage runoff in a lawn setting. (Photo courtesy John Freeborn.)



Performance

Due to the increase in soil porosity, a runoff reduction of approximately 30–50% can be expected when used to augment other BMPs. Calculations for lawn areas that undergo SR and do not receive runoff from other areas show that runoff can be reduced by as much as 75% (VA DCR No. 4 2011). SR is not expected to reduce Total Nitrogen (TN) or Total Phosphorous (TP), although the reduction in stormwater runoff can contribute to a reduction in nutrient loading (VA-DCR No. 4 2011).

Expected Costs

SR is an inexpensive stormwater treatment practice when compared to other alternatives. Cost of compost can range from $15–$30 per cubic yard. Incorporation (tilling, mechanical aeration, or soil loosening) is an additional cost. If applied at a 2-inch depth, cost of compost per acre would be in the $7,000 range (Greg Evanylo, personal communication, 2010). Compost application and incorporation into the site is usually only done once. In turf areas, subsequent applications or "top dressing" can be done twice a year and would add to the base cost (James Michael Goatley, Jr. personal communication, February 9, 2012). In many cases, SR techniques are used in conjunction with another purpose or land use, so the value of land is not included in this analysis.

SUMMARY

Land development activities convert highly permeable surfaces into impervious ones. Conversion often causes an increase in stormwater runoff and a decrease in both surface water quality and infiltration to groundwater. On residential sites, these negative effects can be minimized by incorporating some of the practices described above. Even employing just a single practice can improve the quality and reduce the volume and velocity of stormwater leaving a site. Stormwater runoff can be managed much more efficiently and effectively by combining multiple practices on a site. The effect of implementing stormwater management practices on many individual sites is cumulative and can significantly and positively impact an entire watershed.

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