PUBLIC WORKS TECHNICAL BULLETIN 200-1-121
31 DECEMBER 2013

STORMWATER BEST MANAGEMENT PRACTICES FOR LOW IMPACT DEVELOPMENT (LID) INFRASTRUCTURE

Public Works Technical Bulletins are published by the US Army Corps of Engineers. They are intended to provide information on specific topics in areas of Facilities Engineering and Public Works. They are not intended to establish new Department of Army policy.

DEPARTMENT OF THE ARMY
US Army Corps of Engineers
441 G Street NW
Washington, DC 20314-1000

CECW-CE

Public Works Technical Bulletin 31 December 2013

No. 200-1-121

FACILITIES ENGINEERING
ENVIRONMENTAL

STORMWATER BEST MANAGEMENT PRACTICES FOR LOW IMPACT DEVELOPMENT (LID) INFRASTRUCTURE

1. Purpose

a. This Public Works Technical Bulletin (PWTB) addresses stormwater runoff management and nonpoint source (NPS) pollution controls through small, cost-effective landscape features known as Best Management Practices (BMPs). The goal of low impact development (LID) BMPs is to mimic a site’s predevelopment hydrology by using design techniques to infiltrate, filter, store, evaporate, and detain runoff close to the source.

b. All PWTBs are available electronically at the National Institute of Building Sciences’ Whole Building Design Guide (WBDG) webpage, which is accessible through this link:

http://www.wbdg.org/ccb/browse_cat.php?o=31&c=215

2. Applicability

This PWTB transmits information on LID techniques and technologies that can be applied by resource and land managers on Army installations and other Department of Defense (DoD) facilities.

3. References

a. Army Regulation (AR) 200-1, “Environmental Protection and Enhancement,” 13 December 2007.

b. “Energy Independence and Security Act,” (EISA; Title 42, United States Code [USC], Chapter 52, Section 17094, Section 438), 19 December 2007.

c. The Army Strategy for the Environment, “Sustain the Mission – Secure the Future,” 1 October 2004.

d. US Environmental Protection Agency (USEPA), Office of Water. “Technical Guidance on Implementing the Stormwater Runoff Requirements for Federal Projects under Section 438 of the Energy Independence and Security Act,” EPA 841-B-09-001, December 2009.

e. Federal Water Pollution Control Act Amendments of 1972, commonly referred to as the Clean Water Act (CWA; 33 U.S.C. §1251 et seq.) and its subsequent amendments.

f. Executive Order (EO) 13514, “Federal Leadership in Environmental, Energy and Economic Performance,” 5 October 2009.

g. Unified Facilities Criteria (UFC) 3-210-10, “Low Impact Development,” 15 November 2010.

4. Discussion

a. AR 200-1, as implemented in 2007, contains policy for environmental protection and enhancement, implementation of pollution prevention, conservation of natural resources, sustainable practices, compliance with environmental laws, and restoration of previously damaged or contaminated sites. AR 200-1 requires that installations be good stewards of land resources by controlling sources of erosion to prevent damage from facilities to the land, water resources, and equipment.

b. The EISA contains stormwater standards and requirements for federal development and redevelopment projects. A primary goal of EISA Section 438 and related DoD regulations and policies is to replace typical/conventional construction practices used to manage stormwater with smart LID BMPs. The intent of Section 438 is to promote the responsible management of stormwater to the maximum extent technically feasible. The requirements also make the increased use of LID on federal facilities extremely likely.

c. The Army environmental strategy, “Sustain the Mission – Secure the Future” focuses on the protection and enhancement of the environment.

d. The USEPA technical guidance on Section 438 presents information on tools and design practices to meet requirements of EISA.

e. Among the objectives of the CWA and its subsequent amendments is to restore and maintain the chemical, physical, and biological integrity of the nation's waters by preventing point and nonpoint pollution sources. A military follow-on document promotes responsible stormwater management and states that LID techniques offer a suite of BMPs that “maintain or restore predevelopment hydrology” (US Department of Navy 2007).

f. In Section 1 of EO 13514, a policy is set that requires federal agencies to “conserve and protect water resources through efficiency, reuse, and stormwater management.” Section 14 assigns the USEPA responsibility for issuing stormwater guidance for federal facilities. Information in this PWTB will assist installation personnel in addressing USEPA Goal 2, “Protecting America’s Water.”

g. As directed by DoD policy, UFC 3-210-10 provides technical criteria, technical requirements, and references for the planning and design of applicable projects to comply with stormwater requirements under Section 438 of EISA. It provides planning, design, construction, sustainment, restoration, and cost criteria. It applies to military departments, defense agencies, and the DoD field activities.

h. LID practices are increasingly used in urban and suburban development as a more environmentally and economically sustainable approach to reduce stormwater runoff peak flow and volume as well as NPS pollution. By properly implementing LID stormwater BMPs, the Army will increase sustainability and help achieve Leadership in Energy and Environmental Design (LEED) silver construction criteria. Restoration of sites to predevelopment hydrology will reduce runoff of many pollutants, including nutrients, chemicals, oil and grease, and sediments.

i. Effective site planning along with the use of an “integrated design” approach for the implementation of BMPs are critical aspects of implementing stormwater policy across Army installations to reduce stormwater pollutants and maintain cleaner waters. LID BMP techniques also offer a suite of approaches that, when properly implemented, improve water quality by capturing and controlling stormwater on site and use native vegetation to increase infiltration, remove pollutants, and increase groundwater recharge rates. These approaches include detention ponds, cisterns, rain gardens, bioretention cells, reforestation, permeable pavements, grass, and bioswales. LID features also reduce the overall size of the project footprint due to the distributed nature of stormwater BMPs.

j. The introduction of LID practices means that DoD installations need to adjust the administration of their stormwater programs to account for the changing landscape. Faced with the responsibilities of regulatory compliance and asset management, installations have been hesitant to completely advocate for stormwater programs that introduce a new suite of BMPs.

k. Appendix A provides an extended overview of LID and LID practices, the role of LID in reduction and prevention of NPS pollution, and management of stormwater runoff to benefit the environment.

l. Appendix B is an extended overview of federal rules and regulations that are directly related to LID infrastructure on DoD installations. This appendix also describes selected BMPs and includes a list of DoD installations where LID BMPs have been implemented.

m. Appendix C provides design specifications, construction, and routine maintenance guidance for the field implementation of some typical LID BMPs. This appendix also describes NPS control effectiveness by using case studies and pictures.

n. Appendix D lists references, relevant publications, and materials for additional subject matter information.

o. Appendix E lists acronyms and abbreviations used in this PWTB. It also includes a table for conversions from the inch-pound system of measurement to the International System.

Points of Contact

a. Headquarters, US Army Corps of Engineers (HQUSACE) is the proponent for this document. The point of contact (POC) at HQUSACE is Mr. Malcolm E. McLeod, CEMP-CEP, 202-761-5696, or e-mail: Malcolm.E.Mcleod@usace.army.mil.

b. Questions and/or comments regarding this subject should be directed to the technical POC:

US Army Engineer Research and Development Center (ERDC)
Construction Engineering Research Laboratory (CERL)

ATTN: CEERD-CN-N (Dr. Muhammad Sharif)
PO Box 9005
Champaign, IL 61826-9005
Tel. (217) 373-5843
FAX: (217) 373-7266
e-mail: Muhammad.Sharif@usace.army.mil

FOR THE COMMANDER:

JAMES C. DALTON, P.E., SES
Chief, Engineering and Construction
Directorate of Civil Works

(This page intentionally left blank.)

APPENDIX A: INTRODUCTION

Background

Low impact development (LID) practices are increasingly used as a more environmentally and economically sustainable approach to reduce stormwater runoff and nonpoint source (NPS) pollution in urban and suburban development. With the goal of mimicking a site's predevelopment hydrology, LID can reduce infrastructure costs and improve water quality, aesthetics, and biodiversity. Recognizing that stormwater is one of the most significant contributors of NPS pollution and with increasing interest in sustainable development, the Department of Defense (DoD) has a continued and growing interest in LID technology and practice.

The evolution toward source control approaches has the potential to greatly improve the quality of receiving waters because LID has proven to be an effective means for reducing stormwater peak flows, volume, and pollutant loads. However, the management and operation of stormwater programs and practices is altered by the introduction of decentralized LID best management practices (BMPs). LID differs from the centralized, largely public systems that have been used predominantly for stormwater management because it includes practices distributed throughout the developed landscape. This decentralization impacts the construction, maintenance, and cost considerations that accompany stormwater compliance efforts. (More information on costs is contained in another PWTB available from the WBDG website: http://www.wbdg.org/ccb/browse_cat.php?o=31&c=215.)

When LID was first introduced in the late 20th century as a more hydrological-appropriate method of stormwater management, many of the first impediments were perceived to be technological. The on-site infiltration, evapotranspiration, and reuse of rainwater were a large shift in practice from the conveyance and detention strategies that had predominated stormwater management. With over a decade of LID practices and programs now successfully implemented, the technological issues – while still an important area of research and consideration – are not the predominant impediment to more widespread use of source controls. It is now institutional and cost issues that present the largest impediments to broader LID adoption.

The introduction of LID practices requires DoD installations to adjust the administration of their stormwater programs to account for the changing landscape. Faced with the responsibilities of regulatory compliance and asset management, installations have been hesitant to completely advocate for stormwater programs that introduce a new suite of BMPs. Largely, concerns with LID approaches have included:

- Regulatory credits – Means of accounting for the volume, peak flow, and water quality credits that LID BMPs should be accorded in an overall stormwater management effort.
- Construction and inspection – Protocols that offer assurance that BMPs will be properly constructed to provide appropriate stormwater management.
- Maintenance and long-term operation – Ensuring continued maintenance and performance of BMPs that are essential to water quality and regulatory goals.
- Cost – Construction and long-term costs for multiple types of LID BMPs are important for selecting appropriate stormwater control strategies.

Low Impact Development Overview

LID strategies are increasingly being used to manage stormwater in a variety of public and private applications, and with new stormwater requirements for federal facilities and Executive Orders promoting green construction, the use of LID at DoD installations will increase further. The increased focus on providing appropriate stormwater management and natural resource protection has cost and operational implications that are still in the process of being defined. Effectively managing stormwater has become increasingly costly as the predominant design concern has evolved from flood control to water quality protection. This has required a change in the way that stormwater management and mitigation efforts are planned, designed, constructed, and managed (Weinstein 2009).

Traditional stormwater infrastructure has largely failed to adequately address water quality considerations, and the costs associated with maintaining it continue to increase with age and increasing demand (National Research Council 2008; USEPA 2008, 2009a). The transition to LID strategies to date has occurred because of improved stormwater management capabilities and the potential economic benefits that can be gained from using them. The goal of LID is to use the capacity of natural systems to reduce runoff volumes to improve or protect local water quality. Though the ecological and ecosystem benefits of these techniques have been fairly well established, the understanding of the associated economic value is still developing. This bulletin will help personnel to develop and evaluate new and innovative LID BMPs for use by DoD and Army installations. By better understanding the economics, control effectiveness, and fiscal tradeoffs between conventional and LID practices, DoD installation managers can make more informed and effective allocation decisions (Weinstein 2009).

Stormwater Pollution

Land development and the corresponding changes in land cover have significant impact on hydrology and the movement of water through the landscape. The undeveloped condition is one of little surface runoff because of soils amenable to infiltration and the presence of vegetation to intercept precipitation and evapotranspirate moisture. Compacting soils, introducing impervious surfaces, and removing vegetation creates a significant increase in the volume of stormwater runoff because of the lost natural hydrologic benefits.

These alterations to the hydrologic condition result in changes to: surface runoff volumes and base flows; the frequency and number of runoff events; the intensity and long-term cumulative duration of flows; and the supply and transport of sediment in the stream system. These alterations may also affect the stability of natural or unlined channels, receiving water temperature and chemistry, and habitat integrity. Several impacts of stormwater runoff are discussed below.

- **Increased runoff volume** is caused by reductions in infiltration, surface detention, and evapotranspiration due to increased impervious cover, increased connectedness of impervious cover, soil compaction, and changes in vegetation. It is the primary driver of the downstream impacts of development.

- **Increased peak flow rates** are caused by increased runoff volume due to increased site imperviousness (resulting from development) combined with reduced time of concentration because of runoff from paved surfaces.

- **Base flow and sediment loading changes** are caused by alterations to the hydrologic cycle created by land cover changes and increased imperviousness, which prevent rain from recharging groundwater where it serves as base flow for streams. These changes increase the “flashiness” of streams, resulting in elevated flows during and after storm events, and greatly diminished base flows in between storms. Elevated flows during storm events can erode streambanks, which mobilizes in-stream sediments. In addition, stormwater runoff often contains significant sediment loads and delivers them to receiving waters.

- **Habitat modifications and stream morphology** changes result from increased runoff rates and volumes. Highly erosive stormwater can wash out in-stream structures that serve as habitat for fish, amphibians, and invertebrates. Large storms deepen, widen, and straighten channels, which can disconnect streams from their floodplains and destroy meanders that serve to dissipate hydraulic energy.

- **Runoff temperatures**, particularly from dark-colored paved areas, often reaches a much higher temperature than that of the receiving water. This warm runoff can elevate the temperature of the receiving stream to the detriment of plant and animal populations within the stream. Rooftops and pavements that are 100°F (a temperature common in summer months) can elevate initial rainwater temperature from roughly 70°F to over 95°F as runoff. The elevated temperature of runoff consequently raises the water temperature of receiving streams, where it has metabolic and reproductive impacts on aquatic organisms (USEPA 2009a).

- **Increased pollutant loading** results from runoff that carries a mix of pollutants into receiving waters. Effective pollution control requires understanding the sources, transport, and fate of pollutants. Because of the wide range of pollutants in stormwater and the difficulty in providing effective treatment, the most effective way to limit pollutant discharges is to reduce the volume of runoff generated.

Increased stormwater volumes are the root cause of the stormwater pollution problem (National Research Council 2008). Increased runoff volumes and the greater and/or longer peak flow rates that they create are universally recognized as the cause of the physical alterations of stream channels and the transport of stream channel sediments because of the increased energy that they transfer to these systems. Increased stormwater volume is also the primary cause of the increased pollutant loading from runoff.

Developed areas (impervious surfaces especially) are prime collection sites for pollutants. The variety of pollutant sources (e.g., atmospheric deposition, transportation) prevents adequately limiting the introduction of pollutants into stormwater. Because urban runoff volumes can be orders of magnitude greater than with predevelopment conditions, water quality treatment measures cannot reduce pollutant concentrations to levels needed to achieve water quality standards. Addressing and reducing stormwater runoff volumes is critical in reducing the physical and water quality impacts of urban runoff. This is accomplished most effectively by adopting strategies that use or mimic natural processes to (1) infiltrate and recharge, (2) evapotranspire, and/or (3) harvest and use precipitation near to where it falls.

Managing Stormwater with LID BMPs

LID BMPs are small-scale, distributed stormwater management devices that, as source control measures, use or simulate the actions of natural vegetation to limit the conversion of precipitation to runoff. They are constructed to capture rainwater as near as possible to where it falls, reducing the opportunity for stormwater to pick up pollutants and minimizing the volume of runoff that needs to be treated. In general, they utilize three basic principles: treat runoff as close to the source as possible, manage stormwater at the surface, and maximize soil and vegetation contact during treatment.

Conventional end-of-pipe devices are typically designed to meet a single stormwater management objective, such as peak discharge reduction. LID BMPs have the capability to meet multiple stormwater management objectives by using unit processes of the hydrologic cycle (e.g., infiltration and evapotranspiration). These objectives include the following areas (Weinstein 2006).

- **Volume**: Reducing or delaying the volume of stormwater that is discharged from a site or enters a stormwater collection system.

- **Peak discharge**: Reducing the maximum flow rate of stormwater discharges into the stormwater collection system by decreasing the stormwater volume and lengthening the duration of discharge.

- **Water quality**: Improving water quality through volume reduction, filtering, and biological and chemical processes.

LID BMPs are effective because they employ multiple elements of the natural hydrologic cycle. These elements (described below) are critical to meeting stormwater management and regulatory objectives (Weinstein 2006).

- **Infiltration**: The downward movement of water into the soil via percolation through pore spaces.
- **Evapotranspiration**: The combined effects of evaporation and transpiration in reducing the volume of water in a vegetated area during a specific period of time.
- **Interception**: A form of detention and retention storage that occurs when leaves, stems, branches, and leaf litter catch rainfall.
- **Conveyance**: The transport of surface runoff, from where a raindrop falls to where it enters the receiving body of water.
- **Detention**: The temporary storage of stormwater, which is released over a period of hours or days after rainfall ceases.
- **Retention**: The permanent capture of a volume of stormwater.
- **Reuse**: This is not an element of the hydrologic cycle but an important component of stormwater management. Reuse involves capturing rainwater for later uses, such as nonpotable water applications or landscaping.

LID BMPs can often require a significantly smaller footprint than conventional stormwater management infrastructure because they treat stormwater near the source. This small-scale approach allows LID practices to be integrated into many areas of a site. LID practices integrate easily with the landscape and infrastructure. Where permeable pavement is used, the BMP *is* the infrastructure.

Because they prevent, intercept, and/or treat stormwater near the source, LID practices can be customized to meet the stormwater management objectives of a specific site. Conventional controls typically do not address these objectives until discharges from contributing sub-watersheds converge at a single, centralized point. Centralized approaches allow for the transport of pollutants or large runoff volumes, which presents opportunities for the large-scale dispersion or accumulation of toxins. By contrast, LID practices treat relatively small, dispersed volumes of stormwater before they have a chance to accumulate or spread out over a larger area.

In many areas, this type of treatment is critical to improving the water quality of receiving streams. The majority of existing urbanized areas were developed prior to stormwater controls, meaning that stormwater enters receiving streams with little or no treatment. While other types of water pollution have been decreasing, stormwater pollution continues to increase. LID practices provide good pollutant removals and reduce the volume of stormwater runoff by promoting elements of the natural hydrologic cycle. Reducing both pollutant concentrations and stormwater volumes results in pollutant load reductions (i.e., the total quantity of a pollutant delivered to a receiving stream), which are extremely critical for meeting water quality objectives. Common LID practices described in Appendix C include the following:

- Bioretention (cells, swales, planter boxes)
- Vegetated swales
- Green roofs
- Permeable pavement
- Rainwater harvesting

Integrating LID in Stormwater Management Network

Applying LID requires assessing urban land use and the existing conventional infrastructure. Woven throughout an urban landscape, LID necessitates a different implementation approach and may be implemented in a number of methods. For new construction or Greenfield development, the site may be designed to use only LID practices for all stormwater management needs. In urban retrofit situations, a combination of LID and conventional controls will likely be used for stormwater management. Retrofitting stormwater controls into a space-limited urban area is complicated by existing utilities, compacted and contaminated soils, right-of-ways, and maintenance access. In addition, urban areas often already contain an extensive system of conventional stormwater infrastructure that requires stormwater management approaches to use LID practices that work in concert with the existing system. One of the strengths of LID practices is the multitude of available BMPs that may be used and the manner in which treatment trains may be constituted.

The flexibility of LID practices makes them ideal for functional and sustainable designs and landscapes. The performance capabilities of LID practices are well-suited for the many environmental and regulatory requirements that face both the DoD as well as municipalities. These regulatory requirements include Total Maximum Daily Loads (TMDLs), Combined Sewer Overflow (CSO), Long-Term Control Plans, consent decrees, and other legal actions. LID controls can be, and have been, applied in a number of ways to optimize infrastructure performance and meet regulatory and natural resource goals (Weinstein 2009).

- **Stand-alone systems**: In urban retrofit applications, LID practices can be applied as discrete, stand-alone BMPs to meet specific localized water quality needs.

- **Hybrid systems**: When applied, hybrid systems create a treatment train of either LID practices or LID and conventional controls. This type of approach is often used for separate sewer systems to provide enhanced water quality prior to discharge.

- **Complement to existing conventional infrastructure**: LID practices are often used to relieve the hydraulic burden on conventional infrastructure and enhance its operational performance.

Although the benefits of LID have been broadly documented and numerous entities are aggressively incorporating LID practices into their stormwater management programs, LID adoption continues to be stymied by institutional issues. In some cases, the use of LID will be precluded by the ordinances that local governments have adopted over the years in the name of managed development. Twenty years ago, when the first stormwater management plans were being developed on a wide scale, the end-of-pipe, stormwater detention pond was thought to be the most efficient solution to the problems of stormwater from urban development. Over time, better ways to address stormwater based on the local hydrology and watershed or sewershed drainage patterns have been researched and shown to be superior in the areas of volume reduction and water quality (Weinstein 2009). Changes in the codes and ordinances have not caught up with current BMPs in many cases, which have slowed the adoption of LID. Examples of codes that can prevent or hinder the use of LID are provided below (NRDC 2002).

1. Do building and construction codes restrict core functions of LID practices (e.g., infiltration, stormwater storage)?

2. Have any standards or specifications for LID practices been adopted?

3. Is rooftop or site runoff required to be directed to the street or collection system?

4. Are there minimum driveway widths or restrictions on shared driveways?

5. Is there a prohibition on permeable pavements or “two-track” lane designs?

6. Do standards prevent the temporary ponding of surface runoff?

7. Do regulations require curbs and gutters or prevent open drainage systems?

8. Are incentives in place to use LID practices?

Several municipalities and counties have amended their subdivision and zoning ordinances to allow LID practices to be used to meet their stormwater requirements. Stafford County, Virginia, for example, amended the local development codes, waiving previous requirements like curbs, gutters, and sidewalks and facilitating the use of other LID practices. The county revised its stormwater manual to describe LID practices and how to incorporate them into site design (USEPA 2006).

As previously indicated, additional environmental benefits of integrating LID into stormwater management are detailed in other PWTBs available on the WBDG website (http://www.wbdg.org/ccb/browse_cat.php?o=31&c=215).

APPENDIX B: LID USE AT DOD INSTALLATIONS

Background

The increased use of LID within DoD in recent years has corresponded to an effort to enhance natural resource protection efforts at DoD installations. This emphasis is reflected in a number of directives and regulations, which directly or indirectly promote LID, including the following:

- **Section 438 of the Energy Independence and Security Act**: In 2007, EISA contained new stormwater standards for federal development and redevelopment projects. Section 438 of EISA reads as follows:

  > Stormwater runoff requirements for federal development projects. The sponsor of any development or redevelopment project involving a Federal facility with a footprint that exceeds 5,000 square feet shall use site planning, design, construction, and maintenance strategies for the property to maintain or restore, to the maximum extent technically feasible, the predevelopment hydrology of the property with regard to the temperature, rate, volume, and duration of flow.

- **Executive Orders**: Applicable EOs address stormwater management requirements. For instance:

  > **Executive Order 13514 Federal Leadership in Environmental, Energy, and Economic Performance**
  >
  > **Sec. 1.** *Policy.* In order to create a clean energy economy that will increase our Nation’s prosperity, promote energy security, protect the interests of taxpayers, and safeguard the health of our environment, the Federal Government must lead by example. It is therefore the policy of the United States that Federal agencies shall increase energy efficiency; measure, report, and reduce their greenhouse gas emissions from direct and indirect activities; conserve and protect water resources through efficiency, reuse, and stormwater management; eliminate waste, recycle, and prevent pollution; leverage agency acquisitions to foster markets for

sustainable technologies and environmentally preferable materials, products, and services; design, construct, maintain, and operate high performance sustainable buildings in sustainable locations; strengthen the vitality and livability of the communities in which Federal facilities are located; and inform Federal employees about and involve them in the achievement of these goals.

It is further the policy of the United States that to achieve these goals and support their respective missions, agencies shall prioritize actions based on a full accounting of both economic and social benefits and costs and shall drive continuous improvement by annually evaluating performance, extending or expanding projects that have net benefits, and reassessing or discontinuing under-performing projects.

Finally, it is also the policy of the United States that agencies' efforts and outcomes in implementing this order shall be transparent and that agencies shall therefore disclose results associated with the actions taken pursuant to this order on publicly available Federal websites.

Sec. 2. *Goals for Agencies.* In implementing the policy set forth in section 1 of this order, and preparing and implementing the Strategic Sustainability Performance Plan called for in section 8 of this order, the head of each agency shall:

(d) improve water use efficiency and management by:

(i) reducing potable water consumption intensity by 2 percent annually through fiscal year 2020, or 26 percent by the end of fiscal year 2020, relative to a baseline of the agency's water consumption in fiscal year 2007, by implementing water management strategies including water-efficient and low-flow fixtures and efficient cooling towers;

(ii) reducing agency industrial, landscaping, and agricultural water consumption by 2 percent annually or 20 percent by the end of fiscal year 2020 relative to a baseline of the agency's industrial, landscaping, and agricultural water consumption in fiscal year 2010;

(iii) consistent with State law, identifying, promoting, and implementing water reuse strategies that reduce potable water consumption; and
(iv) implementing and achieving the objectives identified in the stormwater management guidance referenced in section 14 of this order.

Executive Order 13508, "Chesapeake Bay Protection and Restoration"

PART 1 – PREAMBLE

The Chesapeake Bay is a national treasure constituting the largest estuary in the United States and one of the largest and most biologically productive estuaries in the world. The Federal Government has nationally significant assets in the Chesapeake Bay and its watershed in the form of public lands, facilities, military installations, parks, forests, wildlife refuges, monuments, and museums.

Despite significant efforts by Federal, State, and local governments and other interested parties, water pollution in the Chesapeake Bay prevents the attainment of existing State water quality standards and the "fishable and swimmable" goals of the Clean Water Act. At the current level and scope of pollution control within the Chesapeake Bay's watershed, restoration of the Chesapeake Bay is not expected for many years. The pollutants that are largely responsible for pollution of the Chesapeake Bay are nutrients, in the form of nitrogen and phosphorus, and sediment. These pollutants come from many sources, including sewage treatment plants, city streets, development sites, agricultural operations, and deposition from the air onto the waters of the Chesapeake Bay and the lands of the watershed.

Restoration of the health of the Chesapeake Bay will require a renewed commitment to controlling pollution from all sources as well as protecting and restoring habitat and living resources, conserving lands, and improving management of natural resources, all of which contribute to improved water quality and ecosystem health. The Federal Government should lead this effort. Executive departments and agencies

(agencies), working in collaboration, can use their expertise and resources to contribute significantly to improving the health of the Chesapeake Bay. Progress in restoring the Chesapeake Bay also will depend on the support of State and local governments, the enterprise of the private sector, and the stewardship provided to the Chesapeake Bay by all the people who make this region their home.

PART 5 – REDUCE WATER POLLUTION FROM FEDERAL LANDS AND FACILITIES

Sec. 501. Agencies with land, facilities, or installation management responsibilities affecting ten or more acres within the watershed of the Chesapeake Bay shall, as expeditiously as practicable and to the extent permitted by law, implement land management practices to protect the Chesapeake Bay and its tributary waters consistent with the report required by section 202 of this order and as described in guidance published by the EPA under section 502.

Sec. 502. The Administrator of the EPA shall, within 1 year of the date of this order and after consulting with the Committee and providing for public review and comment, publish guidance for Federal land management in the Chesapeake Bay watershed describing proven, cost-effective tools and practices that reduce water pollution, including practices that are available for use by Federal agencies.

- Unified Facilities Criteria (UFC): The UFC system provides planning, design, construction, sustainment, restoration, and modernization criteria, and applies to Military Departments, Defense Agencies, and DoD Field Activities. In particular, the UFC 3-210-10, “Low Impact Development” is intended to provide technical criteria, technical requirements, and references for the planning and design of LID projects (DoD 2010). The requirements in the LID UFC apply to all DoD construction in the United States and US Territories. For DoD construction outside of the United States and its territories, the UFC is intended as a design guide to achieve the "no net increase" goal of stormwater runoff volume or pollutant loads to ensure compliance with agreements with host nations including: Status of Forces Agreement (SOFA), Host Nation Funded Construction Agreements (HNFA), and Bilateral Infrastructure Agreements (BIA). Therefore, construction must ensure compliance with the more stringent of the UFC, the SOFA, the FNFA, and the BIA, as applicable.

BMPs at DoD Installations

The institutional focus on LID has resulted in the use of a number of LID practices at DoD installations across the country. Table B-1 summarizes some of the LID practices that have been used at DoD installations.

This summary shows that vegetated swales and bioretention have tended to be used most often in DoD applications. However, because of expected land uses and stormwater management requirements, practices such as green roofs, permeable pavements, and rainwater harvesting are likely to be used with regular frequency as well.

Table B-1. Summary of LID practices at DoD installations.

			Practice							
Project Name	**Installation**	**State**	**Bioretention (Cells, Swales, Tree Boxes)**	**Green Roof**	**Permeable Pavement**	**Vegetated Swales / Vegetated Buffers**	**Rainwater Harvesting**	**Native Vegetation / Xeriscaping**	**Downspout Disconnection / Reduced Footprint**	**Infiltration Practices / Soil Amendments**
DoD										
New Campus East	National Geospatial Intelligence Agency	VA		✓						
Remote Delivery Facility	Pentagon	VA		✓						
DSCR Rain Garden	Defense Supply Center Richmond	VA	✓							
Air Force										
LID and Bioswales project	Pillar Point AFS*	CA	✓							
21st Space Wing Green Roof	Peterson AFB*	CO		✓						
KMCC Visitors Quarters	Ramstein AB*	Germany		✓						
Xeriscaping Project	Luke AFB	AZ						✓		
Nellis AFB Xeriscaping	Nellis AFB	NV						✓		

Project Name	Installation	State	Practice: Bioretention (Cells, Swales, Tree Boxes)	Green Roof	Permeable Pavement	Vegetated Swales / Vegetated Buffers	Rainwater Harvesting	Native Vegetation / Xeriscaping	Downspout Disconnection / Reduced Footprint	Infiltration Practices / Soil Amendments
Xeriscaping project	Schriever AFB	CO						✓		
Army										
Borrow Pits – LMI* Recommendation	Fort Stewart	GA	✓					✓		
Landscape Retrofit Site 1	Fort Detrick	MD	✓					✓		
Training Grounds Rehabilitation	Fort Irwin: National Training Center	CA								✓
Sequalitchew Creek, EcoPark, and Earthworks	Fort Lewis	WA						✓		
Grounds Rehabilitation	Fort Indiantown Gap Training Center	PA						✓		
Post Exchange Garden	Fort Sam Houston	TX						✓		
DPW Horseshoe bioretention	Fort Bragg	NC	✓							
Menasha USARC* Training Building	Fort Drum	NY	✓							
Parking Lot	Fort Monroe	VA	✓							
Comprehensive Land Mgmt Plan	Army Research Lab	MD	✓							
Community Emergency Service Station	Fort Bragg	NC	✓							
Various Locations	Fort Bragg	NC	✓							
Golden Knights Parachute Team HQ Facility	Fort Bragg	NC						✓	✓	
Vehicle Mainte-nance Facility Parking Lot	Fort Bragg	NC						✓		
Elementary School	Fort Stewart	GA				✓				

Project Name	Installation	State	Practice							
			Bioretention (Cells, Swales, Tree Boxes)	Green Roof	Permeable Pavement	Vegetated Swales / Vegetated Buffers	Rainwater Harvesting	Native Vegetation / Xeriscaping	Downspout Disconnection / Reduced Footprint	Infiltration Practices / Soil Amendments
Tobyhanna Building 11 Green Roof	Tobyhanna Arsenal	PA		✓						
Hospital	Fort Belvoir	VA	✓	✓						
16th MP* Barracks	Fort Bragg	NC								✓
Erosion Remediation Project 97	Fort Jackson	SC			✓					
Fort Bragg East Complex	Fort Bragg	NC							✓	
Sustainable Military Homes	USAG* Hawaii	HI	✓		✓					
Sustainable Parking Lot for Classrooms	Fort Bragg	NC			✓					
(unnamed project)	Rock Island Arsenal	IL			✓					
Mount Vernon Readiness Center	IL Army National Guard	IL			✓					
Environmental Training Facility	Fort Hood	TX			✓			✓		
Pervious Pavement	Fort Lewis	WA			✓					
Parking Lot	Fort Monroe	VA			✓					
Bayscapes Garden	Aberdeen Proving Ground	MD	✓							
Landscape Retrofit Site 2	Fort Detrick	MD	✓							
Fort Eustis rain garden	Fort Eustis	VA	✓							
Parking Lot Removal and Retrofit	Fort Lee	VA	✓							
Park Lot Runoff Retrofit	Fort Meade	MD	✓							
MOTSU Rain Gardens	Military Ocean Terminal Sunny Point	NC	✓							
Post Exchange Retrofit	Fort Belvoir	VA	✓					✓		

Project Name	Installation	State	Practice							
			Bioretention (Cells, Swales, Tree Boxes)	Green Roof	Permeable Pavement	Vegetated Swales / Vegetated Buffers	Rainwater Harvesting	Native Vegetation / Xeriscaping	Downspout Disconnection / Reduced Footprint	Infiltration Practices / Soil Amendments
(Unnamed project #2)	Rock Island Arsenal	IL	✓							
Comprehensive Land Mgmt Plan	Army Research Lab	MD								✓
DISA HQ	Fort Meade	MD			✓					
New England Disaster Training Center	CT National Guard	CT				✓				
Elementary School	Fort Carson	CO						✓		
Green Training Building	Fort Carson	CO						✓		
Cemetery	Fort Bliss	TX						✓		
Family Housing	Fort Huachuca	AZ						✓	✓	
Marine Corps										
MCAS* New River Station Officer's Club and HQ	MCAS New River	NC	✓							
Command deck, Shadow Mountain & Ocotillo Housing Areas	MCAGCC* 29 Palms	CA						✓		
MCAS Miramar xeriscaping	MCAS Miramar	CA						✓		
MCAS Yuma xeriscaping	MCAS Yuma	AZ						✓		
Hockmuth Hall Addition	Marine Corps Base Quantico	VA	✓							
Navy										
Willard Park Dental Clinic LID	Washington Navy Yard	DC	✓				✓			
Naval Base Coronado Xeriscape	Naval Base Coronado	CA						✓		
Navy Exchange Mall	Pearl Harbor	HI						✓		
Air Force Personnel Center	Randolph AFB	TX						✓		

Project Name	Installation	State	Practice: Bioretention (Cells, Swales, Tree Boxes)	Green Roof	Permeable Pavement	Vegetated Swales / Vegetated Buffers	Rainwater Harvesting	Native Vegetation / Xeriscaping	Downspout Disconnection / Reduced Footprint	Infiltration Practices / Soil Amendments
Camp Smith Fire Station	MCB* Hawaii Kaneohe	HI				✓				
Replace 61 (formerly 134) Units at Old Apra Harbor*	COMNAV* Marianas Guam	GU				✓				
Joint Reserve Center, Albany	NAVSUPPU* Saratoga Springs	NY				✓				
Police & Security Operations Facility	NAVPHIBASE* Little Creek	VA				✓				
C-17 NE Assault Landing Zone - OPT 2	McGuire AFB Wrightson	NJ				✓				
Tomahawk Missile Magazine	NAVSUBSUPPFAC NLON* Groton	CT		✓		✓				
Z140 Addition for EFA* Northeast	Naval Station Norfolk	VA				✓			✓	
RTC* Barracks	Naval Station Great Lakes	IL	✓		✓					
Federal Health Care Facility Parking Garage/Site/Util	Naval Health Clinic Great Lakes	IL	✓			✓				
RTC Barracks	Naval Station Great Lakes	IL	✓		✓					
Katrina - Steelworkers Training Facility	CBC* Gulfport	MS				✓				
Katrina - Builders Applied Instruction Facility	CBC Gulfport	MS				✓				
Katrina – NCTC* Academic Instruction Complex	CBC Gulfport	MS				✓				

Project Name	Installation	State	Practice							
			Bioretention (Cells, Swales, Tree Boxes)	Green Roof	Permeable Pavement	Vegetated Swales / Vegetated Buffers	Rainwater Harvesting	Native Vegetation / Xeriscaping	Downspout Disconnection / Reduced Footprint	Infiltration Practices / Soil Amendments
Katrina - Disaster Recovery Training Facility	CBC Gulfport	MS				✓				
Katrina - Tactical Training - Embark	CBC Gulfport	MS				✓				
Katrina - Armory	CBC Gulfport	MS				✓				
Combat Vehicle Maintenance & Preservation Facility	MCLB* Albany	GA				✓				
FEC* Southeast Engrg Operations Center	NAS* Jacksonville	FL				✓		✓		
Joint Aquatic Combat Diver Training	Naval Support Activity Panama City	FL				✓				
Ship Maintenance Consol	Naval Station Mayport	FL				✓				
HMMWV* Support Facilities	Naval Submarine Base Kings Bay	GA				✓				
Dormitory (144 Person)	TAC* Shaw AFB Sumter	SC				✓				
Aerospace Ground Equipment Shop/Storage Facility	TAC Shaw AFB Sumter	SC				✓				
Comprehensive Health Care Center Replacement	Naval Health Clinic Charleston	SC				✓				
Aviation Rescue Swimmer School	NAS Pensacola	FL				✓				
Reserve Training Center	MCAGCC* Twenty-nine Palms	CA				✓				
Taxiway Improvements	MCAS* Camp Pendleton	CA				✓				
Operation Access – SHOBA* - SCI*	NAF* San Clemente	CA				✓				

Project Name	Installation	State	Practice: Bioretention (Cells, Swales, Tree Boxes)	Green Roof	Permeable Pavement	Vegetated Swales / Vegetated Buffers	Rainwater Harvesting	Native Vegetation / Xeriscaping	Downspout Disconnection / Reduced Footprint	Infiltration Practices / Soil Amendments
SOF* MOUTT* Complex, Q763-NAB	Naval Base Coronado	CA			✓					
Parking Facility	Naval Medical Center San Diego	CA				✓				
Academic Facility Addition	Naval Support Detachment Monterey	CA			✓	✓				
Wesley Brown Field House	USNA* Annapolis	MD	✓		✓					
Joint Counter IED* Laboratory	NSA* South Potomac	MD				✓				✓
Hockmuth Hall Addition	Marine Corps Base Quantico	VA	✓							
Clandestine Laboratory Training Center	Drug Enforcement Administration Arlington	VA			✓	✓				
Repairs at Basin 10 and 16 (formerly Drainage Phase IV)	Naval Support Activity	DC				✓				

* AFB – Air Force Base; AFS – Air Force Station; AB – Air Base; CBC – Construction Battalion Center; COMNAV – Commander Naval Forces; DSCR - Defense Supply Center Richmond; EFA – Engineering Field Activity; FEC – Florida East Coast; HMMMV - High Mobility Multipurpose Military Vehicle; HQ – Headquarters; IED – Improved Explosive Device; LMI – LMI Government Consulting ; MCAS – Marine Corps Air Station; MCAGCC – Marine Corps Air Ground Combat Center; MCB – Marine Corps Base; MCLB – Marine Corps Logistics Base;
MOTSU – Military Ocean Terminal Sunny Point; MOUTT - Military Operations Urban Terrain Training; MP – Military Police; NAF – Naval Air Facility; NAVPHIBASE – Naval Amphibious Base; NAVSUPPU – Naval Support Unit; NAVSUBSUPPFAC NLON – Naval Submarine Support Facility, New London; NAS – Naval Air Station; NCTC – Naval Construction Training Center; NSA – Naval Support Activity; RTC – Recruit Training Center; SOF – Special Operations Facility; SCI – San Clemente Island; SHOBA – Shore Bombardment Area;
TAC – Tactical Air Control; USAG – US Army Garrison; USARC – US Army Reserve Center; USNA - US Naval Academy.

Design Considerations

Bioretention

Bioretention cells and swales are vegetated systems that rapidly filter stormwater through bioretention soil media which is typically a mix of sand, topsoil, and mulch. The stormwater is treated by biological and chemical reactions in the mulch, soil matrix, and root zone; physical straining; and infiltration into the underlying subsoil improve runoff water quality. The volume of stormwater is reduced by retaining water in the cell, vegetative uptake and evapotranspiration, and infiltration into the subsoil. Bioretention can be introduced as rain gardens, enhanced tree boxes, planter boxes, curb extensions, or bioswales.

Figure B-1 shows a typical bioretention cross section; Table B-2 describes typical components as given in the National Cooperative Highway Research Program [NCHRP] report.

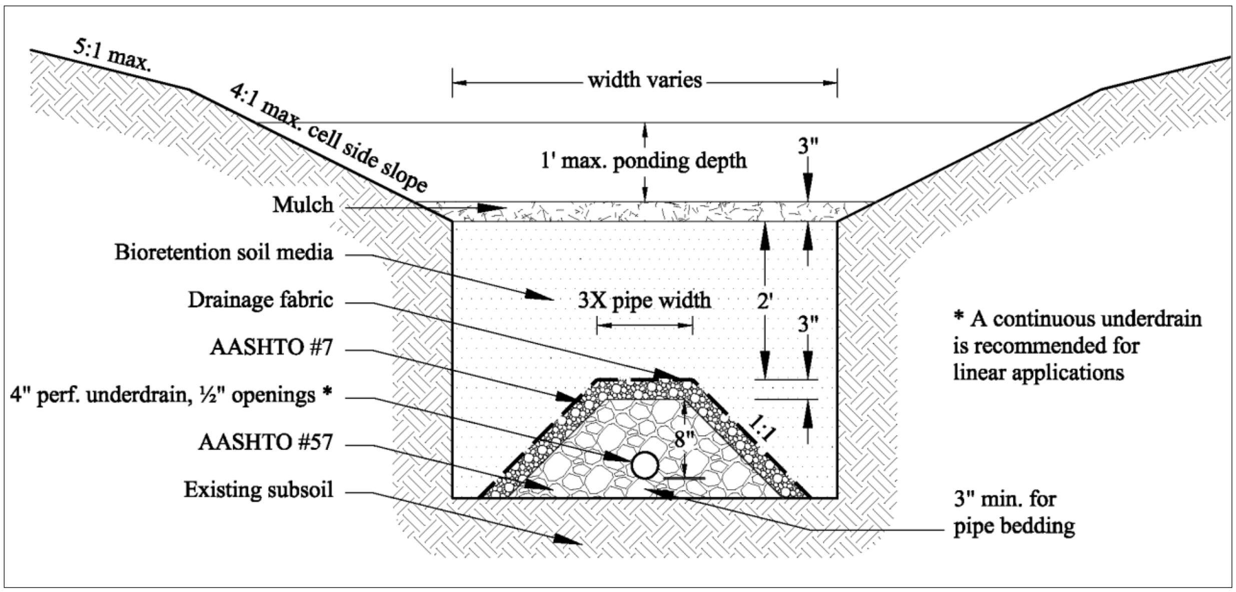

Figure B-1. Typical bioretention cross section (not to scale) (NCHRP 2006).

Table B-2. Typical bioretention components (NCHRP 2006).

Item	**Purpose**
Bioretention soil media (typically comprised of): • 50% sand • 30% topsoil • 20% 2X shredded hardwood mulch	• Growth medium for plants and microbes • Stormwater storage in void space • Pollutant removal: biological, chemical, and physical processes
Mulch • A separate quantity of mulch placed as the top layer of the bioretention system and separate from that mixed into the soil media.	• Captures sediment and pollutants • Protects plants • Increases stormwater retention
Plants • Plants should be salt-tolerant in cold climate regions and must be able to withstand periods of high and low moisture. • Plants should not require irrigation after establishment period. • Native plants are preferable.	• Pollutant removal through root uptake • Roots provide habitat for microbes • Nutrient cycling • Landscaping/habitat • Volume reduction through evapotranspiration • Roots help maintain soil permeability
Filter fabric • Use equivalent opening size of #50 sieve to avoid clogging by fine particles.	• Place between soil media and gravel layers or in-situ native soils to prevent migration of fines
Underdrain pipe (optional) • Minimum 4-in. diameter perforated pipe.	• Provide positive drainage where subsoil has low permeability or when liner is required
Pea gravel (optional) • AASHTO* No. 7 (1/4 in.) • Washed, river-run, round diameter	• Diaphragm to prevent underdrain pipe from clogging
Gravel (optional) • AASHTO No. 57 (3/4 in. to 3/16 in.) • Double-washed blue stone	• Stormwater storage in void space
Observation and cleanout pipe (optional) • Non-perforated pipe. • Join to underdrain with “T” connection.	• Used to determine whether cell is dewatering properly • Backflushing underdrain
Liner (optional) • Plastic pond liner or equivalent.	• Prevent infiltration to sensitive groundwater resources or contaminated soils
*AASHTO - American Association of State Highway and Transportation Officials.	

Vegetated Swales

Vegetated swales are broad, shallow channels designed to convey stormwater runoff and treat it by filtering and infiltration. The swales are vegetated along the bottom and sides of the channel, with side vegetation at a height greater than the maximum design flow depth. The design of swales seeks to reduce stormwater volume through infiltration and interception, uptake, and evapotranspiration by the plants; improve water quality through infiltration and vegetative filtering; and reduce runoff velocity by increasing flow path lengths and channel roughness. Removal of pollutants has been positively linked to the length of time that the stormwater remains in contact with the herbaceous materials and soils. Swales are well suited for use within the right-of-ways of linear transportation corridors.

Figure B-2 shows a typical vegetated swale cross section and Table B-3 describes the typical components.

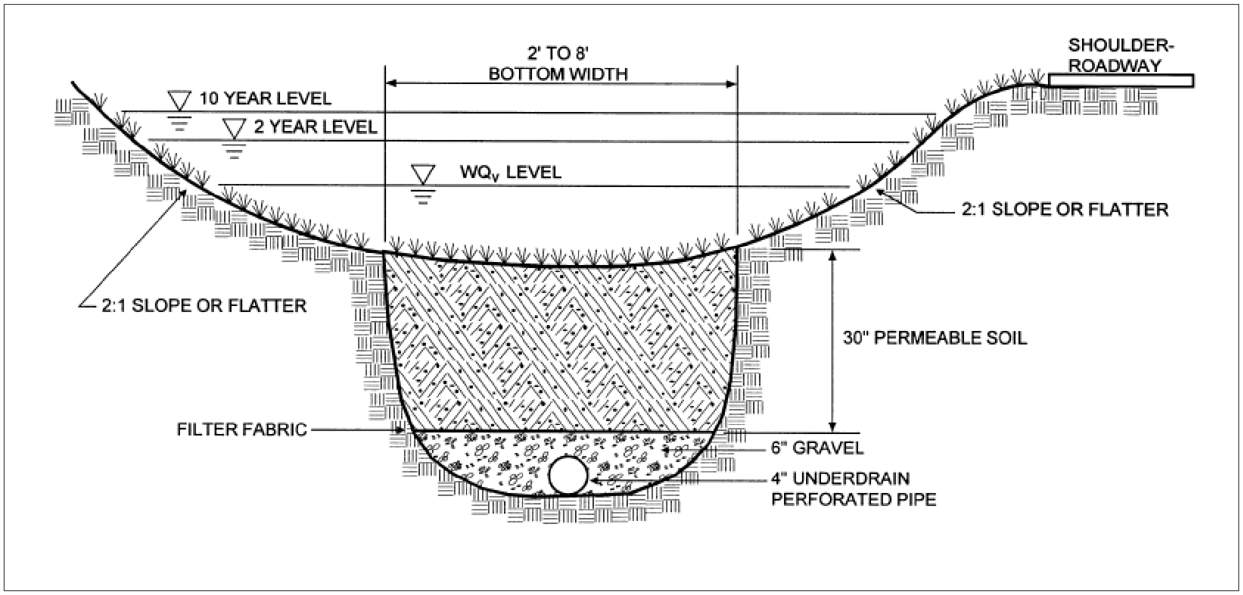

Figure B-2. Typical vegetated swale cross section (MDE [Maryland Department of the Environment] 2000, 3.43).

Table B-3. Typical vegetated swale components (NCHRP 2006).

Item	Purpose
Permeable soil • Soil underlying swale should have an infiltration rate of 0.3 inches per hour or greater.	• Allows infiltration of stormwater • Stormwater storage in void space • Pollutant removal – biological, chemical, and physical processes
Sod	• Provides pollutant removal and channel stability • Reduces stormwater velocities
Grass seed	• Provides pollutant removal and channel stability • Reduces stormwater velocities
Plants • Plants should be salt-tolerant in cold climate regions and must be able to withstand periods of high and low moisture. • Plants should not require irrigation after establishment period. • Native plants are preferable.	• Pollutant removal through root uptake • Roots provide habitat for microbes • Nutrient cycling • Landscaping/habitat • Volume reduction through evapotranspiration • Roots help maintain soil permeability
Filter fabric • Use Equivalent Opening Size of #50 sieve to avoid clogging by fine particles.	• Place between soil media and gravel layers or in-situ native soils to prevent migration of fines
Underdrain pipe (optional) • Minimum 4-in. diameter perforated pipe.	• Provide positive drainage where subsoil has low permeability or when liner is required
Pea gravel (optional) • AASHTO* No. 7 (1/4 in.) • Washed, river-run, round diameter	• Diaphragm to prevent underdrain pipe from clogging
Observation and cleanout pipe (optional) • Non-perforated pipe. • Join to underdrain with “T” connection.	• Used to determine whether cell is dewatering properly • Backflushing underdrain
Liner (optional) • Plastic pond liner or equivalent.	• Prevent infiltration to sensitive groundwater resources or contaminated soils
*AASHTO - American Association of State Highway and Transportation Officials.	

Green Roofs

Green roofs are structural roof components that filter, absorb, and retain/detain the rain that falls on them with a layer of soil media and vegetation. They consist of an impermeable membrane, an engineered soil medium, and plants. Rainfall that infiltrates into the green roof soil media is lost to evaporation or transpiration by plants, or, once the soil has become saturated, percolates through to the drainage layer and is discharged through the roof downspouts. In between storm events, stored water is returned to the atmosphere by evapotranspiration by plants and the medium surface. Green roofs can provide high rates of rainfall retention and decrease peak flow rates, creating hydrologic function approaching that of undeveloped areas.

Figure B-3 shows a typical green roof cross section and Table B-4 describes typical components.

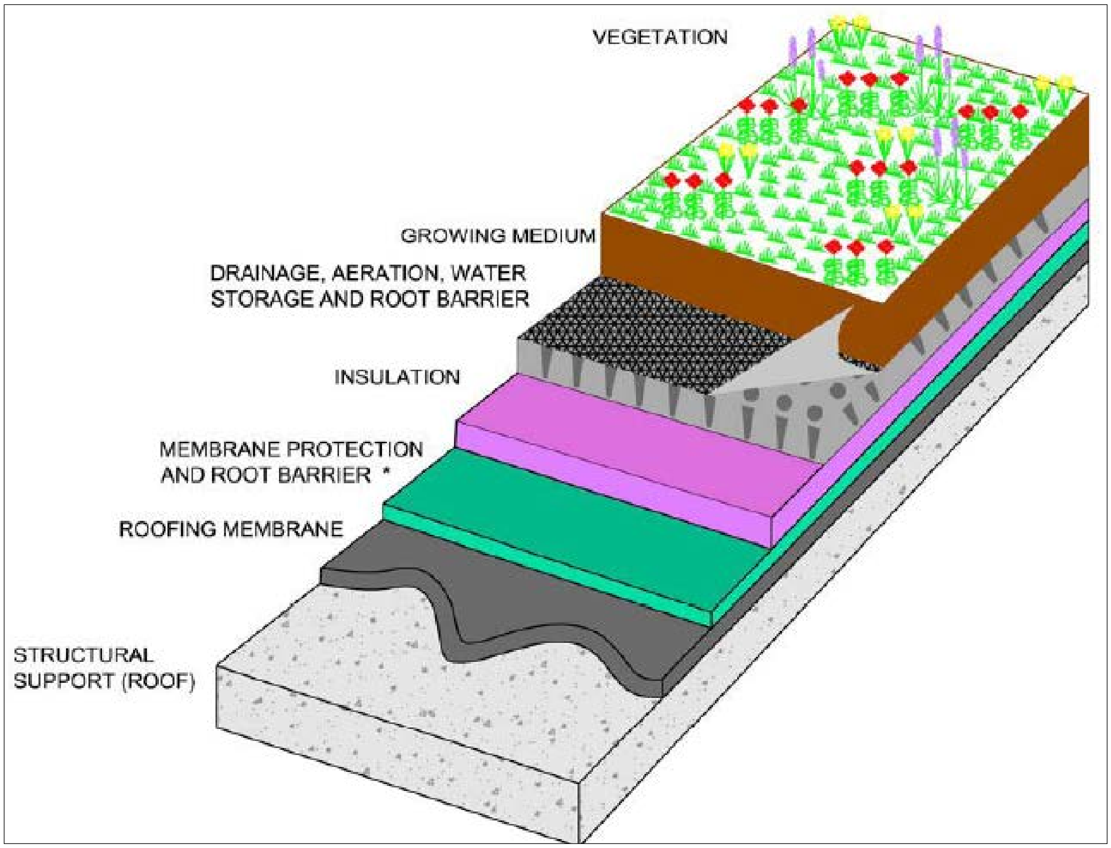

Figure B-3. Typical green roof cross section (MDE 2000, 5.44).

Table B-4. Typical green roof components (NCHRP 2006).

Item	**Purpose**
Plants	• Pollutant removal through root uptake. • Roots provide habitat for microbes. • Nutrient cycling. • Volume reduction through evapotranspiration.
Growing medium (soil)	• Growth medium for plants and microbes. • Stormwater storage in void space. • Pollutant removal: biological, chemical, and physical processes.
Drainage layer	• Allows excess water to drain from the green roof to the building downspouts.
Insulation layer	• Provides an insulation layer between green roof and structural roof.
Root barrier	• Prevents roots from damaging roof membranes.
Waterproof membrane	• Prevents water transmission from green roof to structural roof.
Leak detection layer (optional)	• Used to determine whether waterproof membrane is performing properly.

Permeable Pavement

Permeable pavements contain small voids that allow stormwater to drain through the pavement to an aggregate reservoir and then infiltrate into the soil. They may be a modular paving system (concrete pavers, grass-pave, or gravel-pave) or poured-in-place solutions (porous concrete, permeable asphalt). Permeable concrete and asphalt are similar to their impervious counterparts but are open graded or have reduced fines and typically have a special binder added. Methods for pouring, setting, and curing these permeable pavements also differ from the impervious versions. The concrete and grid pavers are modular systems. Concrete pavers are installed with gaps between them that allow water to pass through to the base. Grid pavers are typically a durable plastic matrix that can be filled with gravel or vegetation. All of the permeable pavement systems have an aggregate base in common which provides structural support, runoff storage, and pollutant removal through filtering and adsorption. Permeable pavements have been used in pedestrian walkways, sidewalks, driveways, parking lots, and low-volume roadways. Permeable pavements are used to reduce the volume of stormwater runoff by converting an impervious area to a treatment unit.

Figure B-4 shows a typical permeable pavement cross section and Table B-5 describes typical components.

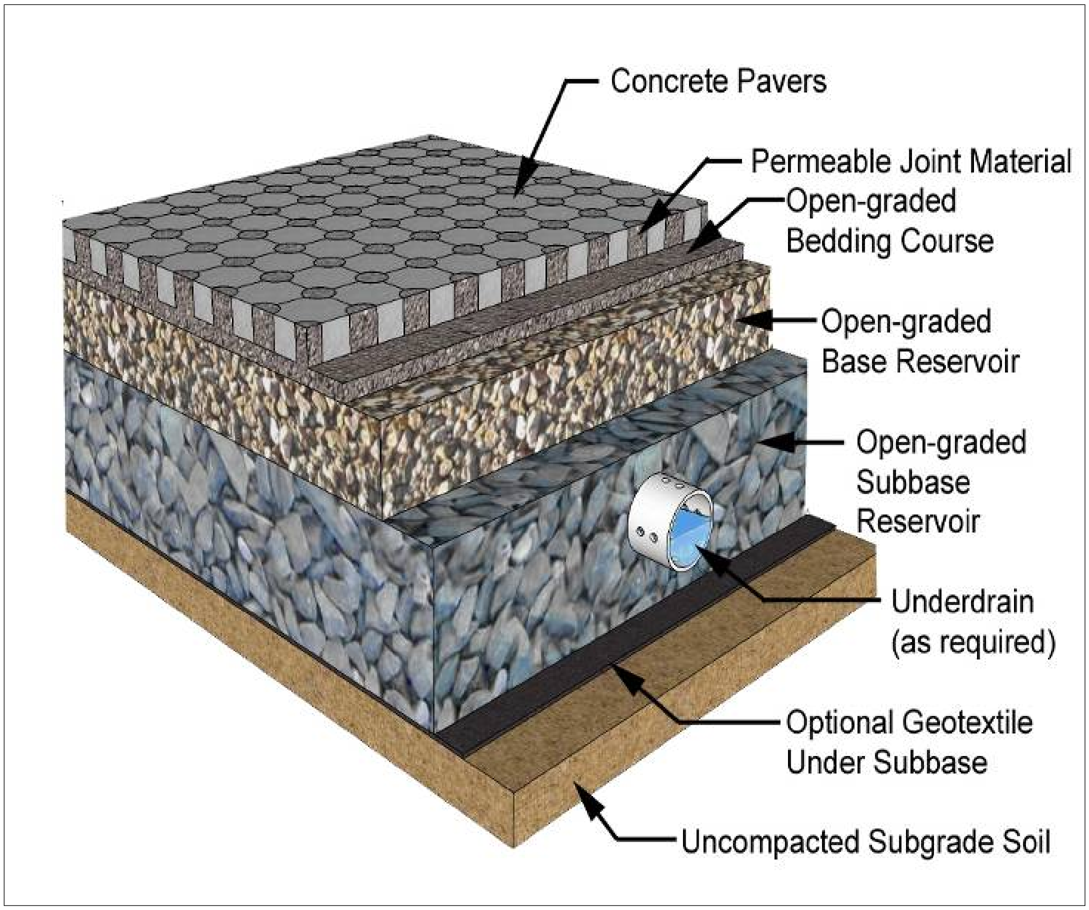

Figure B-4. Typical permeable pavement cross section (Interlocking Concrete Pavement Institute [ICPI]).

Table B-5. Typical permeable pavement components (NCHRP 2006).

Item	Purpose
Permeable pavement	• Supports vehicular traffic and loads. • Void space allows stormwater to infiltrate into gravel storage bed.
Gravel • AASHTO No. 57 (3/4 in. to 3/16 in.) • Double-washed blue stone	• Stormwater storage in void space
Filter fabric • Use Equivalent Opening Size of #50 sieve to avoid clogging by fine particles.	• Place between gravel layers and in-situ native soils
Underdrain pipe (optional) • Minimum 4" diameter perforated pipe.	• Provide positive drainage where subsoil has low permeability or when liner is required
Pea gravel (optional) • AASHTO No. 7 (1/4 in.) • Washed, river-run, round diameter	• Diaphragm to prevent underdrain pipe from clogging
Observation and cleanout pipe (optional) • Non-perforated pipe. • Join to underdrain with "T" connection.	• Used to determine whether cell is dewatering properly • Backflushing underdrain
Liner (optional) • Plastic pond liner or equivalent.	• Prevent infiltration to sensitive groundwater resources or contaminated soils
*AASHTO - American Association of State Highway and Transportation Officials.	

Cisterns

Cisterns are rainwater harvesting and storage systems that capture and store runoff from downspouts to reduce stormwater runoff and provide a nonpotable water source. Cisterns typically hold several hundred to several thousand gallons of rainwater. They can be used in a variety of settings and provide an ideal source of nonpotable water for outdoor irrigation, toilet and urinal flushing, cooling system make-up, and equipment and vehicle washing. The rainwater collection area for cisterns is usually limited to rooftops because it contains lesser concentrations of pollutants than runoff from other surface areas.

Figure B-5 is a schematic of a cistern and Table B-6 describes typical components.

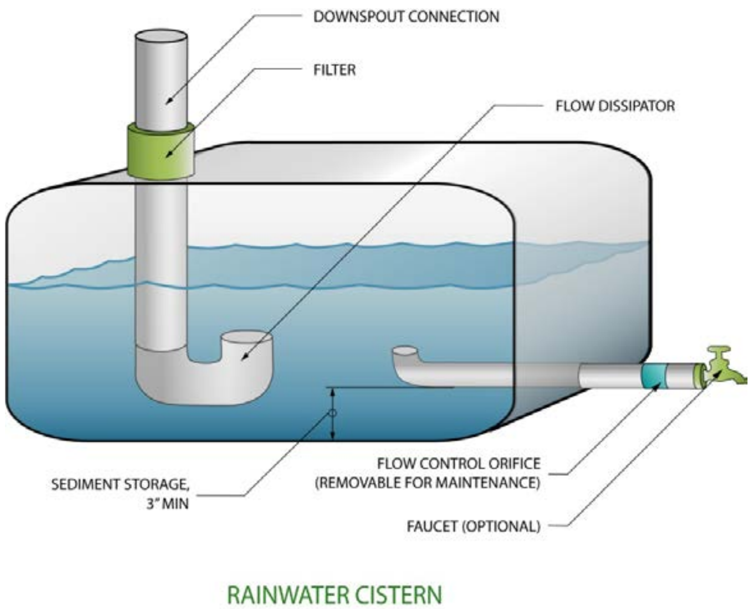

Figure B-5. Cistern schematic (Seattle Public Utilities).

Table B-6. Typical cistern components (NCHRP 2006).

Item	**Purpose**
Cistern	• Stores harvested rainwater
Roof washer	• Filters rainwater prior to entering cistern
Pump	• Delivers cistern water to intended end use
Filter – sand or cartridge (optional)	• Provides additional filtration for cistern effluent prior to reuse
Disinfection unit – UV, ozone, or chlorine (optional)	• Disinfects cistern effluent prior to reuse

APPENDIX C:
BIORETENTION SYSTEMS

Design

Climate/geology: Bioretention can be applied in many climatological and geological situations, with some minor design modifications. In arid climates, bioretention areas should be landscaped with drought-tolerant species. In cold climates, bioretention areas can be used as snow storage areas. If used for this purpose, or if used to treat runoff from a parking lot where salt is used as a deicer, the bioretention area should be planted with salt-tolerant, non-woody plant species.

Soils: Bioretention systems can be applied in almost any soils or topography, since runoff percolates through a man-made soil bed and is returned to the stormwater system. Bioretention systems should be separated somewhat from the ground water to ensure that the ground-water table never intersects with the bed of the bioretention facility. This design consideration prevents possible ground-water contamination.

Site size/slope: Bioretention systems are generally applied to small sites (5 acres or less) such as existing parking lot islands or other landscaped areas. They are also best applied to relatively shallow slopes (usually about 5%). However, sufficient slope is needed at the site to ensure that water that enters the bioretention area can be connected with the storm drain system. Bioretention systems can be strategically placed in “stormwater hot spots,” which are areas where land use or activities generate highly contaminated runoff, with concentrations of pollutants in excess of those typically found in stormwater. Bioretention areas can be used to treat stormwater hot spots as long as an impermeable liner is used to enclose the soil media.

Ground-water recharge: One design alternative to the traditional bioretention practice is a "partial exfiltration" system, used to promote ground-water recharge. When this design variation is used, the underdrain is installed only on part of the bottom of the bioretention system. This design allows for some infiltration, with the underdrain system acting as more of an overflow device. This system should be applied only when the soils and other characteristics are appropriate for infiltration.

Retrofits: Bioretention can be used as a stormwater retrofit, by modifying existing landscaped areas, or when a parking lot is being resurfaced. Bioretention can be used to retrofit stormwater infrastructure by either modifying existing landscaped areas or when a parking lot is being resurfaced. In highly urbanized areas, this retrofit option is one of the few that can be employed. Designers need to consider conditions at the site level. The goal is to incorporate design features to improve the longevity and performance of the practice, while minimizing the maintenance burden.

Specific designs may vary considerably, depending on site constraints or preferences of the designer or community. Some features, however, should be incorporated into most bioretention area designs. These design features can be divided into five basic categories: pretreatment, treatment, conveyance, maintenance reduction, and landscaping.

- **Pretreatment** refers to features of a management practice that cause coarse sediment particles and their associated pollutants to settle. Incorporating pretreatment helps to reduce the maintenance burden of bioretention and reduces the likelihood that the soil bed will clog over time. Several different mechanisms can be used to provide pretreatment in bioretention facilities. Often, runoff is directed to a grass channel or filter strip to filter out coarse materials before the runoff flows into the filter bed of the bioretention area. Other features may include a pea gravel diaphragm, which acts to spread flow evenly and drop out larger particles.

- **Treatment** design features help enhance the ability of a stormwater management practice to remove pollutants. Several basic features should be incorporated into bioretention designs to enhance their pollutant removal. The bioretention system should be sized between 5% and 10% of the impervious area draining to it. The practice should be designed with a soil bed that is a sand/soil matrix, with a mulch layer above the soil bed. The bioretention area should be designed to pond a small amount of water (6-9 in.) above the filter bed.

- **Conveyance** of stormwater runoff into and through a stormwater practice is a critical component of any stormwater management plan. Stormwater should be conveyed to and from practices safely and to minimize erosion potential. Ideally, some stormwater treatment can be achieved during conveyance to and from the practice. Bioretention practices are often designed with an underdrain system to collect filtered runoff at the bottom of the filter bed and direct it to the storm drain system. An underdrain is a perforated pipe system in a gravel bed, installed on the bottom of the filter bed. Designers should provide an overflow structure to convey flow from storms that are not treated by the bioretention facility to the storm drain.

- **Maintenance reduction** can be accomplished by employing strategic design features. In addition to regular maintenance activities needed to maintain the function of stormwater practices, some design features can be incorporated to reduce the required maintenance of a practice. Designers should ensure that the bioretention area is easily accessible for maintenance.

- **Landscaping** is critical to the function and aesthetic value of bioretention areas. It is preferable to plant the area with native vegetation or plants that provide habitat value, wherever possible. Another important design feature is to select species that can withstand the hydrologic regime they will experience. At the bottom of the bioretention facility, plants that tolerate both wet and dry conditions are preferable. At the edges, which will remain primarily dry, upland species will be the most resilient. Finally, it is best to select a combination of trees, shrubs, and herbaceous materials.

Bioretention can be introduced as rain gardens, bioswales, bioretention cells, tree boxes, planter boxes, or curb bump outs. Figure C-1 through Figure C-9 show examples of bioretention.

Figure C-1. Residential rain garden (City of Maplewood, MN).

Figure C-2. Rain garden in Capital Hill, Washington, DC (courtesy of Low Impact Development Center, Inc. of Beltsville, MD; www.lowimpactdevelopment.org.).

**Figure C-3. Vegetated bioswale
(courtesy of Belle Woods Gardens, Frenchtown, NJ).**

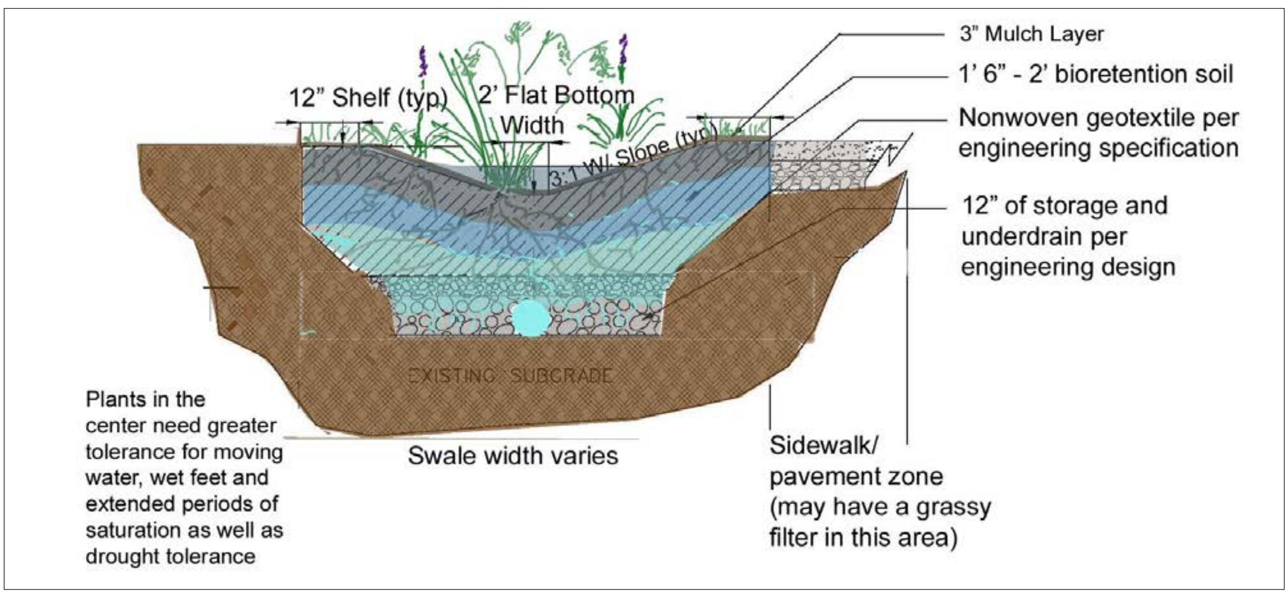

**Figure C-4. Bioswale cross section
(courtesy of Low Impact Development Center, Inc.).**

Figure C-5. Bioretention cell, Washington Navy Yard, DC (courtesy of Low Impact Development Center, Inc.).

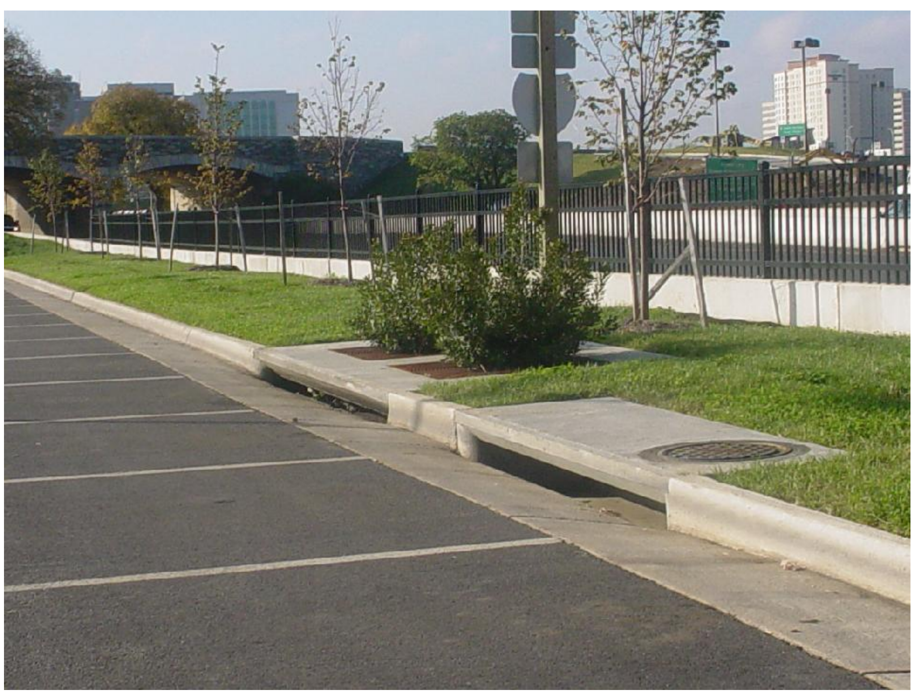

Figure C-6. Tree boxes at the Pentagon (courtesy of Low Impact Development Center, Inc).

Figure C-7. Tree box filter (City of Reno, NV).

Figure C-8. Curb bump out (Portland Bureau of Environmental Services).

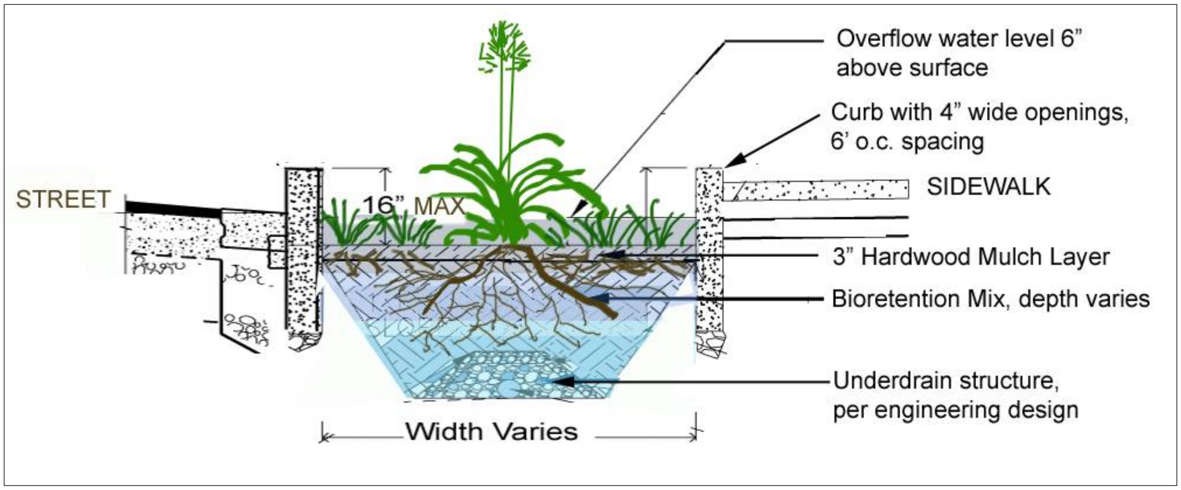

Figure C-9. Curb bump-out cross section (courtesy of Low Impact Development Center, Inc).

Construction

Prior to construction, it is important to make sure that the site does not appear disturbed and does not have excessive sedimentation. To protect from any sedimentation that might occur during the construction process, line the site with a silt fence or bales of straw. The soil walls of the cell should be stabilized in order to avoid washout into gravel and planting soil.

Site grading is an important factor in the effectiveness and safety of bioretention. Grading of any catchment area draining to the facility should be done sparingly and stabilized immediately (within 14 days). A bioretention cell should not be placed in service until all of the contributing drainage area has been stabilized and approved by the inspector. Soil materials should not be delivered until the bioretention site has been excavated or graded and the underdrain systems are in place. Planting materials should not be delivered until after the soil medium has had time to settle to the proper grade elevation.

If the bioretention system is being constructed in a parking lot as a median, it is best to wait until the parking lot's base gravel course is placed before installing the bioretention underdrain, gravel layer, or fill media. Curb openings should be blocked or other measures taken to prohibit drainage from entering the construction area. Prior to covering the underdrain system, the inspector must observe the underdrain itself, the connections, gravel bedding, and any filter fabric. Manufacturer's tickets are required for the gravel, pipe, and filter fabric material. If placing gravel over the underdrain, avoid dropping it from high levels with a backhoe or front-end loader bucket. Spill directly over the underdrain and spread manually.

Avoid over-compaction of the soil material by allowing time for natural compaction and settlement. No additional manual compaction of soil is necessary. To speed up the natural compaction process, the placed soil may be presoaked. Overfill above the proposed surface invert to accommodate natural settlement to the proper grade. Depending on the soil material, up to 20% natural compaction may occur. If construction scheduling permits, it is preferable to allow natural settlement to occur with the help of rain events. When construction vehicles are used, care should be exercised because soil compaction will occur if a vehicle is driven over the bioretention site.

Table C-1 lists sequential construction tasks and the estimated time to complete each task.

Table C-1. Sequence and time of construction tasks (Prince George's County Bioretention Manual, with Low Impact Development Center, Inc. modifications).

Sequence of Construction		**Estimated Time**
1	Install sediment control devices	0.5 day
2	Grade site to elevations shown on plan. If applicable, construct curb openings and/or remove and replace existing concrete. Curb openings should be blocked or other measures taken to prohibit drainage from entering construction area.	1 day
3	Stabilize grading within Limit of Disturbance except for the bioretention area.	0.5 day
4	Excavate bioretention area to proposed invert depth and scarify the existing soil surfaces, taking care not to compact the in-situ materials.	0.5 day
5	Install underdrain system and observation wells, if specified.	0.5 day
6	Backfill bioretention area with planting soil.	0.25 day
7	Wet down the planting soil prior to planting vegetation to allow for settlement.	0.25 day
8	Excavate or fill to achieve proper design grade, leaving space for the upper layer of mulch that will bring the surface to final grade.	0.25 day
9	Plant vegetation	0.25 day

Sequence of Construction		**Estimated Time**
10	Mulch and install erosion protection at entrance points. Remove sediment control practices or entrance blocks with inspector authorization.	0.25 day
	Total estimated construction time:	5.5 days

Maintenance

Bioretention requires typical landscaping maintenance, such as pruning, mulching, and watering (Table C-2). In addition, measures must be taken to ensure that the bioretention area is functioning properly. In many cases, bioretention areas initially require intense maintenance, but less maintenance is needed over time. Maintenance tasks can often be completed by a landscaping contractor, who may already be employed at the site. Landscaping maintenance requirements can be less resource intensive than with traditional landscaping practices such as elevated landscaped islands in parking areas.

Table C-2. Bioretention maintenance tasks (Hunt and Lord 2006).

Task	Frequency	Maintenance Notes
Pruning	1-2 times / year	Nutrients in runoff often cause bioretention vegetation to flourish.
Mowing	2-12 times / year	Frequency depends on location and desired aesthetic appeal.
Mulching	1-2 times / year	
Mulch removal	1 time / 2-3 years	Mulch accumulation reduces available water storage volume. Removal of mulch also increases surface infiltration rate of fill soil.
Watering	1 time / 2-3 days for first 1-2 months. Sporadically after establishment.	If droughty, watering after the initial year may be required.
Fertilization	1 time initially	One time spot fertilization for “first year” vegetation.
Remove and replace dead plants	1 time / year	Within the first year, 10% of plants may die. Survival rates increase with time.
Miscellaneous upkeep	12 times / year	Tasks include trash collection, spot weeding, and removing mulch from overflow device.

Effectiveness

Structural stormwater management practices can be used to achieve four broad resource protection goals. These include flood control, channel protection, ground-water recharge, and pollutant removal. Bioretention addresses these goals in the following manner.

- **Flood control** is not something that bioretention areas are designed to provide. They can, however, divert initial flow, which will aid in maintaining predevelopment hydrology.

- **Channel protection** is not substantially provided by bioretention areas because the scale at which they are typically installed does not allow for the infiltration of large volumes. (They are typically designed to treat and infiltrate the first inch of runoff and are bypassed by larger flows that can erode channels.) Channel protection would be best reached by using bioretention cells in combination with other means, such as ponds or other volume control practices.

- **Ground-water recharge** does not usually happen in bioretention areas, except in the case of the partial exfiltration design.

- **Pollutant removal** data for bioretention, including one field and laboratory analysis of bioretention facilities conducted by Davis et al. (1997), showed very high removal rates (roughly 95% for copper, 98% for phosphorus, 20% for nitrate, and 50% for total Kjeldhal nitrogen [TKN]). Table C-3 shows data from two other studies of field bioretention sites in Maryland.

Table C-3. Pollutant removal effectiveness of two bioretention areas in Maryland (USEPA 1999).

Pollutant	Pollutant Removal
Copper	43% - 97%
Lead	70% - 95%
Zinc	64% - 95%
Phosphorus	65% - 87%
Total Kjeldahl Nitrogen (TKN)	52% - 67%
Ammonium (NH_4^+)	92%
Nitrate (NO_3^-)	15% - 16%
Total nitrogen	49%
Calcium	27%
Source: USEPA 1999	

Assuming that bioretention systems behave similarly to swales, their removal rates are relatively high. However, there is considerable variability in the effectiveness of bioretention areas, and it is believed that properly designing and maintaining these areas, as shown in Figure C-10, may help to improve their performance. Table C-4 provides some design and construction advice for obtaining optimal pollutant removal.

Table C-4. Bioretention design guidelines for specific pollutants (Hunt and Lord 2006).

Target Pollutant	Minimum Fill Media Depth	Target Infiltration Rate	Other Design Guidance
Total Suspended Solids	No minimum fill depth required	Any rate is sufficient; 2–6 in. per hour recommended.	Must keep top layer of cell from being saturated for extended periods.
Pathogens	No minimum fill depth required	Any rate is sufficient; 2–6 in. per hour recommended.	Limiting plant coverage allows more direct sunlight to kill pathogens.
Metals	18 in.	Any rate is sufficient; 2–6 in. per hour recommended.	Must keep top layer of cell from being saturated for extended periods.
Temperature	To be determined. Conservatively, at least 36 in.	To be determined. Slower rates may be preferable (less than 2 in. per hour)	Introduction of IWS* volume at the bottom of the cell may reduce effluent temperature.
Total Nitrogen	At least 30 in. (36 in. preferred)	1-2 in. per hour. Slower rates are better.	Introduction of IWS volume may reduce TN concentrations.
Total Phosphorus	24 in.	2 in. per hour	A low P-Index is essential. Recommended range is from 10 to 30.
*Internal Water Storage Zone			

Figure C-10. Bioretention cell in Adelphi Road median, Adelphi, MD (Low Impact Development Center, Inc.).

Types of Systems

Vegetated Swales

Design

A primary design consideration is how to incorporate design features that will improve the longevity and performance of the swale, while minimizing the maintenance burden. Designers first need to ensure that this management practice is feasible at the site in question because some site conditions (i.e., steep slopes, highly impermeable soils) might restrict the effectiveness of vegetated swales.

Vegetated swales should generally treat runoff from small drainage areas of less than 5 acres. If used to treat larger areas, the flows through the swale become too large to produce designs to treat stormwater runoff in addition to conveyance. Relatively flat sites with a 1%-2% slope are recommended, with 4% slope at most. When site conditions require installing a swale in an area with larger slopes, check dams can be used to reduce the influence of the slope (Figure C-11). Otherwise, the steeper slopes will cause runoff velocities within the channel that become too high, leading to erosion and the prevention of infiltration and to filtering in the swale.

Figure C-11. Grassed swale with a check dam (photo by Delaware Department of Transportation).

The required depth to groundwater depends on the type of swale used. In the dry swale and grassed channel options, the bottom of the swale should be constructed at least 2 ft above the groundwater table to prevent a moist swale bottom or contamination of the ground water. In the wet swale option, water quality treatment is provided by creating a standing or slow-flowing wet pool that infiltrates directly into the underground-water table and, thus, the bioswale bottom can be placed anywhere irrespective to groundwater depth.

Swales are well-suited for treating highway or residential road runoff because they are linear practices that require a relatively large area of pervious surfaces. For this reason, swales are not ideally suited for ultra-urban areas. Swales are also well-suited to perform as one of a series of stormwater BMPs (a “treatment train”), conveying water to a detention pond and receiving water from filter strips. Additionally, they provide an especially appropriate retrofit opportunity in the modification of existing drainage ditches. Ditches have traditionally been designed only to convey stormwater, but the use of grassed swales can assist with pollutant removal and infiltration efforts.

Figure C-12. Vegetated swale (courtesy of Mission Engineers, Inc. of Santa Clara, CA).

Although there are different design variations of the swale, some considerations are common to all designs. An overriding similarity is the cross-sectional geometry. Swales often have a trapezoidal or parabolic cross section with relatively flat side slopes (flatter than 3:1), though rectangular and triangular channels can also be used. Designing the channel with flat side slopes increases the wetted perimeter. The wetted perimeter is the length along the edge of the swale cross section where runoff flowing through the swale contacts the vegetated sides and bottom. Increasing the wetted perimeter slows runoff velocities and provides more contact with vegetation to encourage sorption, filtering, and infiltration. Another advantage to flat side slopes is that runoff entering the grassed swale from the side receives some pretreatment along the slope.

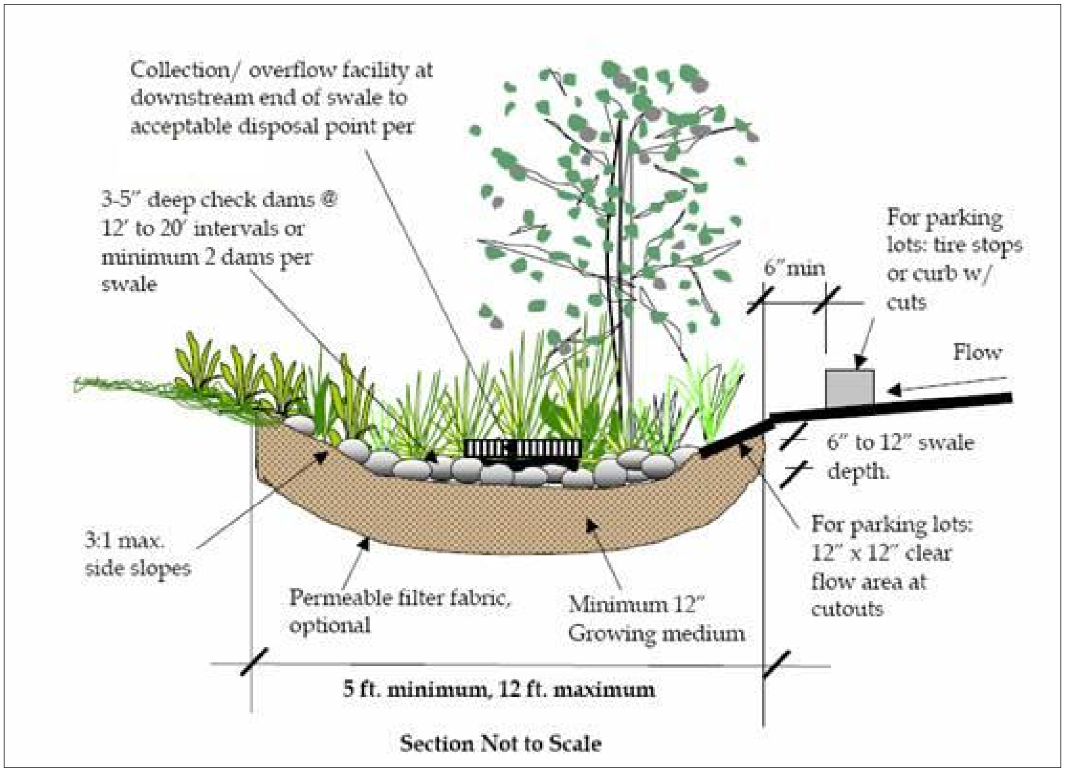

Figure C-13. Typical vegetated swale (City of Portland 2004 Stormwater Management Manual).

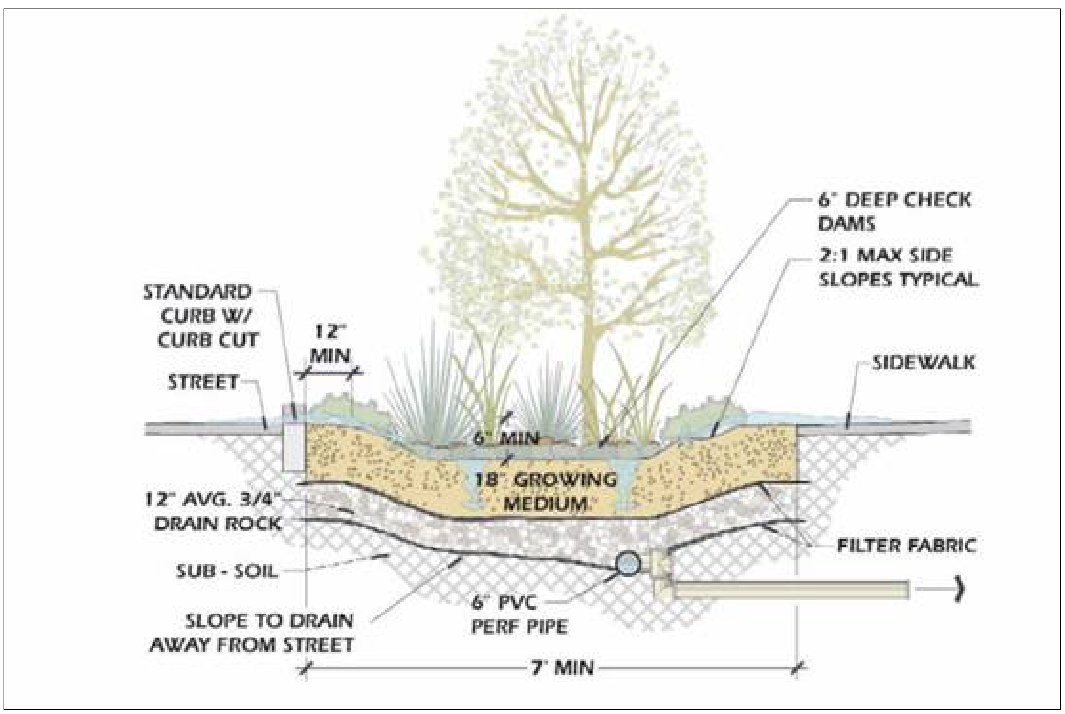

Figure C-14. Street swale schematic (City of Portland 2004 Stormwater Management Manual).

Another similarity among designs is the type of pretreatment needed. In all design options, a small forebay should be used at the front of the swale to trap incoming sediments. A pea gravel diaphragm (a small trench filled with river-run gravel) should be constructed along the length of the swale and used as pretreatment for runoff entering the sides of the swale. Other features designed to enhance the performance of grassed swales are a flat longitudinal slope (generally between 1% and 2%) and a dense vegetative cover in the channel. The flat slope helps to reduce the flow velocity within the channel. The dense vegetation also helps reduce velocities, protects the channel from erosion, and acts as a filter to treat stormwater runoff.

Three different variations of open channel practices include the grassed channel, the dry swale, and the wet swale, are discussed below.

- **Grassed channels** are the most similar type of swale to a conventional drainage ditch, with the major differences being flatter side slopes, longitudinal slopes, and a slower design velocity for water quality treatment of small storm events. Of all of the options, grassed channels (Figure C-15) are the least expensive but also provide the least reliable pollutant removal. An excellent application of a grassed channel is as pretreatment to other structural stormwater practices. A major difference between the grassed channel and many other structural practices is the method used to size the practice. Most stormwater management water quality practices are sized by volume. This method sets the volume available in the practice equal to the water quality volume, or the volume of water to be treated in the practice. The grassed channel is a flow-rate-based design. Based on the peak flow from the water quality storm (this varies regionally, but a typical value is the 1-in./24-hr storm), the channel should be designed so that runoff takes, on average, 10 minutes to flow from the top to the bottom of the channel. A procedure for this design can be found in *Design of Stormwater Filtering Systems* (Center for Watershed Protection 1996).

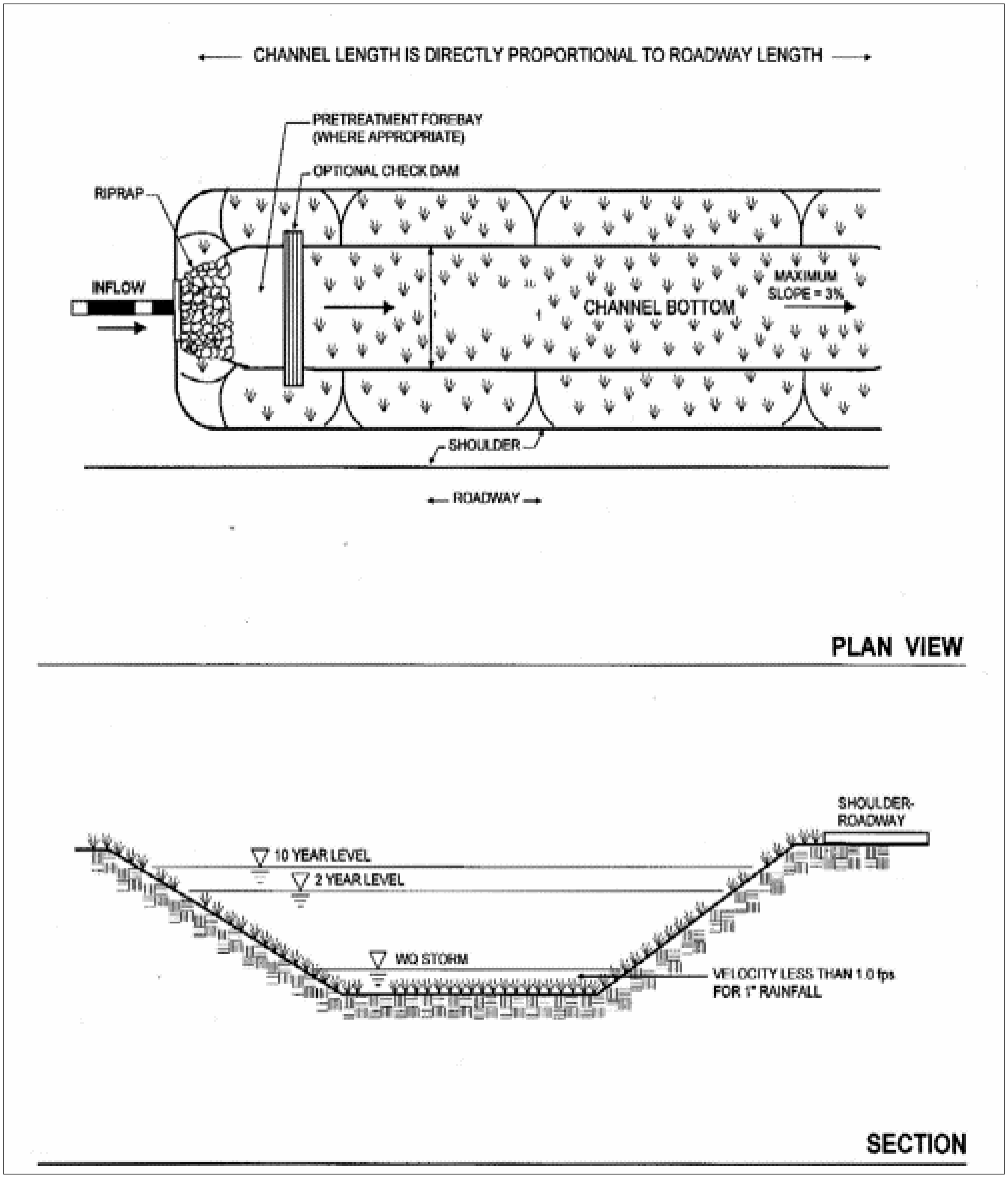

Figure C-15. Grassed channel schematic (Center for Watershed Protection).

- **Dry swales** incorporate a fabricated soil bed into their design (Figure C-16). The native soil is replaced with a sand/soil mix that meets minimum permeability requirements. An underdrain system is installed at the bottom of the soil bed. This underdrain is a gravel layer that encases a perforated pipe. Stormwater treated in the soil bed flows into the underdrain, which routes this treated stormwater to the storm drain system or receiving waters. Dry swales are a relatively new design, but studies of swales with a native soil similar to the man-made soil bed of dry swales suggest high pollutant removal.

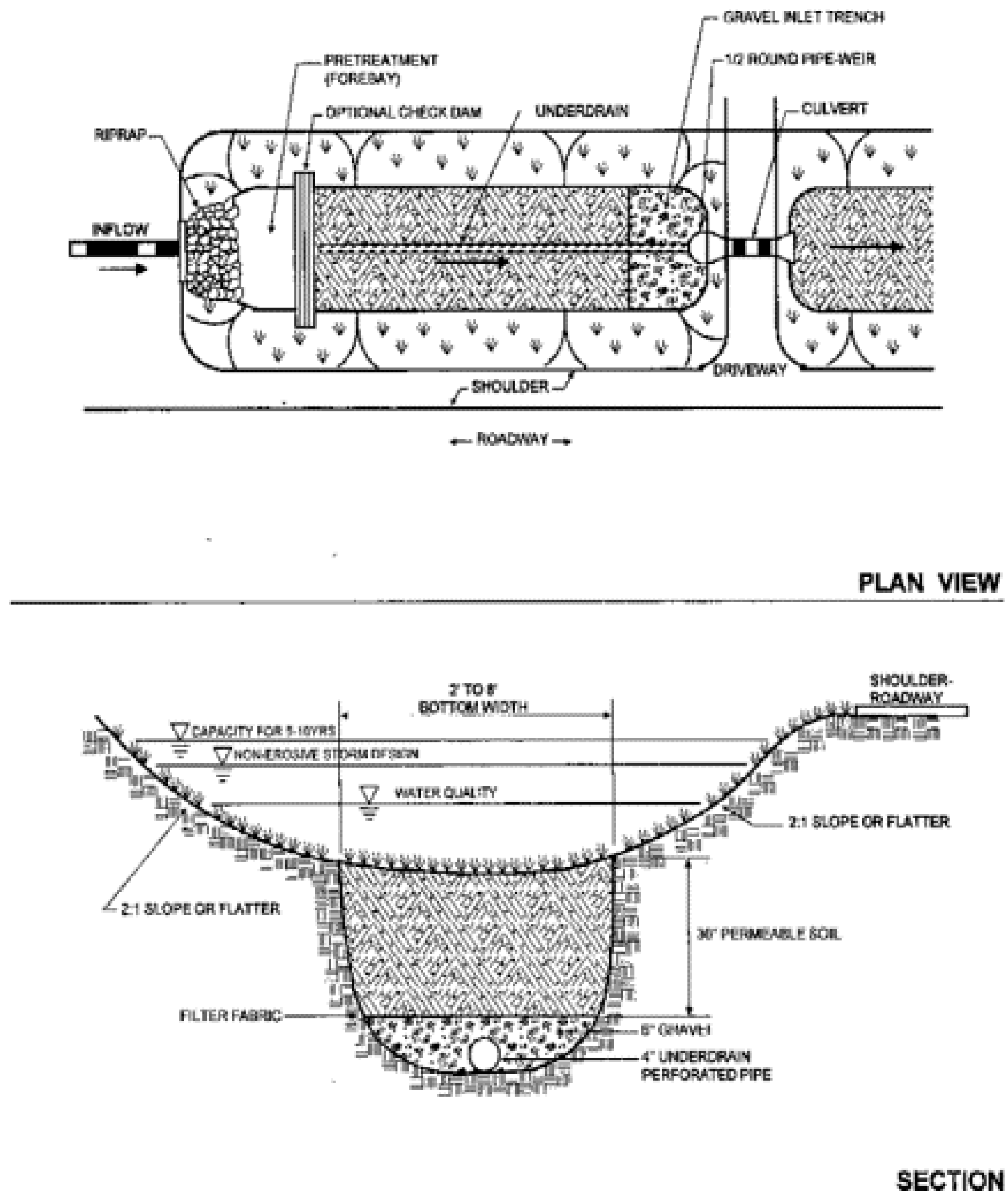

Figure C-16. Dry swale schematic (Center for Watershed Protection, Inc.).

- **Wet swales** intersect the ground water and behave similarly to a linear wetland cell. This design variation (Figure C-17) incorporates a shallow permanent pool and wetland vegetation to provide stormwater treatment. This design also has potentially high pollutant removal. Wet swales are not commonly used in residential or commercial settings because the shallow standing water may be a potential mosquito breeding area.

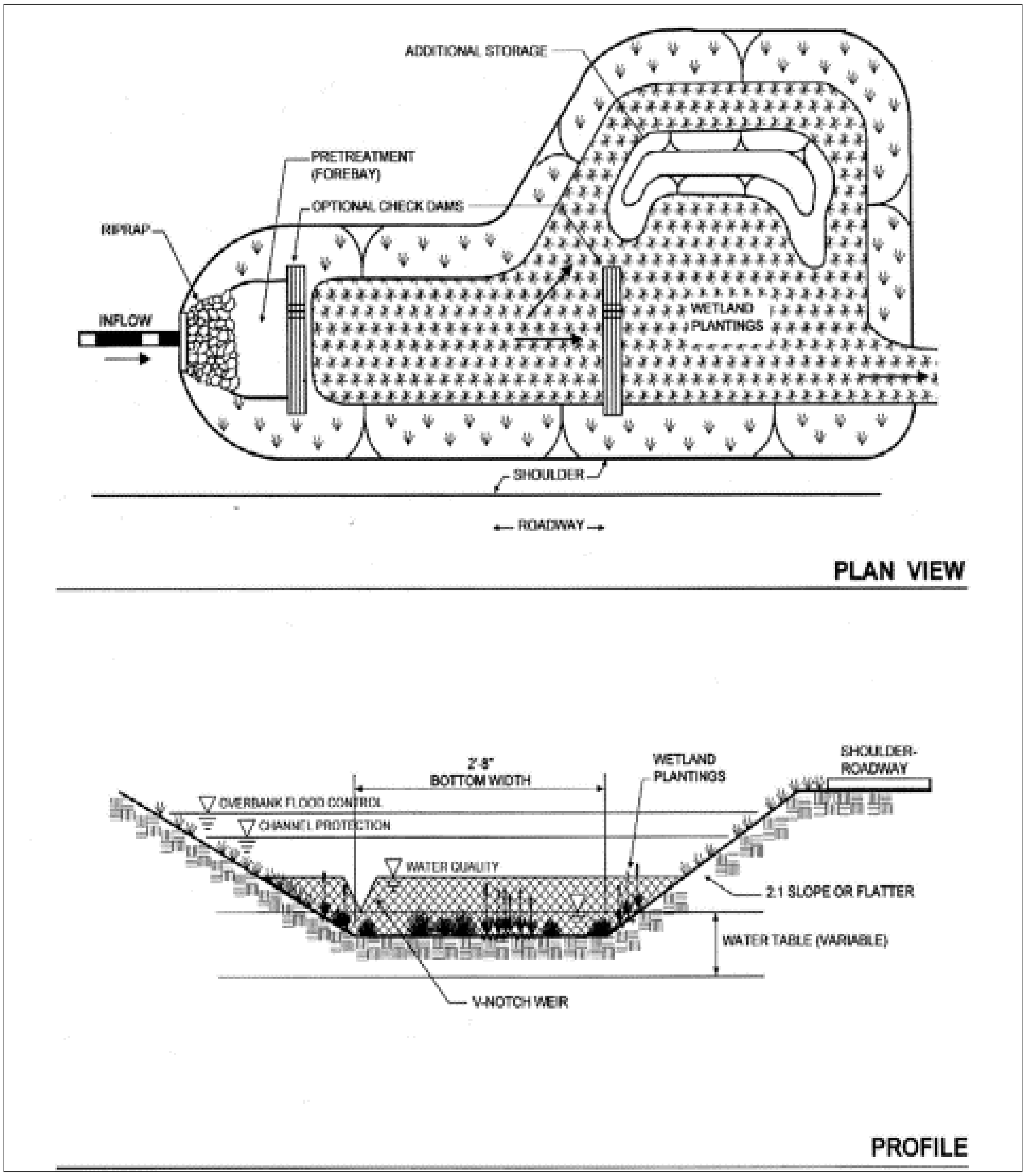

Figure C-17. Wet swale schematic (Center for Watershed Protection, Inc.).

Swales can be applied in most regions of the United States. In arid and semi-arid climates, however, the value of these practices needs to be weighed against the water needed to irrigate them. Swales can be used on most soils, with some restrictions on the most impermeable soils. If constructing a dry swale, for example, a fabricated soil bed replaces on-site soils in order to ensure that runoff is filtered as it travels through the soils of the swale.

In cold or snowy climates, swales may serve a dual purpose by acting as both a snow storage/treatment and a stormwater management practice. This dual purpose is particularly relevant when swales are used to treat road runoff. If used for this purpose, swales should incorporate salt-tolerant vegetation, such as creeping bent grass.

In arid or semi-arid climates, swales should be designed with drought-tolerant vegetation, such as buffalo grass. Also, the value of vegetated practices for water quality needs to be balanced against the cost of water needed to maintain them in arid and semi-arid regions.

Construction

Be sure to check local county requirements for swale construction. Factors such as depth, hours of standing water permitted, and placement restrictions may vary. A construction site should be clearly marked in order to avoid soil disturbance. Avoidance includes keeping vehicular traffic, except for certain construction vehicles, further than 10 ft away from the swale area. When construction vehicles are used, care should be exercised because soil compaction is likely to occur if a vehicle is driven over the swale site.

Machinery and equipment should not be cleaned or washed near swales, because the dirt and debris will dry and produce a layer of impermeable material that can hinder the infiltration process. Imported top soil or sand is also likely to decrease infiltration capability because of the layered subsurface that would develop. On-site top soil should be used whenever possible. Additionally, protection from stormwater runoff during construction is necessary for preventing erosion and sedimentation. Any accumulation of sediments that does occur during construction must be removed during the final grading stages.

Planting in a swale can be accomplished by the use of sod or seeding. It is important to stabilize the channel while the vegetation is becoming established, either with a temporary grass cover or with natural or synthetic erosion control products. In colder climates with short growing seasons, the desired level of vegetation might take 2-3 growing seasons to achieve. In these instances, continued protection against erosion is needed.

Accurate grading is essential in the construction process. Without it, a properly functioning swale would be difficult to construct and could result in a hazardous situation. In addition to treating runoff for water quality, swales must convey runoff from larger storms safely. Typical designs allow the runoff from the 2-year storm (i.e., the storm that occurs, on average, once every 2 years) to flow through the swale without causing erosion. Swales should also have the capacity to pass larger storms (typically a 10-yr storm) safely. Post-construction monitoring should be performed to ensure the swale is working properly and safely.

Maintenance

Maintenance of swales is minimal. It mostly involves litter control and maintaining the grass or wetland plant cover. Table C-5 lists maintenance tasks and the frequency at which they should be performed.

Table C-5. Swale maintenance (source: US EPA Swale Factsheet).

Activity	Schedule
• Inspect pea gravel diaphragm for clogging and correct any problems. • Inspect grass along side slopes for erosion and formation of rills/gullies and correct. • Remove trash and debris accumulated in the inflow forebay. • If being used to store cleared snow, remove sediment from sand and gravel de-icers come spring. • Inspect and correct erosion problems in the sand/soil bed of dry swales. • Based on inspection, plant an alternative grass species if the original grass cover has not been successfully established. • Replant wetland species (for wet swale) if not sufficiently established.	Annual (semi-annual for the first year)
• Roto till or cultivate the surface of the sand/soil bed of dry swales if the swale does not draw down within 48 hours. • Remove sediment build-up within the bottom of the swale once it has accumulated to 25 percent of the original design volume.	As needed (infrequent)
• Mow grass to maintain a height of 3–4 inches	As needed (frequent seasonally)

Figure C-18. Vegetated swale with potential for natural debris (RiverSides 2006).

Effectiveness

Structural stormwater management practices can be used to achieve four broad resource protection goals. These include flood control, channel protection, ground-water recharge, and pollutant removal. Grassed swales can be used to meet ground-water recharge and pollutant removal goals.

- **Ground-water recharge**: Grassed channels and dry swales can provide some ground-water recharge as infiltration is achieved within the practice. Wet swales, however, generally make little, if any, contributions to ground-water recharge. Infiltration is impeded by the accumulation of debris on the bottom of the swale.

- **Pollutant removal**: While it is difficult to distinguish between different designs based on the amount of available data, grassed channels generally have poorer removal rates than wet and dry swales, although wet swales may export soluble phosphorous (Harper 1988; Koon 1995). The data for grassed channels suggest relatively high removal rates for some pollutants, negative removals for some bacteria, and fair performance for phosphorous. One study of available performance data (Schueler 1997) estimates the removal rates for grassed channels. The estimates are shown in Table C-6.

Table C-6. Pollutant removal rates for grassed swales.

Pollutant	**Removal Rates**
Total Suspended Solids	81%
Total Phosphorous	29%
Nitrate Nitrogen	38%
Metals	14% to 55%
Bacteria	-50%
Source: Schueler 2007, with Low Impact Development Center, Inc. modification.	

Seasonal differences in swale performance have been reported. Pollutant removal efficiencies can be markedly different during the growing and dormant periods (Driscoll and Mangarella 1990). In seasonal climates, fall and winter temperatures force vegetation into dormancy, thereby reducing uptake of runoff pollutants and removing an important mechanism for flow rate reduction. Furthermore, decomposition of accumulated organic matter can lead to production of nutrients in a soluble form, making them free to be transported downstream. Freezing temperatures greatly reduce infiltration in dry swales, removing an important pollutant removal mechanism.

Figure C-19 depicts a vegetated swale in use at the edge of a parking lot.

Figure C-19. Vegetated swale at a parking lot (photo courtesy of Sue Donaldson).

Green Roofs

Design

Green roofs (Figure C-20) can be installed during initial construction or placed on buildings as part of a retrofit. The amount of stormwater that a green roof mitigates is directly proportional to the area it covers, the depth and type of the growing medium, the slope, and the type of plants selected. The larger the green roof area, the more stormwater mitigated. Green roofs are appropriate for industrial and commercial facilities and large residential buildings such as condominiums or apartment complexes. Green roofs can also prove useful for small residential buildings under some circumstances. Green roofs should be easily accessible, and employees or residents should understand the maintenance requirements necessary to keep the roof functional.

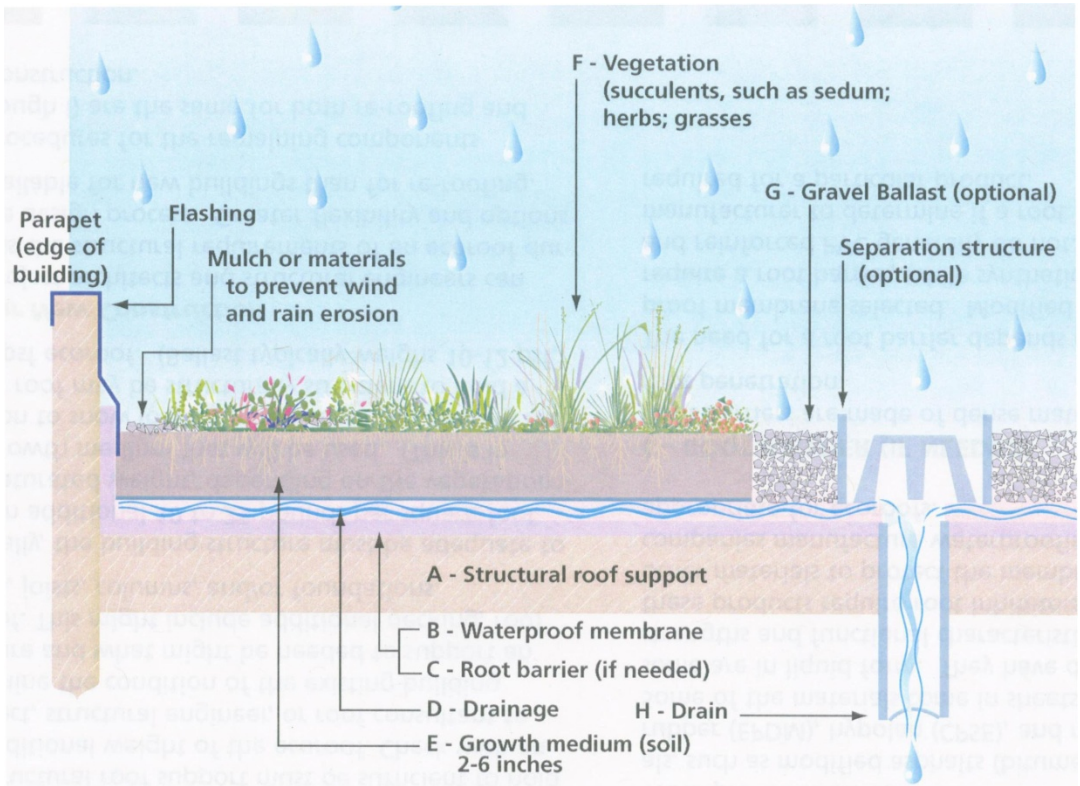

Figure C-20. Typical green roof cross section (not to scale) (Portland Bureau of Environmental Services).

Green roofs can be designed to be either *intensive, semi-intensive,* or *extensive*. The type of design chosen will depend on loading capacity, budget, design goals, and stormwater retention desired.

- **Intensive green roofs** have greater than 6 in. of substrate and support a wide variety of plants, shrubs, and small trees. They are often designed to be accessible to the public for recreational use. Intensive green roofs (Figure C-21) are particularly attractive for developers, property owners, and municipalities in areas where land prices command a premium, but where property owners want to provide some of the amenities associated with parks.

Figure C-21. Intensive green roof (American Hydrotech, Inc.).

- **Semi-intensive green roofs** can be defined as a hybrid between intensive and extensive green roofs, where at least 25% of the roof square footage is above or below the 6-in. threshold. Like intensive roofs, semi-intensive roofs are often designed to be used by the public or building tenants as a park or relaxation area. However, they also require greater capital and maintenance investments than extensive green roofs.

- **Extensive green roofs** generally have 6 in. or less of growing medium. These roofs typically consist of sedums, grasses, and wildflowers. Extensive green roofs (Figure C-22) provide many of the environmental benefits of intensive green roofs, but they are designed to be very low-maintenance and are not typically designed for public access.

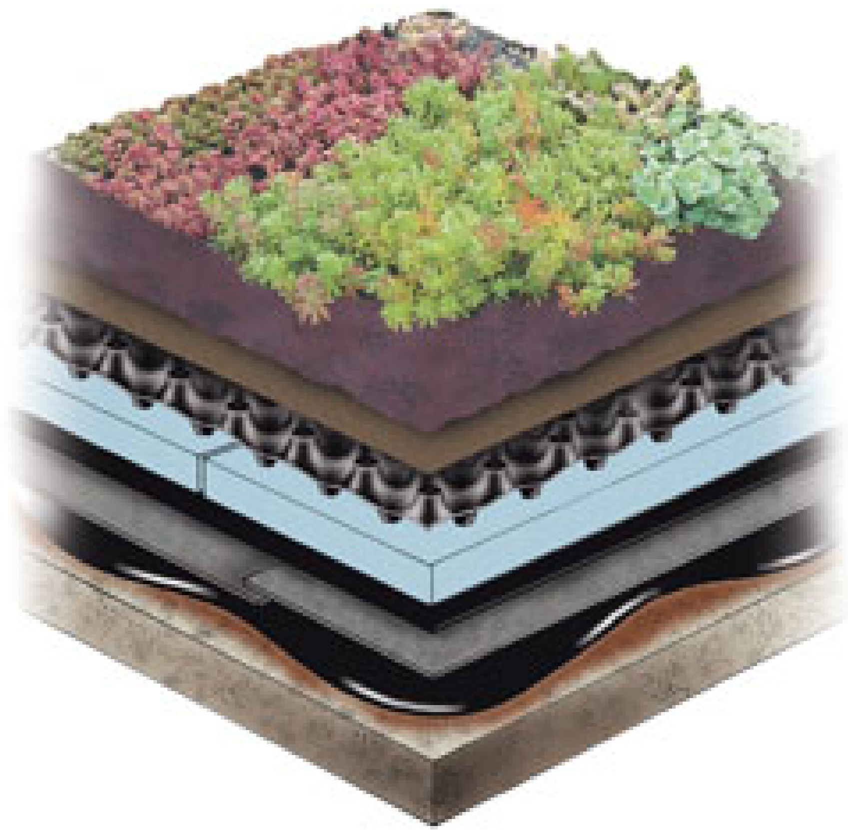

Figure C-22. Extensive green roof.(American Hydrotech, Inc.)

There will also be variations in the type of green roof selected depending on climate, types of plants chosen, soil layer depth desired and feasibility and other design considerations. A building must be able to support the loading of green roof materials under fully saturated conditions. These materials include a waterproofing layer, a soil or substrate layer, and a plant layer. Green roofs can be constructed layer by layer, or can be purchased as a system. Some vendors offer modular trays containing the green roof components. Figure C-23 illustrates a modular tray being used in 2006 at Tobyhanna Army Depot, the first Army post to install a green roof. Figure C-24 shows modular trays being installed 2 years later at Fort Hood, Texas, on the roof of Building 11’s Wing C. Figure C-25 is a green roof at Peterson Air Force Base in Colorado, showing what a modular tray roof might look like after installation.

Figure C-23. Installation of a green roof on the Headquarters Building at Tobyhanna Army Depot, PA (photo by Steve Grzedzinski).

Figure C-24. Installation of a green roof on Building 11's Wing C at Fort Hood, TX (photo by Steve Grzedzinski).

Figure C-25. Green roof atop 21st Space Wing Headquarters Building at Peterson Air Force Base, CO (photo by Thea Skinner).

In most climates, green roofs will need to have drought tolerant plant species or an irrigation system to sustain vegetation. The slope of green roofs can range from 0 to 40 degrees. In new construction, buildings should be designed to manage a potentially increased load associated with the green roof. When designing green roofs for existing structures, engineers must take the load restrictions of the building into account.

Green roofs can be used effectively to reduce stormwater runoff from commercial, industrial, and residential buildings. In contrast to traditional asphalt or metal roofing, green roofs absorb, store, and later evapotranspire initial precipitation, thereby acting as a stormwater management system and reducing overall peak flow discharge to a storm sewer system. Furthermore, conventional roofing can act as a source for numerous toxic pollutants including lead, zinc, pyrene, and chrysene (Van Metre and Mahler 2003).

Green roofs can potentially reduce the discharge of pollutants such as nitrogen and phosphorous due to soil microbial processes and plant uptake. However, initial studies conflict as to the removal efficiency of nutrients, particularly nitrogen, by green roofs. If implemented on a wide scale, green roofs will reduce the volume of stormwater entering local waterways, resulting in less in-stream scouring, lower water temperatures, and improved water quality. In urban areas with combined sewer systems, stormwater and untreated human and industrial waste are collected in the same pipe. During periods of heavy rainfall and snow melt, these systems can become overwhelmed by the volume of water and overflow into nearby water bodies resulting in CSOs. Since green roofs can reduce the volume of stormwater discharged, CSOs can also be reduced, thus preventing the discharge of millions of gallons of sewage into local waterways.

Green roofs offer additional benefits including reduction of urban heat island effects, increased thermal insulation and energy efficiency, increased acoustic insulation, and increased durability and lifespan compared to conventional roofs. Europeans, led by the Germans, have been using green roofs for decades and have found them to be a cost-effective method to mitigate some environmental impacts of development.

Construction

Green roofs can be applied to new construction or retrofitted to existing construction. They are applicable on residential, commercial, and industrial buildings and are easily constructed on roofs with up to a 20% slope. Many cities such as Chicago and Washington are actively encouraging green roof construction as a means to reduce stormwater runoff and CSOs (see Figure C-26 through Figure C-28). Other municipalities are encouraging green roof development with tax credits, density credits, or allowing a small impervious credit to be applied to other structural BMP requirements.

Figure C-26. Green roof on Chicago City Hall (photo by Dennis Fiser).

Figure C-27. Green roof on Seattle City Hall (courtesy of SvR Design Company, Seattle, WA).

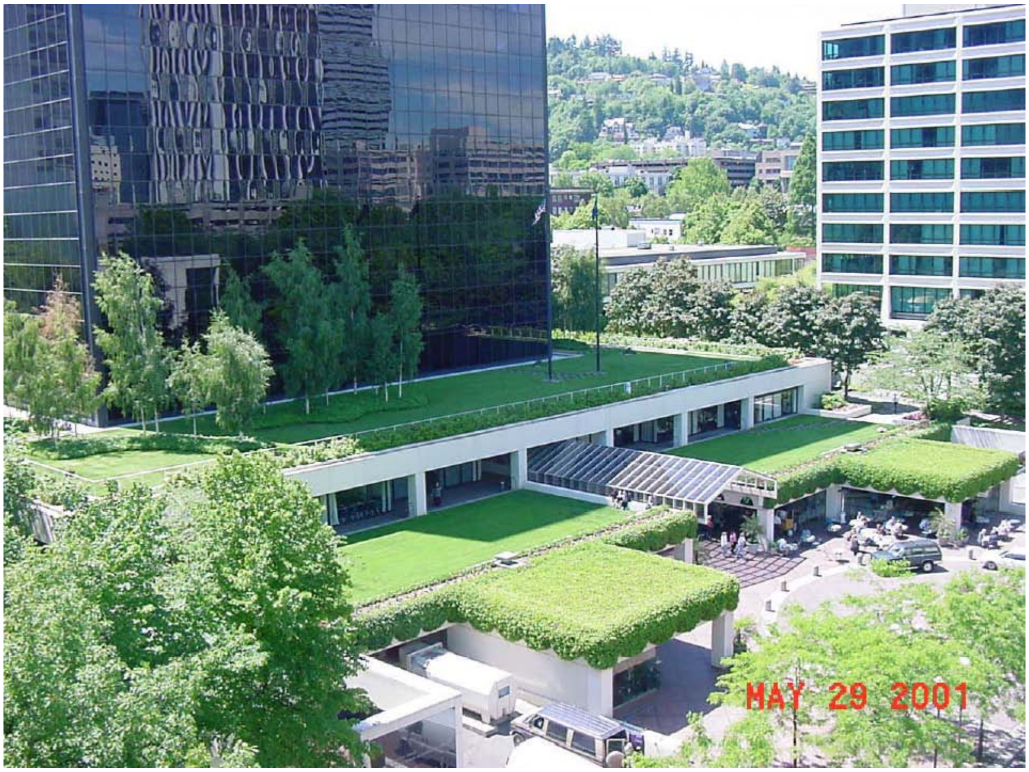

Figure C-28. Roof garden SW 2nd Avenue, Portland, OR (courtesy of Low Impact Development Center, Inc.).

Green roofs are applicable in all parts of the country. In climates with extreme temperatures, green roofs provide additional building insulation, which makes them more financially justifiable for many facility operators. Green roofs are ideal for ultra-urban areas where little pervious surface exists (Figure C-29) because they provide stormwater benefits and other valuable ecological services without consuming additional land. In a 2005 modeling study of Washington, DC, Casey Trees and Limno-Tech found that green roofs on 20% of buildings over 10,000 sq ft could add an additional 23 million gallons of storage and reduce outflow to the storm sewer or combined sewer systems by an average of just under 300 million gallons per year. According to the authors, this would reduce the annual number of CSO events in the District of Columbia by 15%.

Figure C-29. Hamilton Apartments in Portland, OR (courtesy of Low Impact Development Center, Inc.).

A stormwater retrofit is a stormwater management practice (usually structural) put into place after development has occurred, to improve water quality, protect downstream channels, reduce flooding, or meet other specific objectives. Green roofs are a useful tool for retrofitting existing impervious areas associated with building footprints. Most existing flat-roofed buildings are constructed in such a way that they can accommodate the weight of an extensive green roof without structural modifications. Although retrofitting existing structures with green roofs can be more complex and expensive than on new facilities, technological advances are bringing that cost down.

Maintenance

Immediately after construction, green roofs need to be monitored regularly to ensure the vegetation thrives. During the first season, green roofs may need to be watered periodically if there is not sufficient precipitation. After the first season, extensive green roofs may only need to be inspected and lightly fertilized approximately once per year. The roofs may need occasional weeding and may require some watering during exceptionally dry periods. If leaks should occur in the roof, they are relatively easy to detect and repair. Intensive green roofs need to be maintained as any other landscaped area. This can involve gardening and irrigation, in addition to other roof maintenance (Figure C-30). Green roofs are less prone to leaking than conventional roofs. In most cases, detecting and fixing a leak under a green roof is no more difficult than doing the same for a conventional roof.

Figure C-30. Carnegie Mellon University green roof maintenance in Pittsburgh, PA (courtesy of Kelly Luckett).

Effectiveness

Green roofs have been shown to be effective at removing some pollutants and reducing peak flows associated with storm events. As a general rule, developers can assume that extensive green roofs will absorb 50% of rainfall. In a modeling study, Casey Trees and Limno-Tech (2005) assumed that extensive green roofs absorbed 2 in. of rainfall and intensive green roofs stored 4 in. of rainfall. Due to evapotranspiration and plant uptake, this storage is assumed to recharge once every 4 days. A study by Moran et al. (2005) found that monthly stormwater retention rates varied between 40% and 100% on two green roofs in the Neuse River watershed, North Carolina. The study showed a decrease in peak flow runoff and total stormwater runoff. It also showed a gradual and delayed release of the stormwater that was ultimately discharged. The reduction of peak flow discharge potentially mitigates stream channel scouring, resulting in improved aquatic habitat and lessening the risk of downstream property damage and flooding.

Figure C-31shows the results of a green roof pilot test performed in Canada. The graph illustrates that stormwater retention was greater on the green roof compared to the reference roof. The green roof was an extensive roof, consisting of 6 in. of growing medium and planted grass. With the exception of June, when almost 180 mm of rainfall far exceeded storage capacity of 6-in. soil media depth, all months showed that the green roof retained a large fraction of stormwater that would have otherwise become runoff.

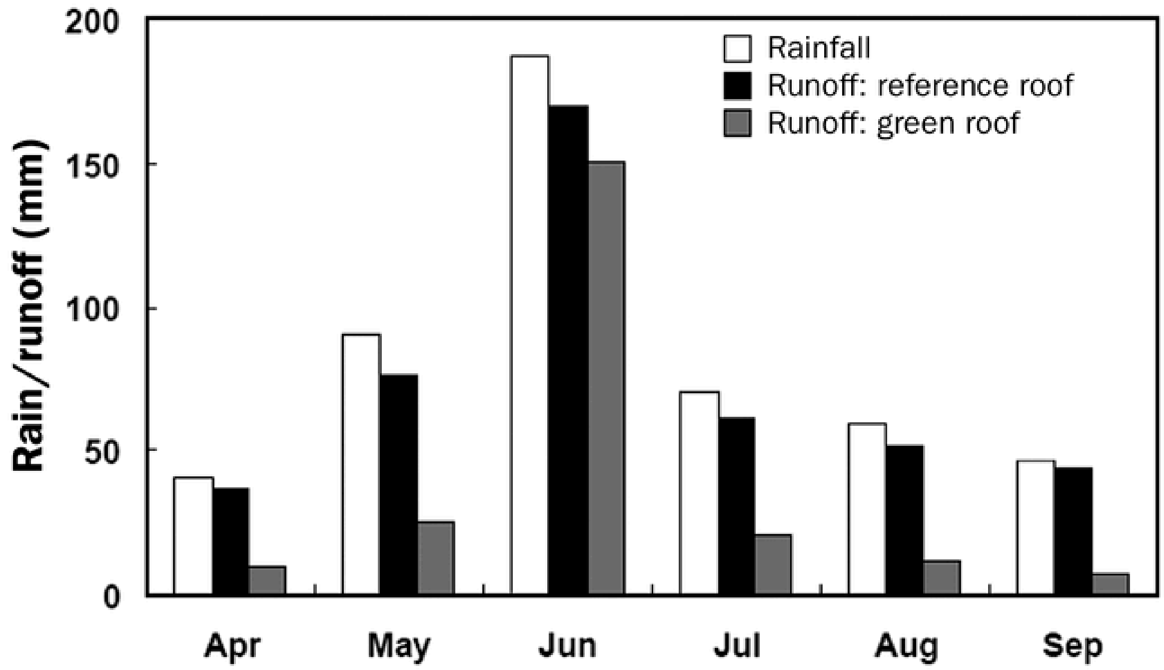

Figure C-31. Study results comparing roof runoff. (Oberndorpher et al. 2007)

Pennsylvania State University's Green Roof Research Center has also noted a decrease in both total stormwater runoff and peak-flow discharge. Figure C-32 and Figure C-33 show both the decrease in total discharge and peak flow run-off from roof area associated with three green roofs. In this 1+ in. storm event, the green roofs captured approximately 25% of total runoff compared to the conventional roofs. During the period of 23 May to 1 June 2003, 2.21 in. of rain fell, of which the green roof detained 1.05 in. (~47%). The Center noted that spring 2003 was wet and cool.

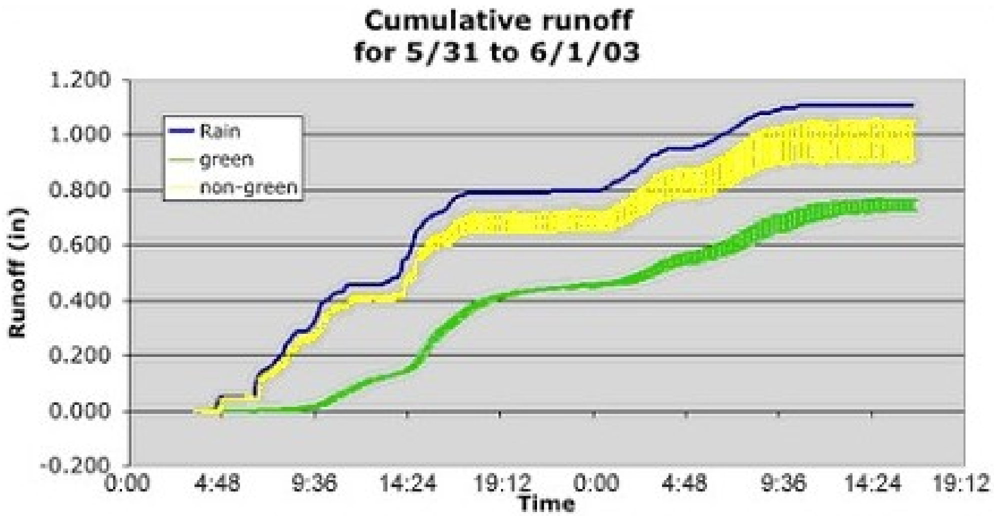

Figure C-32. Cumulative runoff
(Source: Penn State Green Roof Research Center).

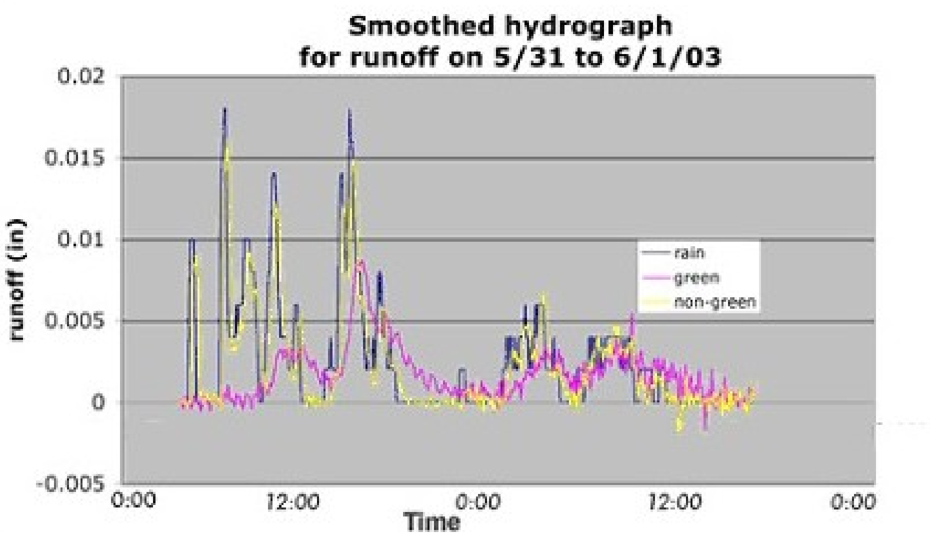

Figure C-33. Smoothed hydrograph
(Source: Penn State Green Roof Research Center).

Green roofs have also been shown to regulate temperature fluctuations, acting as an insulation buffer for the buildings they cover. In the fall of 2009, the Miami Science Museum launched their Green Roof Demonstration Project. One of the main goals is to learn which type of green roof design will keep temperatures the coolest above the roof and inside the building. Figure C-34 shows that the green roof was able to keep temperatures well below the outdoor temperatures during a hot afternoon. It was also able to keep the “under roof” temperature relatively consistent.

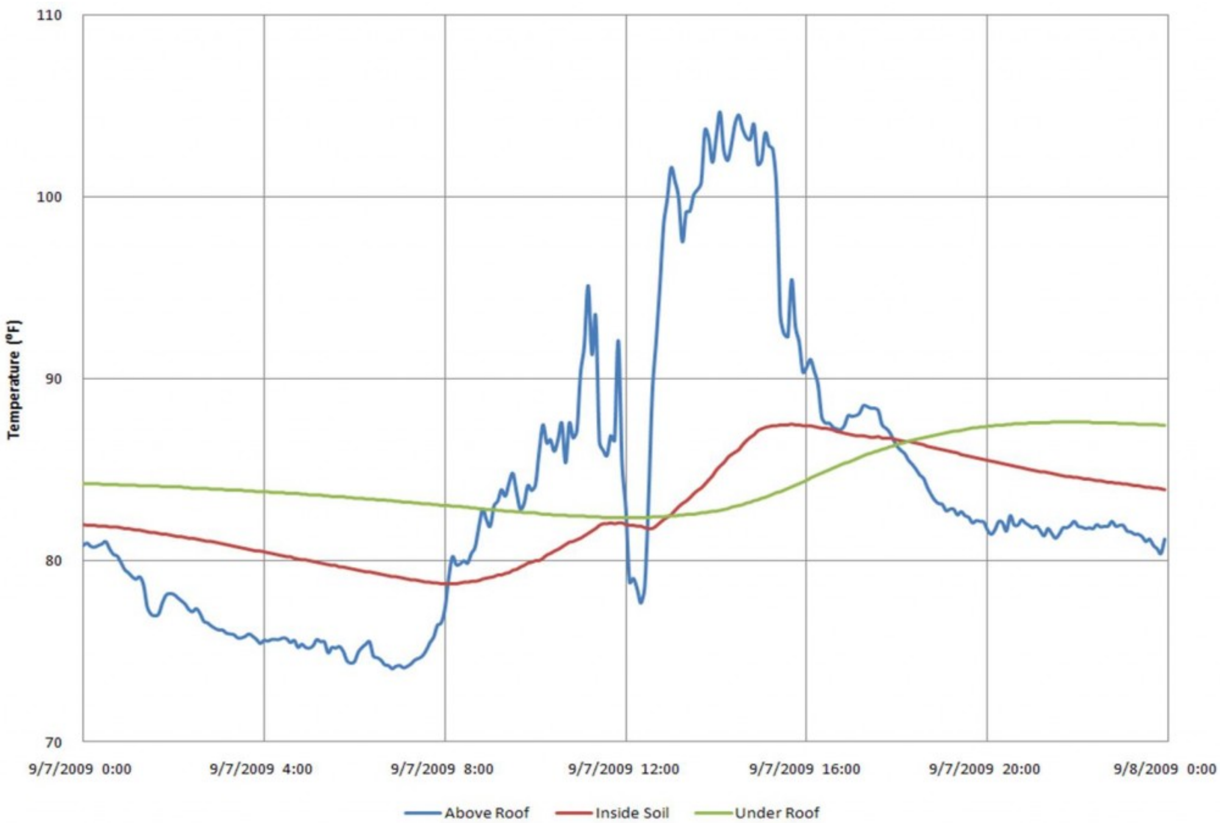

Figure C-34. Green roof temperature study, 7 September 2009; drop in temperature at 12:00 was due to brief rain shower (courtesy of the Miami Science Museum).

Permeable Pavements

Design

Permeable pavements should be designed and sited to intercept, contain, filter, and infiltrate stormwater on site. Several design possibilities can achieve these goals. For example, it can be installed across an entire street width or an entire parking area. The pavement can also be installed in combination with impermeable pavements to infiltrate runoff and initiate a treatment train. Several applications use permeable pavement in parking lot lanes or parking stalls to treat runoff from adjacent impermeable pavements and roofs. This design economizes permeable pavement installation costs while providing sufficient treatment area for the runoff generated from impervious surfaces. Inlets can be placed in the permeable pavement to accommodate overflows from extreme storms. The stormwater volume to be captured, stored, infiltrated, or harvested determines the type and scale of permeable pavement required. The three most commonly used types of permeable pavement are Permeable

Interlocking Concrete Pavement (PICP), Pervious Concrete, and Porous Asphalt.

Table C-7 explains the components needed for permeable pavement design and compares the requirements for each type of pavement. The layers and amount of materials needed are mostly circumstantial. The load-bearing and infiltration capacities of the subgrade soil, the infiltration capacity of the paver surface, and the storage capacity of the stone base/subbase are the key stormwater design parameters. To compensate for the lower structural support capacity of clay soils, additional subbase depth is often required. The increased depth also provides additional storage volume to compensate for the lower infiltration rate of the clay subgrade. Underdrains are often used when permeable pavements are installed over clay, thus enabling the clay to infiltrate some water, and serving to filter and drain the remainder. In addition, an impermeable liner may be installed between the subbase and the subgrade to limit water infiltration when clay soils have a high shrink-swell potential or there is a high depth to bedrock or water table (NCSU 2008).

Table C-7. Design component comparison of permeable pavements (source: Low Impact Development Center, Inc.).

Design Sections of Permeable Pavement		**PICP**	**Pervious Concrete**	**Porous Asphalt**
Surface Pavement	Necessary thickness will depend on intended use and estimated traffic loads.	Vehicular: 3-1/8 in. Pedestrian: 2-3/8 in.	4-8 in.	2-4 in.
Choke Course	Permeable layer consisting of small-sized, open-graded aggregate providing a level bed for the pavement.	N/A	1-2 in. thick	1-2 in. thick
Open-graded bedding course	Permeable layer consisting of small-sized open-graded aggregate providing a level bed for pavers	2 in.	N/A	N/A
Open-graded base reservoir	Aggregate layer beneath the choker consisting of crushed stones 3/16 to 3/4 in.	3-4 in. thick	3-4 in. thick	3-4 in. thick

Design Sections of Permeable Pavement		**PICP**	**Pervious Concrete**	**Porous Asphalt**
Open-graded subbase reservoir	Aggregate layer with larger stone sizes than the base (typically 3/4- to 2-and-1/2-in. stones). Like the base layer, water is stored in the spaces among the stones. The subbase layer thickness depends on water storage requirements and traffic loads. A subbase layer may not be required in pedestrian or residential driveway applications. In such instances, the base layer is increased to provide water storage and support.	Depending	Depending	Depending
Underdrain	In instances where pavement is installed over low-infiltration rate soils, an underdrain facilitates water removal from the base and subbase. The underdrain is perforated pipe that ties into an outlet structure. Supplemental storage can be achieved by using a system of pipes in the aggregate layers. The pipes are typically perforated and provide additional storage volume beyond the stone base.	Depending	Depending	Depending
Geotextile	Used to separate the subbase from the subgrade and prevent the migration of soil into the aggregate subbase or base.	Optional	Optional	Optional
Subgrade	The layer of soil immediately beneath the aggregate base or subbase. The infiltration capacity of the subgrade determines how much water can exfiltrates from the aggregate into the surrounding soils. The subgrade soil is generally not compacted.	Yes	Yes	Yes

Additional specifics relating to each of the three types of permeable pavement are listed below.

- **Permeable interlocking concrete pavement** (PICP) consists of manufactured concrete units designed with small openings between permeable joints (Figure C-35). The openings typically comprise 5%–15% of the paver surface area and are filled with highly permeable, small-sized aggregates. An attractive option for permeable pavement, there are many different paver designs on the market (Figure C-36).

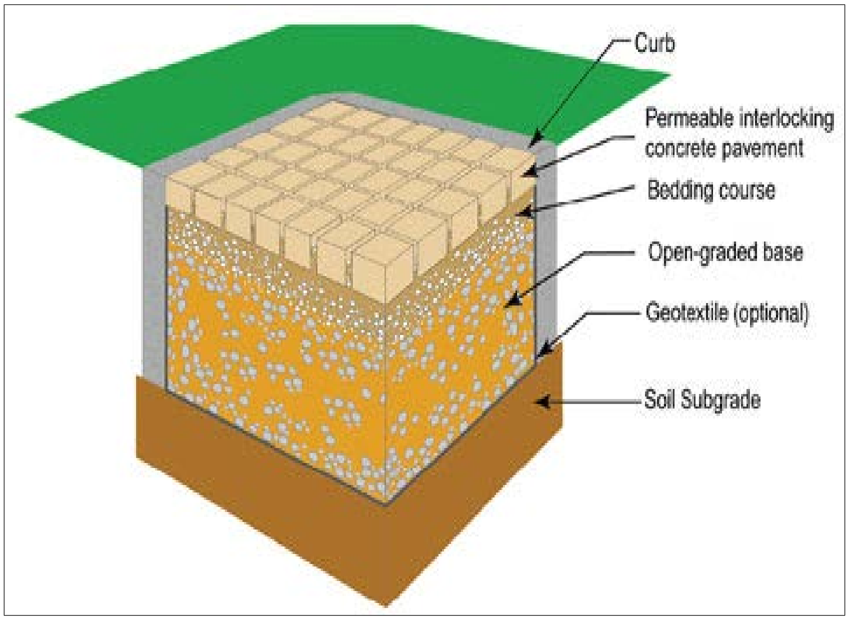

Figure C-35. Typical permeable pavement cross section (Interlocking Concrete Pavement Institution).

Figure C-36. Permeable pavers at Washington Navy Yard (Low Impact Development Center, Inc.).

- **Pervious concrete pavement** consists of Portland cement, open-graded coarse aggregate (typically 5/8–3/8 in.), and water. Admixtures can be added to the concrete mixture to enhance strength, increase setting time, or add other properties. The thickness of pervious concrete ranges from 4–8 in. depending on the expected traffic loads (Figure C-37 and Figure C-38). Note that pervious concrete has reduced strength compared with conventional concrete, and it will not be appropriate for applications with high volumes and extreme loads.

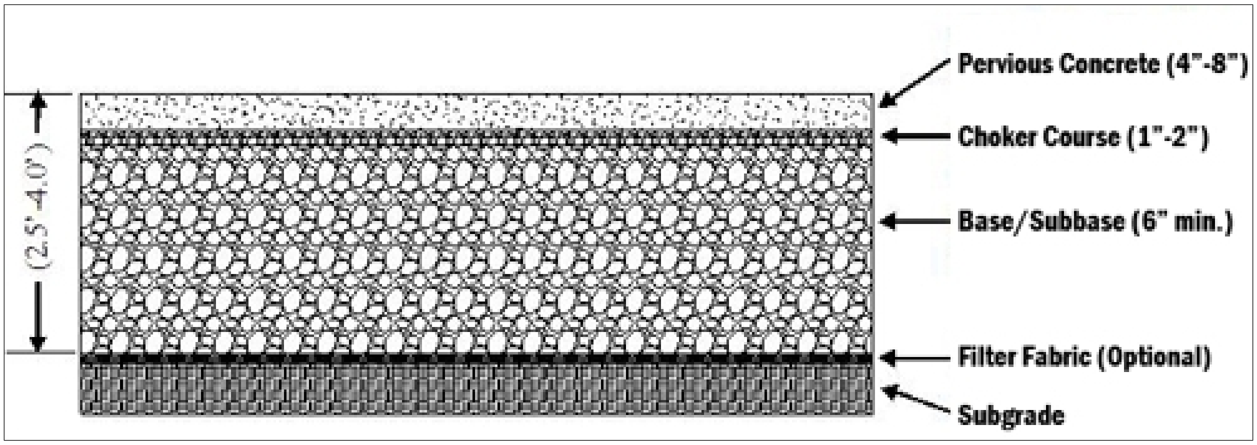

Figure C-37. Typical pervious concrete pavement section (source: USEPA).

Figure C-38. Pervious concrete (photo courtesy of National Ready Mix Concrete Association [NRMCA]).

- **Porous asphalt** (Figure C-39 and Figure C-40) consists of open-graded coarse aggregate, bonded together by bituminous asphalt. Polymers can also be added to the mix to increase strength for heavy load applications. Note that porous asphalt strength is reduced compared with conventional asphalt, and it will not be appropriate for applications with high volumes and extreme loads. The thickness of porous asphalt ranges from 2–4 in. depending on the expected traffic loads. For adequate permeability, the porous asphalt should have a minimum of 16% air voids.

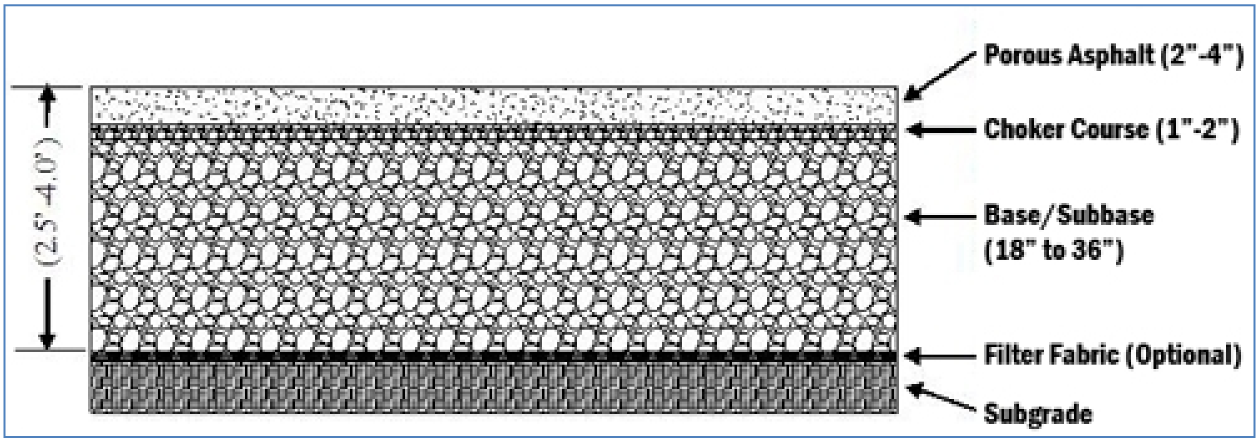

Figure C-39. Typical porous asphalt pavement section (source: USEPA).

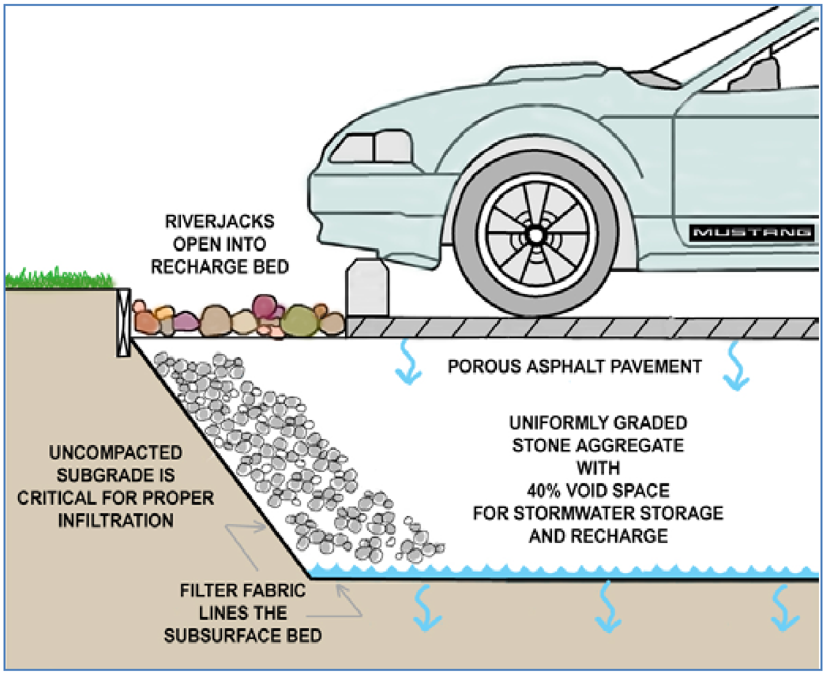

Figure C-40. Permeable paver cross section (SCA Consulting Group, Lacey, WA).

Construction

Construction methods, requirements, and time will vary depending on the type of pavement used. A common critical objective, however, is to prevent sediment from entering the base of the permeable pavement during construction. It should be verified that the soil subgrade is free of standing water and that the base and subbase materials are free from standing water, uniformly graded, free of any organic material or sediment, debris, and ready for placement. Runoff from disturbed areas should be diverted away from the permeable pavement until it is stabilized. For construction locations with slopes greater than 2%, terracing of the soil subgrade base may likely be needed to slow any runoff flowing through the completed pavement structure.

- **PICP** construction will vary based on the manufacturer and style chosen. For the most part, PICP can either be installed by hand (Figure C-41) or machine (Figure C-42). Installing with a machine will save construction time and money. The use of PICP allows construction to occur in freezing temperatures. Additionally, PICP can handle traffic almost immediately because there is no time needed for curing (Figure C-43).

Figure C-41. Manual PICP installation (Portland Bureau of Environmental Sciences).

Figure C-42. Mechanical PICP installation (LPS Pavement).

Figure C-43. Navy Yard parking lot PICP retrofit (Low Impact Development Center, Inc.).

- **Pervious concrete** installation requires trained and experienced producers and construction contractors (Figure C-44 and Figure C-45). The installation of pervious concrete differs from conventional concrete in several ways. The pervious concrete mix has low water content and will therefore harden rapidly. Pervious concrete needs to be poured within 1 hour of mixing. The pour time can be extended with the use of admixtures. A manual or mechanical screed set 1/2 in. above the finished height can be used to level the concrete.

Floating and troweling are not used, as those may close the surface pores. Consistent porosity through the concrete structure is critical in preventing freeze-thaw damage. Consolidation of the concrete, typically with a steel roller, is recommended within 15 minutes of placement. Pervious concrete also requires a longer time to cure. The concrete should be covered with plastic within 20 minutes of setting and allowed to cure for a minimum of 7 days (NRMCA 2008).

Figure C-44. Installation of pervious concrete using a Bunyan roller screed (photo courtesy of Dan Huffman, NRMCA).

Figure C-45. Pervious concrete walkway (NRMCA).

- **Permeable asphalt** can be constructed using the same mixing and laying equipment that is used for conventional asphalt (Figure C-46). The method for laying the asphalt will also be similar. During compaction of the asphalt, minimal pressure should be used to avoid closing pore space (Figure C-47). Vehicular traffic should be avoided for 24–48 hr after pavement is installed (Figure C-48).

Figure C-46. Construction of permeable asphalt, Fort Hood, TX (photo by Fort Hood Environmental Support Team).

Figure C-47. Porous vs. standard asphalt after rain event (photo courtesy of Cahill Associates).

Figure C-48. Permeable asphalt at Fort Hood, Texas (photo by Fort Hood Environmental Support Team).

Maintenance

The most prevalent maintenance concern in the use of PICP is the potential clogging of the pavement's pores, or joints. Fine particles that can clog the pores, or openings, are deposited on the surface from vehicles, the atmosphere, and runoff from adjacent land surfaces. Clogging will increase with age and use. Even though more particles become entrained in the pavement surface, it does not become impermeable. Studies of the long-term surface permeability of permeable pavements have found high infiltration rates initially, followed by a decrease, and then leveling off with time (Bean et al. 2007). With initial infiltration rates of hundreds of inches per hour, the long-term infiltration capacity remains high even with clogging. When clogged, surface infiltration rates usually well exceed 1 in. per hour, which is sufficient in most circumstances for the surface to effectively manage intense stormwater events (ICPI 2008).

- **Permeable interlocking concrete pavement** permeability can be increased with vacuum sweeping (Figure C-49) or, in extreme circumstances, replacing the aggregate between pavers.

- **Pervious concrete** permeability was studied by surveying 11 pervious concrete sites; the infiltration rates ranged from 5 in./hr to 1,574 in./hr. The sites taking runoff from poorly maintained or disturbed soil areas had the lowest infiltration rates, but they were still high relative to rainfall intensities (Bean et al. 2007a). Permeability can be increased with vacuum sweeping (Figure C-50). In areas where extreme clogging has occurred, 1/2-in. holes can be drilled through the pavement surface every few feet to allow stormwater to drain to the aggregate base. Many large cuts and patches in the pavement will weaken the concrete structure. Freeze/thaw cycling is a major cause of pavement breakdown, especially for parking lots in northern climates. Properly constructed permeable concrete can last 20 to 40 years because of its ability to handle temperature impacts (Gunderson 2008).

- **Porous asphalt** permeability can be increased with vacuum sweeping. In areas where extreme clogging has occurred, 1/2-in. holes can be drilled through the pavement surface every few feet to allow stormwater to drain to the aggregate base. A stone apron around the pavement connected hydraulically to the aggregate base and subbase can be used as a backup to surface clogging or pavement sealing. Due to the well-draining stone bed and deep structural support of porous asphalt pavements, they tend to develop fewer cracks and potholes than conventional asphalt pavement. When cracking and potholes do occur, a conventional patching mix can be used. Freeze/thaw cycling is a major cause of pavement breakdown, especially for parking lots in northern climates. The lifespan of a northern parking lot is typically 15 years for conventional pavements; porous asphalt parking lots can have a lifespan of more than 30 years because of the reduced freeze/thaw stress (Gunderson 2008).

Figure C-49. Vacuum for permeable pavement (photo courtesy of Billy Goat Industries).

Figure C-50. Street sweeper (photo courtesy of Elgin Sweeper Company).

Cold weather and frost penetration do not negatively impact surface infiltration rates. Permeable pavement freezes as a porous medium rather than a solid block because permeable pavement systems are designed to be well-drained; infiltration capacity is preserved because of the open void spaces (Gunderson 2008). Although permeable pavements do not treat chlorides from road salts, they require less applied deicers than nonpermeable surfaces. Deicing treatments are a significant expense and chlorides in stormwater runoff have substantial environmental impacts. Reducing chloride concentrations in runoff is only achieved through reduced application of road salts because stormwater BMPs are not effective at chloride removal. Road salt application can be reduced up to 75% using permeable pavements (UNHSC 2007).

In cold climates, sand should not be applied for snow or ice conditions to any type of pervious pavement. However, snowplowing can proceed as with other pavements and salt can be used in moderation. Plowed snow piles should not be left to melt over the pervious concrete because possible high sediment concentrations can clog the drainage more quickly. Permeable pavements have been found to work well in cold climates since the rapid drainage of the surface reduces the occurrence of freezing puddles and black ice. Melting snow and ice infiltrate directly into the pavement, which facilitates faster melting (Gunderson 2008).

Effectiveness

All permeable pavements are on-site stormwater management practices and will have the same or very similar effectiveness with regard to reducing the volume and rate of stormwater runoff as well as pollutant concentrations. Porous asphalt, pervious concrete, and permeable pavers all have the same underlying stormwater storage and support structure. The only difference is the permeable surface treatment. The choice of permeable surface is relevant to user needs, cost, material availability, constructability, and maintenance, but it has minimal impact on overall stormwater retention, detention, and treatment of the system.

Permeable pavement reduces pollutant concentrations through several processes. The aggregate filters the stormwater and slows it sufficiently to allow sedimentation to occur. The subgrade soils are also a major factor in treatment. Sandy soils will infiltrate more stormwater but have less treatment capability. Clay soils have a high cation exchange capacity and will capture more pollutants but will infiltrate less. Also, studies have found that in addition to beneficial treatment bacteria in the soils, beneficial bacteria growth has been found on established aggregate bases. In addition, permeable pavement can process oil drippings from vehicles (Pratt 1999).

Permeable pavement transforms areas once a source of stormwater to a treatment system, effectively reducing or even eliminating runoff that would have been generated from an impervious paved area. Because it reduces the effective impervious area of a site, permeable pavement should receive credit as a pervious cover in drainage system design. The infiltration rate of properly constructed pervious pavement and base generally exceeds the design storm peak rainfall rate; the subsoil infiltration rate and base storage capacity are the factors determining stormwater detention potential.

Rainwater Harvesting

Design

Rooftop runoff is the type of stormwater cisterns typically collect, because it often contains lower pollutant loads than surface runoff. It can therefore be used as nonpotable water for outdoor irrigation, toilet and urinal flushing, cooling system make-up, and equipment and vehicle washing with a lesser concern for sedimentation and pollution. Rooftop runoff also provides accessible locations for collection. Roof downspouts can easily be disconnected and redirected to a cistern. Cisterns can be installed indoors or out, above or below grade. If installed in cold climates, cisterns will need insulation on exposed surfaces. If placed on rock, they will need insulation for the bottom surface.

When selecting a location for cistern installation, note that roofs constructed with tar, gravel, treated cedar shakes, or old asbestos shingle roofs may produce too much contamination for rainwater harvesting. Similarly, rainwater should not be harvested if it is conveyed via gutters with lead soldering or lead-based paints. Roofs exposed to airborne particles originating from cement kilns, gravel quarries, crop dusting, or concentrated automobile emissions will create runoff that could adversely affect the rainwater quality.

Cisterns can vary in size and may have storage capacity of up to several thousand gallons. It is important to gauge what size and storage capacity is right for the site and facility. Low storage capacities will limit rainwater harvesting so that the system may not be able to provide water in a low rainfall period, and increased storage capacities add to construction and operating costs. A factor that will assist in determining the size of the cistern is the volume of water available for capture. An analysis of precipitation records should be performed to determine the amount, frequency, and seasonal variation of rainfall for the area. Including several years of data is recommended in order to account for dry and wet years. The anticipated daily or monthly demand for the harvested rainwater should also be determined. This will first require determining what the end use of the collected water will be; then predicting the amount needed. Toilet and urinal flushing impart a consistent daily demand on a water system, while outdoor irrigation may be somewhat more episodic. Using a garden water meter to measure the number of gallons running through a hose or other device is an effective method in estimating how much water is used for outdoor irrigation and equipment and vehicle washing. The total surface area of the roof is another factor in determining cistern size.

The volume of water that can be collected from a given rain event can be calculated as:

$$V\ (gal) = Area\ of\ Collection\ Surface\ (ft^2) \times Rainfall\ (in.) / 12\ in./ft \times 0.8\ (Capture\ Efficiency) \times 7.48\ gal/ft^3$$

Generally all rainwater tank/cistern designs should include these components:

- A solid secure cover
- A leaf / mosquito screen at cistern entrance
- A coarse inlet filter with clean-out valve
- An overflow pipe
- A manhole, sump, and drain to facilitate cleaning

- An extraction system that does not contaminate the water (e.g., a tap or pump)
- A soak-away to prevent spilled water from forming puddles near the tank

Additional features might include:

- A device to indicate the amount of water in the tank
- A sediment trap, tipping bucket, or other "foul flush" mechanism
- A lock on the tap

All components of a cistern should be designed to provide treatment sufficient for the intended end uses. This involves minimizing the introduction of pollutants. When rainwater is collected from rooftops, gutters should contain screens in order to prevent debris from clogging the collection system and/or fouling the harvested water. The screens should have openings no larger than 1/2 in. across their entire length, including the downspout opening. To allow the initial portion of runoff to bypass the cistern, a first flush diverter may be used. If additional primary filtration is desired, roof washers are another option. Roof washers can act as first flush diverters and also contain filter media (e.g., sand, gravel, filter fabric) to remove particulates that have passed through the leaf screens in the gutters. For nonpotable indoor uses (where local codes and ordinances allow), additional treatment can be provided following the collection tank. Additional cartridge filtration can be provided to prevent suspended particles from entering pipes. When treatment such as filtration or disinfection is provided on cisterns, it is intended to protect the collection tanks from fouling and/or to improve the quality of water for reuse applications.

Cistern tanks should have three openings where pipes will be placed: an inlet, outlet/outflow (or faucet), and overflow. Overflows should be directed away from structures and toward pervious areas to allow for infiltration. Pipes connected to the outflow (or any part of the harvesting system) should not ever connect to potable water piping. High levels of caution are needed to ensure the integrity of the separation between the potable system and the harvesting system. Dedicated piping should be color-coded and labeled as harvested rainwater, not for consumption. Faucets supplied with nonpotable rainwater should also contain signage identifying the water source as nonpotable and not for consumption.

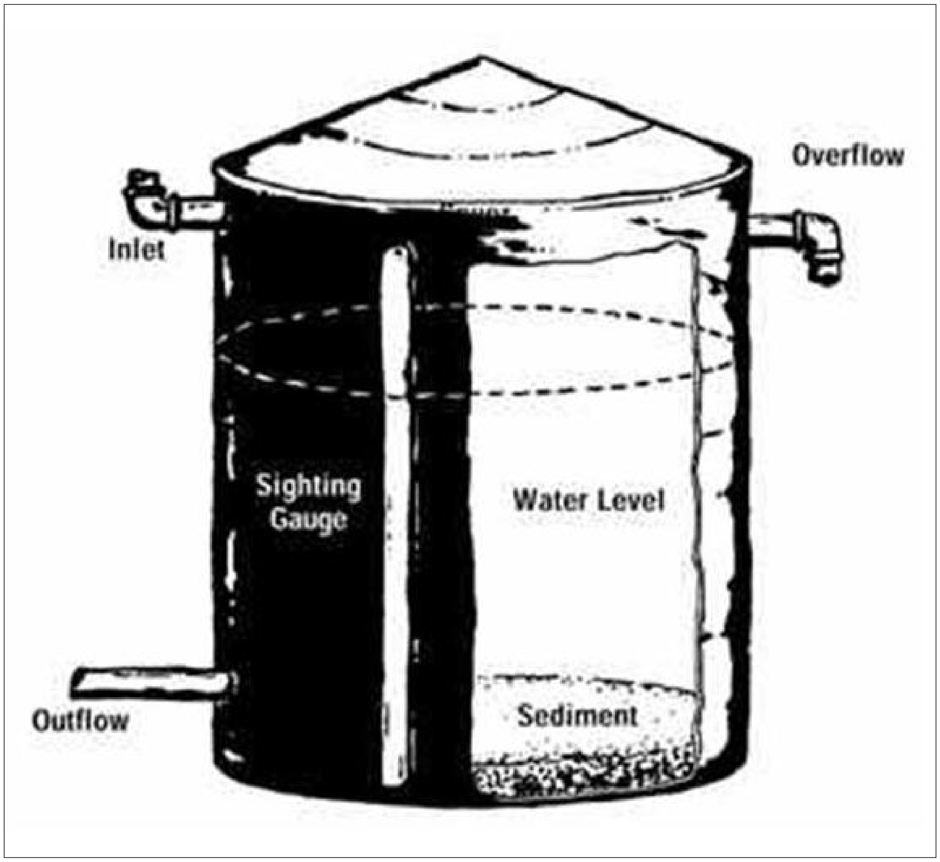

Figure C-51. Cistern
(source: Texas Guide on Rainwater Harvesting).

The designated dual piping system is also part of the cross-contamination prevention measures.

When make-up water is required for the cistern from the municipal system, steps must be taken to prevent cross-contamination. Cross-contamination measures will be similar to those for reclaimed and greywater systems. The make-up supply to the cistern is the point of greatest risk for cross-contamination of the potable supply. A backflow prevention assembly on the potable water supply line, an air gap, or both must be provided to prevent collected rainwater from entering the potable supply. Specific requirements can be obtained by local water system authorities.

Efficient operation and the intended end uses will determine the level of treatment needed in a cistern. There is minimal human health risk presented when harvested rainwater is used for nonpotable uses (e.g., toilets, urinals). When harvested water is used for higher end contact uses, additional filtration and disinfection is required. Typical water quality criteria for various uses are provided in Table C-8. Detailed specifications and design guidance can be found through the American Rainwater Catchment Systems Association (http://www.arcsa.org).

Table C-8. Minimum water quality guidelines and treatment options for stormwater reuse.

Use	**Minimum Water Quality Guidelines**	**Suggested Treatment Options**
Potable indoor uses	Total coliforms – 0 Fecal coliforms – 0 Protozoan cysts – 0 Viruses – 0 Turbidity < 1 NTU	Pre-filtration – first flush diverter Cartridge filtration – 3 micron sediment filter followed by 3 micron activated carbon filter Disinfection – chlorine residual of 0.2 ppm or ultraviolet (UV) disinfection
Nonpotable indoor uses	Total coliforms < 500 cfu per 100 mL Fecal coliforms < 100 cfu per 100 mL	Pre-filtration – first flush diverter Cartridge filtration – 5 micron sediment filter Disinfection – chlorination with household bleach or UV disinfection
Outdoor uses	N/A	Pre-filtration – first flush diverter
*cfu – colony forming units *NTU – nephelometric turbidity units (Source: Texas Rainwater Harvesting Manual)		

A design consideration involving the overflow pipe is to connect it to the inlet of a second cistern tank. This would be appropriate for areas with heavy rainfall or large facilities with a high demand for nonpotable water. Figure C-52 illustrates what this might look like.

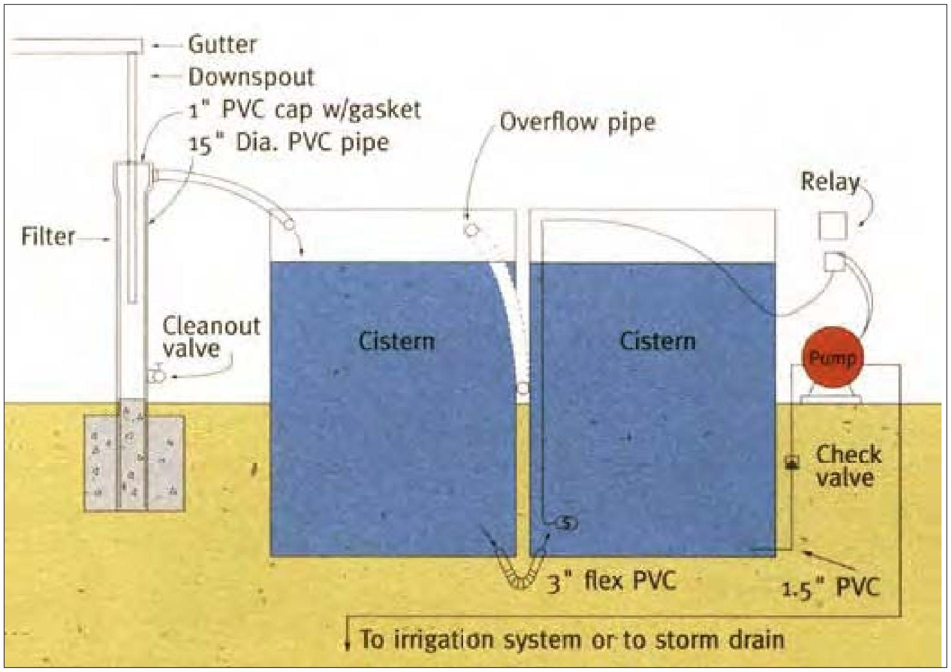

Figure C-52. Cistern overflow
(photo courtesy of Tree People).

The system of cisterns in Figure C-53 receives rainwater from an elevated channel that transports the rainwater to the collection tanks.

Figure C-53. Linked cisterns
(photo courtesy of Sunset Publishing Corporation).

The system of cisterns in Figure C-54 is also connected via overflow pipes. This type of set up would be appropriate for a smaller building for which space was a concern.

Figure C-54. Cistern system (photo courtesy of Technicians for Sustainability).

Cisterns can also be designed to be part of a “treatment train” by directing overflow to a bioretention system for additional volume reduction and water quality treatment. This applies in instances where the quantity of runoff from a storm event exceeds the volume of the collection tank, when the cistern’s outflow pipe comes into play. The following cistern in Figure C-55 has its outflow pipe routing excess rainwater to a rock and gravel bed containing vegetation.

Figure C-55. Cistern at a shopping center in Allen Park, MI (courtesy of SEMCOG Regional Planning Partnership).

The schematic in Figure C-56 demonstrates a reverse scenario, where the outlet leads to bioretention and the overflow discharges to the storm drain.

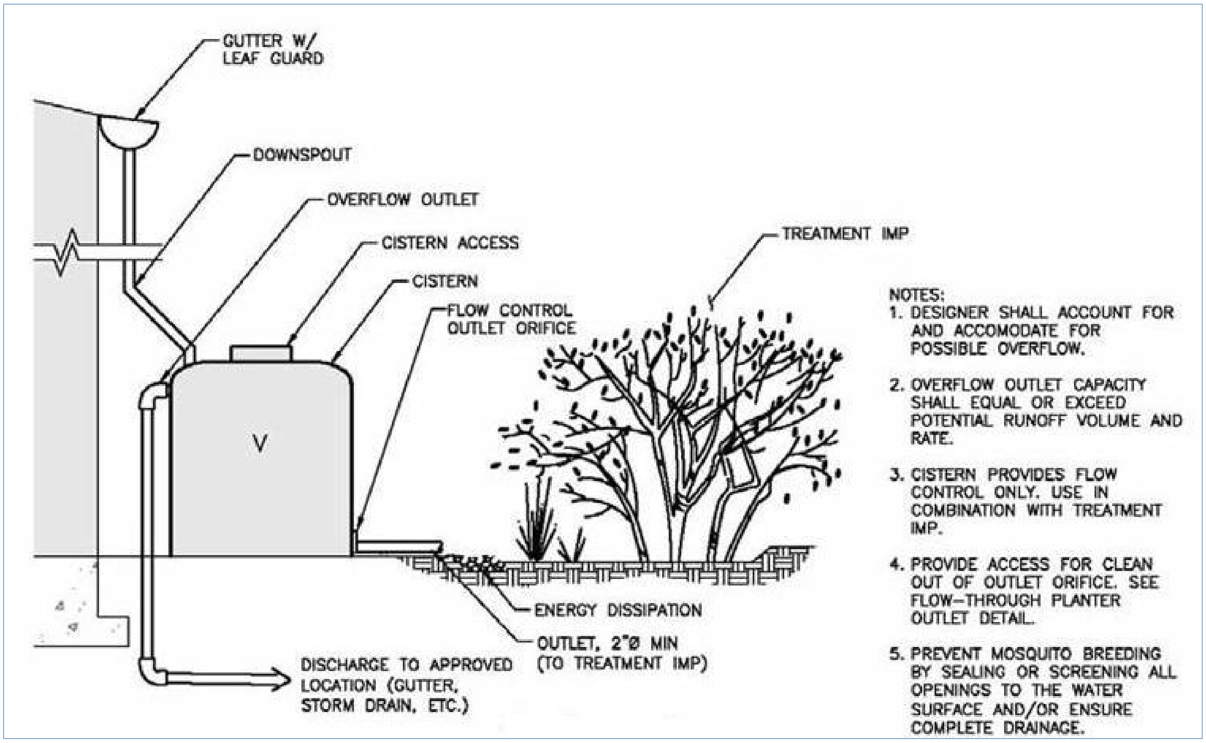

Figure C-56. Cistern outlet to bioretention (City of Encinitas, California).

Construction

Cisterns can be constructed of nearly any impervious, water retaining material. However, it is generally advisable to select a material that is rated for potable water use by the National Sanitation Foundation to prevent the introduction of any additional contaminants into the harvested rainwater. Commercially available systems are typically constructed of high density plastics. They can also be made of metal or concrete and can be cast-in-place. Outdoor tanks should be constructed of opaque materials or otherwise shaded or buried to prevent damage from sunlight. They should also contain adequate screening at each opening to prevent insects from entering the tank.

Other materials utilized for the construction of cisterns can include redwood, polyethylene, fiberglass, metal, concrete, plaster (on walls), ferro-cement and impervious rock such as slate and granite. Typical components of a cistern roof top catchment system include: the roof, gutters, and downspouts with connection to top of cistern, and outflow connections for appropriate uses (i.e., irrigation).

When constructing a cistern, ensure that the outlet for overflow is created a few inches from the top of collection tank and that it is sized to safely discharge excess volume when the tank is full. When cisterns are installed below grade, observation risers should rise at least 6 in. above grade in order to allow room for sediment storage. Due to the amount of water pressure the outlet will receive, a bulkhead fitting should be used to prevent leaks. This is done simply by drilling a hole in the cistern and threading the bulkhead through. This tactic can be done by the cistern vendor, usually at extra expense.

When constructing underground cisterns (Figure C-57), local utility companies should be contacted in order to locate any underground pipes or cables that may be in the installation site. Product literature should be consulted to determine backfill material, excavation depths, and the depth of the soil required above the cistern.

Figure C-57. Construction of a large underground cistern (photo courtesy of Rainwater Recovery Systems, LLC).

The following instructions provide a simple sequence for constructing a cistern below ground:

1. Excavate the hole to the required dimensions. This is usually done with a back hoe. For example, 8 ft by 12 ft and 8 ft deep. Make sure the hole has been dug to the dimensions you desire or your storage will be seriously compromised.

2. Pour the cistern floor. First form up the floor of the cistern much as you would a sidewalk, driveway, or other flat work. Construct a rectangular framework from 2 x 4s and secure it with 2 x 4 stakes driven into the ground at intervals of about 2 feet.

3. Form the cistern walls. The cistern walls should be constructed by first building the outside forms and then installing #6 rebar wired together on an approximate 1-ft grid. Set the grid into the holes bored into the concrete floor of the cistern with a hammer drill. With the reinforcing grid in place build the inside forms. Make sure the walls are adequately braced and then pour the concrete.

4. Let the concrete set for the required time period recommended by the manufacturer and then remove the forms.

5. Seal the inside of the cistern; a Portland-based product with a latex additive is recommended, possibly Damtite, or another acceptable alternative available at your local building supply store.

6. Create the lid and hatches. The lid can be made of any acceptable material but should fit snuggly to keep potential pests from entering.

When cisterns are used for nonpotable indoor uses, be sure to schedule a municipal inspection during installation.

Maintenance

Maintenance requirements will vary based on the design of the cistern, and whether or not the water is being used indoors or outdoors. Maintenance also varies on the type of winter the cistern will face. Colder climates will require closer attention, and “winterization” steps might be necessary. Semi-annual inspections should be conducted. Specifically, roof catchments should be inspected for particulate matter (PM) or other parts of the roof that might be entering the gutter and downspout; gutters and downspouts should be inspected for leaks or obstructions; and roof washers, cleanout plugs, screens, covers, and overflow pipes should be inspected and replaced as needed.

Annual municipal inspections of the backflow prevention systems are recommended. Annual water quality testing is recommended when harvested rainwater is used for indoor uses. Regular inspection and replacement of treatment system components such as filters or UV lights is also recommended. Cisterns should be flushed annually in order to remove any accumulated sediment. For underground cisterns, vacuum removal of sediment will be necessary. Properly designed and maintained cisterns present less potential for mosquito breeding and the infestation of other pests when compared to other conventional BMPs.

Effectiveness

When properly installed, cisterns reduce the peak discharge rate and runoff volume through retention. However, when compared to other BMP options, the peak discharge is minimally impacted by the use of cisterns. An initial runoff volume is retained by the storage devices, ranging from approximately 50 gallons to several thousand for each device, prior to the remaining runoff bypassing the systems. When used throughout a watershed or stormwater collection basin, cisterns will modestly impact the peak stormwater flow rate.

Modest water quality improvements will be gained by using rain barrels and cisterns to reduce the volume of stormwater available to convey pollutants.

APPENDIX D: REFERENCES AND RESOURCES

References

Bean, R., W. Hunt, and D. Bidelspach. 2007. "Field Study of Four Permeable Pavement Sites in Eastern North Carolina for Runoff Reduction and Water Quality Impacts." *Journal of Irrigation and Drainage Engineering* 133 (6), 583–592.

Casey Trees Endowment Fund and Limno-Tech, Inc. 2005. Re-greening Washington DC: A Green Roof Vision Based on Quantifying Stormwater and Air Quality Benefits. Available at http://www.caseytrees.org.

Center for Watershed Protection (CWP). 1996. *Design of Stormwater Filtering Systems*. Prepared by the Center for Watershed Protection, Ellicott City, MD, for the Chesapeake Research Consortium, Solomons, MD, and USEPA Region V, Chicago, IL.

City of Portland. 2004. *Stormwater Management Manual* (Revision #3). Portland, OR: Environmental Services, City of Portland, Clean River Works.

Davis, A., M. Shokouhian, H. Sharma, and C. Henderson. 1997. *Bioretention Monitoring-Preliminary Data Analysis*. Environmental Engineering Program of the University of Maryland, College Park, MD.

DoD. 2010. "Low Impact Development." UFC 3-210-10. Washington, DC: Department of Defense.

Driscoll, E., and P. Mangarella. 1990. Urban Targeting and BMP Selection. Prepared by Woodward-Clyde Consultants, Oakland, CA, for US Environmental Protection Agency, Washington, DC.

EO 13514. 2009. "Federal Leadership in Environmental, Energy, and Economic Performance," President Barack Obama, 5 October 2009.

Gunderson, J. 2008. "Pervious Pavements: New Findings about Their Functionality and Performance in Cold Climates." *Stormwater* 9(6), September. Available at http://www.stormh2o.com/SW/Articles/Pervious_Pavements_1071.aspx

Harper, H. 1988. *Effects of Stormwater Management Systems on Groundwater Quality*. Prepared for Florida Department of Environmental Regulation, Tallahassee, FL, by Environmental Research and Design, Inc., Orlando, FL.

Hunt, W. F., and W.G. Lord. 2006. *Bioretention Performance, Design, Construction, and Maintenance*. Raleigh, NC: North Carolina Cooperative Extension. Available at: http://www.bae.ncsu.edu/stormwater/PublicationFiles/Bioretention2006.pdf

ICPI (Interlocking Concrete Pavement Institute). 2008. "Permeable Interlocking Concrete Pavement (PICP) – Municipal Officials Fact Sheet."

Kohler, M., K. K. Y. Liu, and B. Rowe. 2007. Green roofs as urban ecosystems: Ecological structures, functions, and services. BioScience 57: 823-833.

Koon, J. 1995. *Evaluation of Water Quality Ponds and Swales in the Issaquah/East Lake Sammamish Basins*. Seattle, WA: King County Surface Water Management and Olympia, WA: Washington Department of Ecology.

MDE (Maryland Department of the Environment). 2000. *2000 Maryland Stormwater Deisgn Manual Volume I: Stormwater Management Criteria. Baltimore, MD: MDE Water management Administration.* Available at: http://www.mde.maryland.gov/programs/Water/StormwaterManagementProgram/MarylandStormwaterDesignManual/Pages/Programs/WaterPrograms/SedimentandStormwater/stormwater_design/index.aspx

Moran, A., B. Hunt, and J. Smith. 2005. "Hydrologic and Water Quality Performance from Green Roofs in Goldsboro and Raleigh, North Carolina," p. 512-525 In *Proc. of 3rd North American Green Roof Conference: Greening Rooftops for Sustainable Communities*. Washington, DC: 4-6 May 2005.

National Research Council. 2008. *Urban Stormwater Management in the United States*. Washington, DC: The National Academies Press.

Natural Resources Defense Council (NRDC). 2002. *Out of the Gutter: Reducing Polluted Runoff in the District of Columbia*.

NCHRP. 2006. *Evaluation of Best Management Practices for Highway Runoff Control: Low Impact Development Design Manual for Highway Runoff Control*. Project 25-20(01) Report #565, National Cooperative Highway Research Program. Washington, DC: Transportation Research Board of National Academies.

North Carolina State University (NCSU) and North Carolina A&T State University Cooperative Extension. 2008. *Urban Waterways - Permeable Pavement: Research Update and Design Implications*. Report #E08-50327.

Oberndorfer, E., J. Lundholm, B. Bass, R. R. Coffman, H. Doshi, N. Dunnett, S. Gaffin, M. Kohler, K. K. Y. Liu, and B. Rowe. 2007. Green roofs as Urban Ecosystems: Ecological Structures, Functions, and Services. *BioScience* 57: 823-833.

Pratt, C. J. 1999. “Use of Permeable, Reservoir Pavement Constructions for Stormwater Treatment and Storage for Re-Use.” *Water Science Technology* 39(5):145-151.

Schueler, T. 1997. Comparative Pollutant Removal Capability of Urban BMPs: A Reanalysis. *Watershed Protection Techniques* 2(2):379-383.

Texas Water Development Board. 2005. *The Texas Manual on Rainwater Harvesting – Third Edition*. Austin, TX: TWDB.

UNHSC (University of New Hampshire Stormwater Center). 2007. *University of New Hampshire Stormwater Center 2007 Annual Report*. Durham, NH.

US Congress. 2007. Energy Independence and Security Act (EISA), Title 42, United States Code (USC), Chapter 52, Section 17094, Section 438 – “Stormwater Runoff Requirements for Federal Development Projects,” 19 December.

US Department of the Navy (DON). 2007. “DON Low Impact Development (LID) Policy for Stormwater Management.” 16 November. Washington, DC: Assistant Secretary of the Navy (Installations and Environment), . (Available as a PDF at www.lowimpactdevelopment.org)

USEPA. n.d. NPDES: “Grassed Swales.” Washington, DC: US Environmental Protection Agency. Available online: http://cfpub.epa.gov/npdes/stormwater/menuofbmps/index.cfm?action=factsheet_results&view=specific&bmp=75.

USEPA. 1999. Storm Water Technology Fact Sheet: “Bioretention.” EPA 832-F-99-012. Washington, DC: US Environmental Protection Agency, Office of Water.

______. 2006. “Many Paths Lead to the Adoption of Low Impact Development.” In *Nonpoint Source News-Notes* Issue #76 (August). Washington, DC: US Environmental Protection Agency

______. 2008. *Clean Watersheds Needs Survey 2004: Report to Congress*. Washington, DC: US Environmental Protection Agency.

______. 2009a. State and Local Climate and Energy Program: "Heat Island Effect." Washington, DC: US Environmental Protection Agency. Available online: http://www.epa.gov/heatisld/ (accessed May 2010).

______. 2009b. *National Water Quality Inventory: Report to Congress, 2004 Reporting Cycle*. EPA 841-R-08-001. Washington, DC: US EPA Office of Water.

______. 2010. *Heat Island Effect: Heat Island Impacts.* Available at: http://www.epa.gov/heatisld/impacts/index.htm.

Van Metre, P. C., and B. J. Mahler. 2003. "The Contribution of Particles Washed from Rooftops to Contaminant Loading to Urban Streams." *Chemosphere* 52:1727–1741.

Weinstein, N. 2006. Decentralized Stormwater Controls for Urban Retrofit and Combined Sewer Overflow Reduction – Phase 1, WERF Report 03-SW-3. Water Environment Research Foundation.

______. 2009. Decentralized Stormwater Controls for Urban Retrofit and Combined Sewer Overflow Reduction – Phase 2, WERF Report 03-SW-3A. Water Environment Research Foundation.

Related Literature and Resources

Adams, M.C. 2003. "Porous Asphalt Pavement with Recharge Beds: 20 Years & Still Working." *Stormwater Magazine*.

American Rainwater Catchment Systems Association:

American Society of Landscape Architects. 2006. *Green Roof Demonstration Project Fact Sheet.* Washington, DC: American Society of Landscape Architects. (www.asla.org)

American Rainwater Catchment Systems Association http://www.arcsa.org

American Waterworks Association Research Foundation. 1999. *Residential End Uses of Water*. Denver, CO.

Barrett, M., P. Kearfott, and J. Malina. 2006. "Stormwater Quality Benefits of a Porous Friction Course and its Effect on Pollutant Removal by Roadside Shoulders." *Water Environment Research, Water Environment Federation* 78(11):2177-2185.

Bean, E. Z., W. F., Hunt, and D. A. Bidelspach. 2005. "A Monitoring Field Study of Permeable Pavement Sites in North Carolina." Presented at 8th Biennial Conference on Stormwater Research & Watershed Management, sponsored by the Southwest Florida Water Management District and Florida Department of Environmental Protection.

Bean, E.Z., W.F. Hunt, D.A. Bidelspach, and J.T. Smith. 2004. Study on the Surface Infiltration Rate of Permeable Pavements, 1st Water and Environment Specialty Conference of the Canadian Society for Civil Engineering. Saskatoon, Saskatchewan, Canada.

Ben-Horin, E. 2007. *Rainwater as a Resource: A Report on Three Sites Demonstrating Sustainable Stormwater Management*. Los Angeles, CA: Tree People. http://www.treepeople.org/rainwater-resource.

Booth, D. B., and J. Leavitt. 1999. Field Evaluation of Permeable Pavement Systems for Improved Stormwater Management, *American Planning Association Journal* 65(3):314-325.

Brattebo, B. O., and D. B. Booth. 2003. Long-Term Stormwater Quantity and Quality Performance of Permeable Pavement Systems, Water Resources, Elsevier Press.

Brown, W., and T. Schueler. 1997. *The Economics of Stormwater BMPs in the Mid-Atlantic Region*. Prepared for the Chesapeake Research Consortium, Edgewater, MD, by the Center for Watershed Protection, Ellicott City, MD.

Cahill, T. H., M. Adams, and C. Marm. 2003. Porous Asphalt: The Right Choice for Porous Pavements. *Hot Mix Asphalt Technology* 26-40.

City of New York. 2008. *PlaNYC – Sustainable Stormwater Management Plan 2008*.

City of Portland Bureau of Development Services. 2010. Swales. Accessed 21 April 2010. http://www.portlandonline.com/bds/index.cfm?a=79039&c=40878

City of San Diego. *Water Conservation Program – Rainwater Harvesting Information* http://www.sandiego.gov/water/conservation/rainwater.shtml

City of Tucson. 2003. *Water Harvesting Guidance Manual.* http://dot.ci.tucson.az.us/stormwater/downloads/2006WaterHarvesting.pdf

Clausen, J. C., and J. K. Gilbert. 2006. Stormwater Runoff Quality and Quantity from Asphalt, Paver, and Crushed Stone Driveways in Connecticut. *Water Research* 40:826-832.

Collins, K. A., W. F. Hunt, and J. M. Hathaway. 2008. Hydrologic Comparison of Four Types of Permeable Pavement and Standard Asphalt in Eastern North Carolina. *Journal of Hydrologic Engineering* 13(12):1146-1157.

County of San Louis Obispo. 2009. Low Impact Development Handbook: Strategies for Post-Construction Stormwater Management in New Development and Redevelopment. http://www.slocounty.ca.gov/Assets/PW/stormwater/LID+Manual+April+09.pdf.

Currie, B.A., and B. Bass. 2005. "Estimates of Air Pollution Mitigation with Green Plants and Green Roofs Using the UFORE model." In *Proceedings of the Third American Green Roof Conference: Greening Rooftops for Sustaining Communities* held in Washington, DC. 4-6 May, 2005. 495-511.

Dorman, M. E., J. Hartigan, R. F. Steg, and T. Quasebarth. 1989. *Retention, Detention and Overland Flow for Pollutant Removal From Highway Stormwater Runoff*. Vol 1, FHWA/RD 89/202. Washington, DC: Federal Highway Administration.

Duffy, E. 2008. The green green roofs of home. Available at: http://naturalpatriot.org/2008/01/19/the-green-green-roofs-of-home/. Accessed on 13 April 2010.

DuluthStreams.org. Tools for Stormwater Management: Grassed Swales. Accessed 21 April 2010: http://www.duluthstreams.org/stormwater/toolkit/swales.html

Engineering Technologies Associates and Biohabitats. 1993. *Design Manual for Use of Bioretention in Stormwater Management*. Prepared for Prince George's County Government, Watershed Protection Branch, Landover, MD.

EO (Executive Order) 13508. 2009. "Chesapeake Bay Protection and Restoration," President Barack Obama, 12 May 2009.

Fassman, E., and S. Blackbourn. 2006. Permeable Pavement Performance for Use in Active Roadways in Auckland, New Zealand, University of Auckland.

Federal Highway Administration. Dry and Wet Vegetated Swales Factsheet. Accessed 20 April 2010: http://www.fhwa.dot.gov/environment/ultraurb/3fs10.htm

Green Roofs for Healthy Cities. Accessed 6 July 2005: http://www.greenroofs.org.

Goldberg, J.S. 1993. *Dayton Avenue Swale Biofiltration Study*. Seattle, WA: Seattle Engineering Department.

Grant, Gary, L. Engleback, and B. Nicholson. 2003. *Green Roofs: Their Existing Status and Potential for Conserving Biodiversity in Urban Areas,* Report No. 498, English Nature Research Reports.

Haugland, J. 2005. *Changing Cost Perceptions: An Analysis of Conservation Development.* Elmhurst, IL: Conservation Research Institute.

Hossain, M., L. A. Scofield, and W. R. Meier. 1992. Porous Pavement for Control of Highway Runoff in Arizona: Performance to Date. *Transportation Research Record No. 1354*, pp 45-54. Washington, DC: Transportation Research Council.

Hunt, W. F., and K. A. Collins. 2008. *Permeable Pavement: Research Update and Design Implications*, North Carolina State University Cooperative Extension, Raleigh, NC. Publication #AGW-588-14.

Interlocking Concrete Pavement Institute (ICPI). 2000. *Permeable Interlocking Concrete Pavements - Design, Specification, Construction, Maintenance*, 3rd Edition.

Jones, M., and W. Hunt. 2008. *Urban Waterways - Rainwater Harvesting: Guidance for Homeowners*. North Carolina Cooperative Extension Service.

Jones, R. C., and C. C. Clark. 1987. Impact of Watershed Urbanization on Stream Insect Communities. *Water Resources Bulletin* 23(6):1047-1055.

Kessner, K. 2000. “How to Build a Rainwater Catchment Cistern.” *The March Hare*, Summer 2000. http://www.dancingrabbit.org/building/cistern.php.

Legret, M., and V. Colandini. 1999. Effects of a Porous Pavement with Reservoir Structure on Runoff Water: Water Quality and Fate of Heavy Metals. *Water Science and Technology* 39(2):111-117.

Kercher, W. C., J. C. Landon, and R. Massarelli. 1983. Grassy swales prove cost-effective for water pollution control. *Public Works* 16:53-55.

King County Washington. *King Street Center, Water Reclamation.* http://www.kingcounty.gov/environment/wtd/Construction/EnhanceEnvironment/GreenBuilding.aspx#2

MacMullan, E., and S. Reich. 2007. *The Economics of Low-Impact Development: A Literature Review*, ECONorthwest.

Mentens, J., D. Raes, and M. Hermy. 2006. Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century, *Landscape and Urban Planning* 77(3):217-226.

National Ready Mix Concrete Association (NRMCA). 2004. Freeze-Thaw Resistance of Pervious Concrete, Silver Spring, MD. Available at:http://www.nrmca.org/aboutconcrete/Pervious%20Concrete%20-%20-%20Freeze-Thaw%20Durability%20per%20NRMCA.pdf, (accessed February 2009).

National Ready Mix Concrete Association (NRMCA), 2008. Pervious Concrete: When it rains… it drains (website). Silver Spring, MD, 2008, available at: http://www.perviouspavement.org/index.html, (accessed February 2009).

National Asphalt Pavement Association. 2008. *Porous Asphalt Pavements for Stormwater Management: Design, Construction, and Maintenance Guide* (IS-131). Lanham, MD.

Natural Resources Defense Council (NRDC). 2006. Building Green – Case Study, Santa Monica, CA: NRDC. http://www.nrdc.org/buildinggreen/casestudies/nrdcsm.pdf

National Research Council (NRC) 2008. Urban Stormwater Management in the United States: Committee on Reducing Stormwater Discharge Contributions to Water Pollution. National Academies Press, Washington, DC, www.nap.edu

New York State Department of Environmental Conservation. 2008. *New York State Stormwater Management Design Manual*.

Oakland, P. H. 1983. "An Evaluation of Stormwater Pollutant Removal Through Grassed Swale Treatment." In: *Proceedings of the International Symposium of Urban Hydrology, Hydraulics and Sediment Control* (Pages 173–182), held in *Lexington, KY*.

Occoquan Watershed Monitoring Laboratory. 1983. *Final Report: Metropolitan Washington Urban Runoff Project*. Prepared for the Metropolitan Washington Council of Governments, Washington, DC. Manassas, VA: Occoquan Watershed Monitoring Laboratory.

Organization of American States, Unit of Sustainable Development and Environment General Secretariat. 1997. *Source Book of Alternative Technologies for Freshwater Augmentation in Latin America and the Caribbean: Rainwater harvesting from rooftop catchments.* Washington, DC. http://www.oas.org/dsd/publications/Unit/oea59e/ch10.htm.

Pacific Institute. 2003. *Waste Not, Want Not: The Potential for Urban Water Conservation in California*. http://www.pacinst.org/reports/urban_usage/waste_not_want_not_full_report.pdf

Pitt, R., and J. McLean. 1986. *Toronto Area Watershed Management Strategy Study: Humber River Pilot Watershed Project*. Ontario Ministry of Environment, Toronto, ON.

Prince George's County. 2001. *The Bioretention Manual.* Department of Environmental Resources Programs and Planning Division, Maryland.

Riversides.org. 2009. Vegetated Swales. Accessed 21 April 2010. http://www.riversides.org/rainguide/riversides_hgr.php?cat=2&page=39&subpage=92&subpage2=44.

Roseen, R. M., and T. P. Ballestero. 2008. "Porous Asphalt Pavements for Stormwater Management in Cold Climates." National Asphalt Pavement Association's magazine, *Hot Mix Asphalt Technology*, May/June 2008, p 26-27.

Rushton, B. T. 2001. Low Impact Parking Lot Design Reduces Runoff and Pollutant Loads. *Journal of Water Resources Planning and Management,* May/June 2001, 172-179.

Sabin, L. D., J. H. Lim, K. D. Stolzenbach, and K. C. Schiff. 2005. Contribution of trace metals from atmospheric deposition to stormwater runoff in a small impervious urban catchment. *Water Research* 39(16):3929-37.

Saulny, S. 2007. In Miles of Alleys, Chicago Finds Its Next Environmental Frontier. *New York Times*.

Scholz-Barth, K. 2001. Green Roofs, Stormwater Management from the Top Down. Environmental Design and Construction. Accessed 27 June 2005: http://www.edcmag.com.

Sailor, D. 2004. *Atmospheric Modeling of the Potential Impacts of Green Roofs on Portland's Urban Climate.* Portland, OR: Portland State University, Department of Mechanical Engineering.

Seattle Metro and Washington Department of Ecology. 1992. *Biofiltration Swale Performance: Recommendations and Design Considerations*. Publication No. 657. Seattle, WA: Water Pollution Control Department.

Seattle Public Utilities http://www.seattle.gov/util/About_SPU/Drainage_&_Sewer_System/GreenStormwaterInfrastructure/index.htm.

Sferra, L. 2008. *Understanding Bioretention Hydraulics and Construction.* GDP Group.

Southeastern Wisconsin Regional Planning Commission. 1991. *Costs of Urban Nonpoint Source Water Pollution Control Measures*. Technical Report No. 31. Waukesha, WI: Southeastern Wisconsin Regional Planning Commission.

SpokaneCounty.org. 2009. Grassy Swale Information. Accessed 20 April 2010: http://www.spokanecounty.org/stormwater/content.aspx?c=1779

Stratus Consulting. 2009. *A Triple Bottom Line Assessment of Traditional and Green Infrastructure Options for Controlling CSO Events in Philadelphia's Watersheds*, Philadelphia, PA: Water Department, Office of Watersheds, August.

Texas Rainwater Harvesting Evaluation Committee. 2006. *Rainwater Harvesting Potential and Guidelines for Texas, Report to the 80th Legislature*, Texas Water Development Board, Austin, TX.

University of Utah. 2009. User’s Guide to the BMP and LID Whole Life Cost Models – Version 2.0, Water Environment Research Foundation.

Urban Drainage and Flood Control District. 2008. Pervious Concrete Evaluation Materials Investigation, Denver, Colorado. Project # CT14, 571-356. Prepared by Thompson Materials Engineers, Inc.

US EPA, *Clean Watersheds Needs Survey 2004: Report to Congress,* January 2008.

US EPA. 2007. *Reducing Stormwater Costs through Low Impact Development (LID) Strategies and Practices*, EPA 841-F-07-006. Washington, DC.

______. 2008. Green Roofs Fact Sheet. Washington, DC: Office of Water.

Van Seters, T. 2007. *Performance Evaluation of Permeable Pavement and a Bioretention Swale*. Seneca College, King City, Ontario, Interim Report #3. Downsview, Ontario: Toronto and Region Conservation Authority.

Vingarzan, R., and B. Taylor. 2003. *Trend Analysis of Ground Level Ozone in the Greater Vancouver/Fraser Valley Area of British Columbia.* Environment Canada - Aquatic and Atmospheric Sciences Division.

Washington Aggregates & Concrete Association. 2006. “Pervious Concrete Project Profile,” accessed February 2009 at: http://www.washingtonconcrete.org/assets/ProfileStratfordPlace.pdf).

Wang, T., D. Spyridakis, B. Mar, and R. Horner. 1981. *Transport, Deposition and Control of Heavy Metals in Highway Runoff*. FHWA-WA-RD-39-10. Seattle, WA: University of Washington, Department of Civil Engineering.

Welborn, C., and J. Veenhuis. 1987. *Effects of Runoff Controls on the Quantity and Quality of Urban Runoff in Two Locations in Austin, TX*. USGS Water Resources Investigations Report No. 87-4004. Reston, VA: US Geological Survey.

Yousef, Y., M. Wanielista, H. Harper, D. Pearce, and R. Tolbert. 1985. *Best Management Practices: Removal of Highway Contaminants by Roadside Swales*. Orlando, FL: University of Central Florida and Florida Department of Transportation.

Yu, S., S. Barnes, and V. Gerde. 1993. *Testing of Best Management Practices for Controlling Highway Runoff*. FHWA/VA-93-R16. Charlottesville, VA: Virginia Transportation Research Council.

APPENDIX E:
ABBREVIATIONS AND UNIT CONVERSION FACTORS

Abbreviations

Term	Spellout
AASHTO	American Association of State Highway and Transportation Officials
AR	Army Regulation
ARCSA	American Rainwater Catchment Systems Association
BIA	Bilateral Infrastructure Agreements
BMP	best management practice
CECW	Directorate of Civil Works, U. S. Army Corps of Engineers
CEMP-CE	Directorate of Military Programs, U. S. Army Corps of Engineers
CERL	Construction Engineering Research Laboratory
cfu	colony forming units
CO	carbon monoxide
CSO	combined sewer overflow
CWA	Clean Water Act
CWP	Center for Watershed Protection
DPW	Directorate of Public Works
DoD	Department of Defense
DON	Department of the Navy
EISA	Energy Independence and Security Act
EO	Executive Order
ERDC	Engineer Research and Development Center
HNFA	Host Nation Funded Construction Agreements
HQUSACE	Headquarters, US Army Corps of Engineers
ICPI	Interlocking Concrete Pavement Institute

Term	Spellout
IWS	internal water system
LEED	Leadership in Energy and Environmental Design
LID	low impact development
MDE	Maryland Department of the Environment
NCHRP	National Cooperative Highway Research Program
NCSU	North Carolina State University
NO_3	nitrate
NPDES	National Pollution Discharge Elimination System
NPS	nonpoint source
NRDC	Natural Resources Defense Council
NRMCA	National Ready Mix Concrete Association
NTU	nephelometric turbidity units
O_3	ozone
PICP	permeable interlocking concrete pavement
PM10	particulate matter less than 10 microns in diameter
POC	point of contact
PWTB	Public Works Technical Bulletin
SEMCOG	Southeast Michigan Council of Governments
SO_2	sulfur dioxide
SOFA	Status of Forces Agreement
TKN	total kjeldahl nitrogen
TMDL	total maximum daily load
TN	total nitrogen
UFC	Unified Facilities Criteria
UNHSC	University of New Hampshire Stormwater Center
USC	United States Code

Term	Spellout
USEPA	United States Environmental Protection Agency
UV	ultraviolet
WBDG	Whole Building Design Guide
WERF	Water Environment Research Foundation

Unit Conversion Factors

This PWTB provides units of measure in the inch-pound system. The following conversion chart may be used to convert measurements to the international system if needed.

Multiply	By	To Obtain
acres	4,046.873	square meters
cubic feet	0.02831685	cubic meters
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
gallons (US liquid)	3.785412 E-03	cubic meters
inches	0.0254	meters
square feet	0.09290304	square meters
square inches	6.4516 E-04	square meters