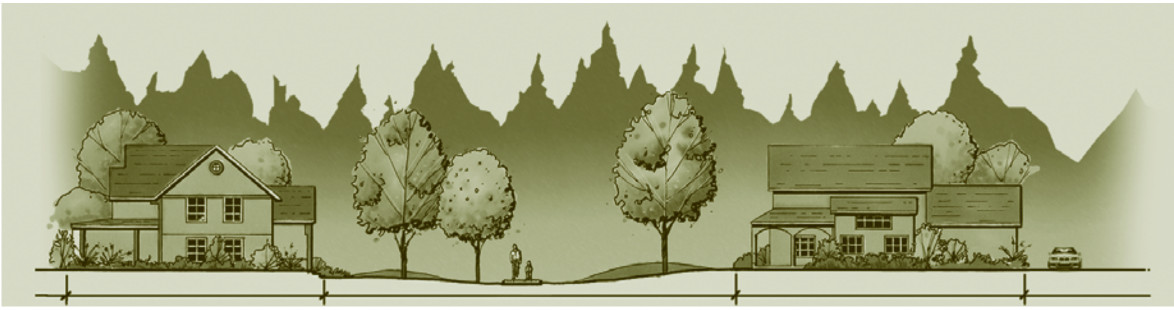
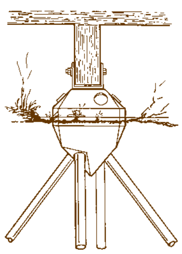


LOW IMPACT DEVELOPMENT

TECHNICAL GUIDANCE MANUAL FOR PUGET SOUND



JANUARY 2005

Puget Sound Action Team • Washington State University Pierce County Extension

LOW IMPACT DEVELOPMENT

TECHNICAL GUIDANCE MANUAL FOR PUGET SOUND

JANUARY 2005
[Revised May 2005]

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Permeable paver detail *(Gary Anderson)*.
Bioretention swale, Seattle *(Seattle Public Utilities)*.
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Table of Contents

Preface

Low impact development (LID) is a stormwater management strategy that emphasizes conservation and use of existing natural site features integrated with distributed, small-scale stormwater controls to more closely mimic natural hydrologic patterns in residential, commercial, and industrial settings.

Many of the tools used for LID are not new. Village Homes in Davis, California, constructed in the early 1970s, is perhaps the earliest recognized example of a residential subdivision that manages stormwater through open conveyance systems and provides storm flow retention in open space integrated throughout the development. During the early 1980's European cities began using distributed, integrated stormwater management practices to reduce flows from combined sewer systems. In the late 1980's, Larry Coffman with the Department of Environmental Resources in Prince George's County, Maryland began working on a plant, soil-microbe filter designed to mimic natural forest hydrologic characteristics (bioretention, or rain gardens). Today LID strategies are an integral part of Prince George's County's stormwater management approach and numerous developments across the U.S., Canada, and Europe include LID practices.

In Puget Sound, state and local government agencies and university extension programs have offered and continue to offer numerous workshops, conferences, and courses for engineers, planners, architects, and elected officials. These focus on the problems associated with stormwater runoff, the limitations of conventional management practices, and the LID approach to protect ground and surface waters. As a result of these efforts, several local governments and state agencies are incorporating LID techniques into their stormwater manuals, development regulations, and regional guidance. Many of the organizations are using LID techniques in commercial, residential, and municipal projects. The most active of these organizations include: the cities of Seattle, Olympia, and Bellingham; King, Snohomish, and Pierce counties; Washington departments of Ecology and Transportation; and the Puget Sound Action Team (Action Team).

Initial findings from limited monitoring in Puget Sound and other studies from the U.S., Europe, Canada, and Japan indicate that LID practices can be valuable tools to reduce the adverse effects of stormwater runoff on streams, lakes, wetlands, and Puget Sound. However, important questions remain regarding relative cost, design, maintenance, and long-term performance. To answer these questions and better understand the full potential and limitations of LID in the Puget Sound region, additional research and monitoring of individual LID techniques and pilot projects are needed.

Demonstration projects and monitoring are needed to understand the long-term performance and maintenance requirements of bioretention swales and cells, permeable paving, and other LID practices in difficult (and common) Puget Sound settings, such as native soils with low infiltration rates and higher urban densities. Pilot projects will also provide data comparing LID construction costs and market performance to conventional development and stormwater management strategies.

While uncertainties regarding LID exist, current data and the need for additional tools to manage stormwater runoff warrant initiating the next steps: (1) implement and monitor demonstration projects; (2) develop regulatory guidance for LID practices; and (3) remove local regulatory barriers that discourage use of LID strategies.

New stormwater management tools are needed to address a number of critical environmental issues facing Puget Sound. Chinook and chum salmon and bull trout are listed as threatened under the federal Endangered Species Act, and scientists have cited loss of habitat due to development and stormwater runoff as one factor that has contributed to their population declines. The Washington Department of Ecology (Ecology) estimates that about one-third of all polluted waters on the section 303(d) list are degraded because of stormwater runoff. Puget Sound is one of the best regions in the world to grow clams, oysters, and other shellfish, yet thousands of acres of shellfish growing areas are closed to harvest due to stormwater runoff and other pollutant sources. Finally, more than 70 smaller local governments in Puget Sound will soon be required to comply with a federally mandated stormwater permit under the National Pollutant Discharge Elimination System Program. Newly permitted local governments will be seeking stormwater management techniques that help them comply with permit conditions and protect surface waters in an efficient, cost-effective manner.

To better address these issues, two state offices have taken significant steps related to LID. Ecology, collaborating with local government stormwater managers and Washington State University, has completed initial guidelines for flow reduction credits when LID techniques are used in projects in western Washington. The credits, included in Ecology's 2005 *Stormwater Management Manual for Western Washington* and in Chapter 7 of this manual, will provide designers with additional tools to retain stormwater on-site and reduce the size of conventional facilities that control storm flows. The Action Team, the broad partnership to conserve and recover Puget Sound, has identified LID as a priority action for the 2001-03, 2003-05, and now the 2005-07 biennial work plans to the Washington State Legislature. This emphasis has produced a national conference, regional workshops, local technical and financial assistance, and special projects, including development of this technical guidance manual. The *Puget Sound Water Quality Management Plan*, the state and federal plan to protect and restore Puget Sound, also calls on all local governments in Puget Sound to adopt new or revise existing ordinances to allow and encourage LID techniques.

Purpose of this Manual

The purpose of this manual is to provide stormwater managers and site designers with a common understanding of LID goals, objectives, specifications for individual practices, and flow reduction credits that are applicable to the Puget Sound region.

In addition to the guidelines for specific practices, this manual provides research and data related to those practices to help managers and designers make informed decisions when adapting LID applications to their jurisdictions. Low impact development is a new and evolving management approach; accordingly, this document will evolve and be periodically updated as additional research becomes available and professionals in the region gain more practical experience. This is a technical manual and the information provided is targeted for engineers, planners, landscape architects, technical staff to policy makers, and developers.

How this Manual is Organized

Chapter one of the manual sets the context for the LID approach with an introduction to Puget Sound lowland hydrology and the effects of urban development on streams, wetlands, and Puget Sound. Chapter one also establishes the goals and objectives for LID. Chapters on site assessment, planning and layout, vegetation protection, and clearing and grading follow, and emphasize the importance of planning and protecting native vegetation and soils in the LID approach. Chapter six provides general guidance for six integrated management practices (IMPs), as well as detailed construction and material specifications for many of the IMPs. Chapter seven provides the new credits in the Western Washington Hydrology Model that will allow engineers to reduce the size of conventional flow control facilities when using LID practices. Finally, several appendices include sample specifications, lists of plants appropriate for LID applications, and tables summarizing bioretention and permeable paving research. Bolded words within the text of the manual are defined in the glossary of terms.

Low Impact Development Applications

The LID approach can be applied in a variety of settings including: large lots in rural areas; low, medium, and high-density development within urban growth boundaries; redevelopment of highly urbanized areas; and commercial and industrial development. LID applications can be designed for use on glacial outwash and alluvium soils, as well as soils with low infiltration rates, such as dense silt loams or till mantled areas.

1 Introduction

In this chapter...

- *Puget Sound hydrology*
- *Current stormwater management*
- *Impacts of urbanization*
- *Low impact development goals and objectives*

1.1 Puget Sound Hydrology

Native forests of the Puget Sound lowlands intercept, store, and slowly convey precipitation through complex pathways. Water budget studies of wet coniferous forests in western Washington, British Columbia, and the United Kingdom indicate that approximately 50 percent of the annual rainfall is intercepted by foliage and evaporated during the rainy season. Bauer and Mastin (1997) found that interception and evaporation from vegetation during the winter months (approximately 50 percent) far exceeded estimates for western Washington, and attributed the high rate to the large surface area provided by evergreen trees, relatively warm winter temperatures, and the advective evaporation of precipitation. Bidlake and Payne (2001) and Calder (1990) also found that the aerodynamically rough forest canopy and **advection energy** supported evaporation rates of intercepted precipitation that were higher than estimated radiation-based potential **evapotranspiration**.

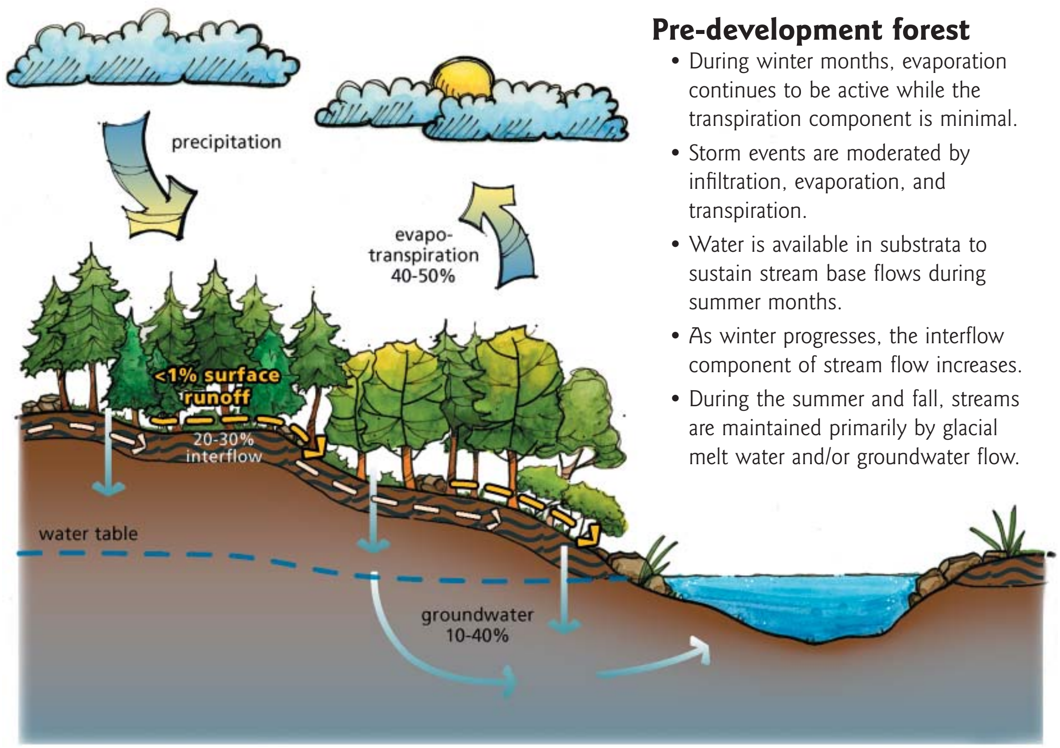
Water budget studies of wet coniferous forests in western Washington, British Columbia, and the United Kingdom indicate that approximately 50 percent of the annual rainfall is intercepted by foliage and evaporated during the rainy season.

Native soils also play a critical role in storage and conveyance of Pacific Northwest (PNW) rainfall. Typically, 2 to 4 feet of soil, high in organic material and biologically active near the surface, overlays the subsurface geology. Solar radiation and air movement provide energy to evaporate surface soil moisture that contributes to the overall evapotranspiration component. Soil biota and organic matter chemically and physically bind mineral particles into stable aggregates that build soil structure, increase soil porosity, and provide 20 to 30 percent of active water storage by volume. Shallow subsurface flow (interflow) moves slowly down slope or down gradient over many hours, days or weeks through these upper soil layers. Depending on the underlying soil type and structure, 10 to 40 percent of the annual precipitation moves to deeper groundwater (Bauer and Mastin, 1997).

For most storm events, the gentle rainfall intensities are less than the combined capacity of the interception loss, and vegetation and soil storage in native Puget Sound forests; as a result, overland flow does not occur or is minimal (Booth, Hartley and Jackson, 2002). Instead, the storm flow moves downslope below the surface at a much slower rate than overland flow and displaces antecedent, subsurface water in areas near streams, lakes and wetlands (Bauer and Mastin, 1997). The displaced soil water adjacent to water bodies contributes to stream flows or wetland and lake levels rather than the entire watershed. As storms and the wet season progress, available soil storage capacity declines and the saturated or contributing areas near receiving waters increase as does the response to storm events (Booth et al., 2002).

Figure 1.1 Water budget for pre-development Puget Sound lowland forests.

Graphic by AHBL Engineering



Pre-development forest

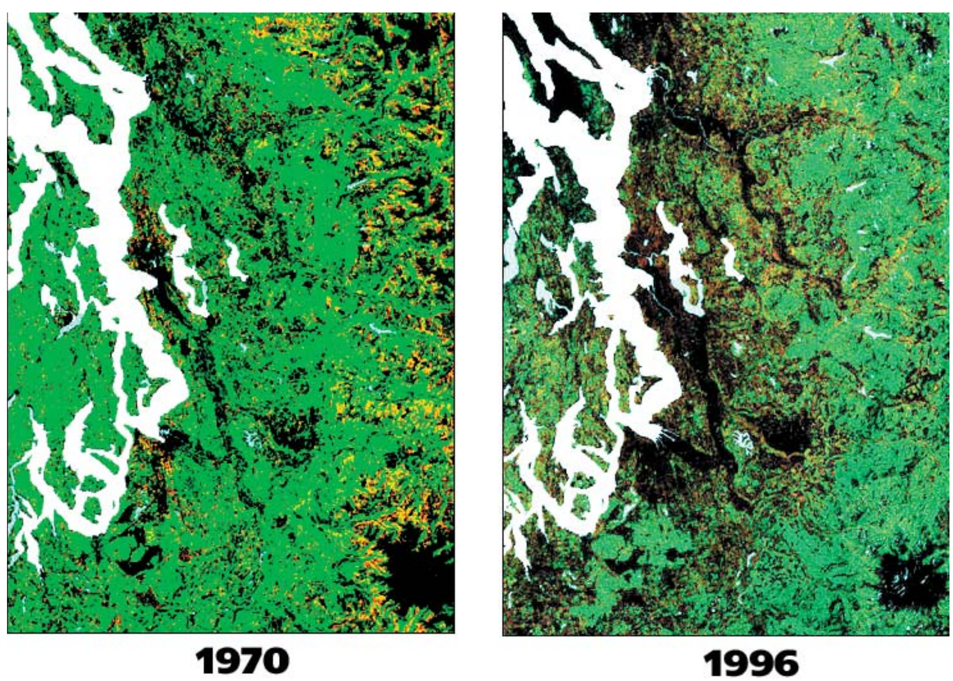
- During winter months, evaporation continues to be active while the transpiration component is minimal.
- Storm events are moderated by infiltration, evaporation, and transpiration.
- Water is available in substrata to sustain stream base flows during summer months.
- As winter progresses, the interflow component of stream flow increases.
- During the summer and fall, streams are maintained primarily by glacial melt water and/or groundwater flow.

1.2 Impacts of Urbanization

The transition from a native landscape to a built environment increases the impervious surface coverage of roads, parking areas, sidewalks, rooftops, and landscaping. These changes reduce, disrupt or entirely eliminate native vegetation, upper soil layers, shallow depressions, and native drainage patterns that intercept, evaporate, store, slowly convey, and infiltrate stormwater. As development progresses, the area in small watersheds that contribute overland flow to receiving waters in minutes increases while the area that stores and delivers subsurface flow over periods of hours, days or weeks diminishes (Booth et al., 2002).

Figure 1.2 Satellite images of Puget Sound in 1970 and 1996. (Dark color in lowlands areas indicates clearing of vegetation and development.)

Source: American Forests



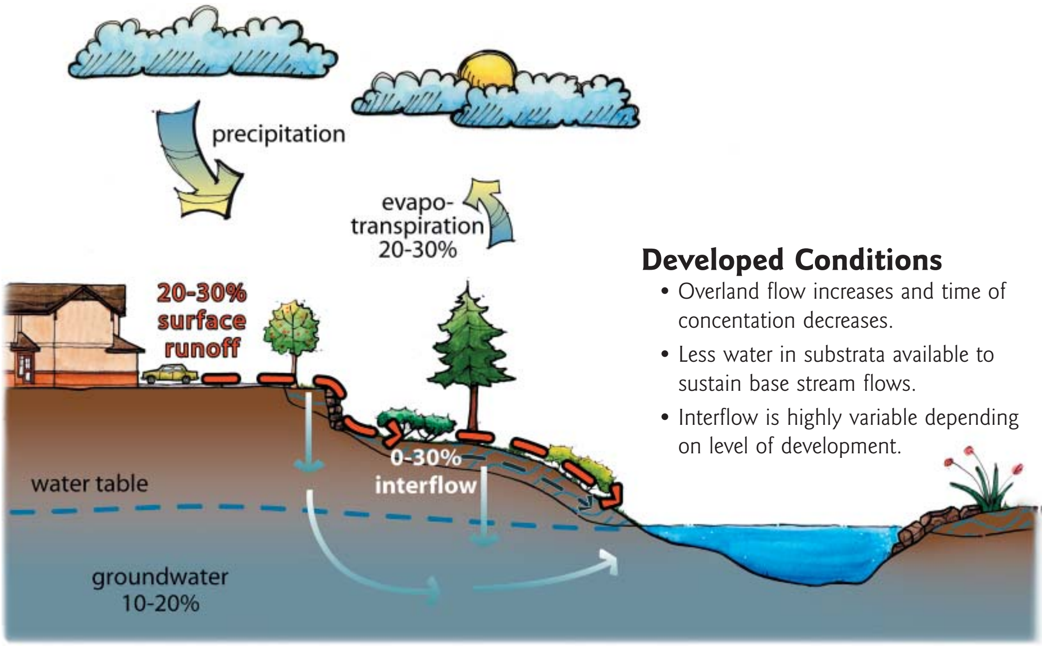


Figure 1.3 Water budget for typical suburban development in the Puget Sound lowlands.

Graphic by AHBL Engineering

Loss of native soils and vegetation within the watershed and associated changes in hydrologic regimes can significantly degrade stream habitat (Booth, 1991). **Bankful discharges**—the 1- to 1.5-year return storm flow that does much of the work to form a stream channel—increase in magnitude and frequency (Center for Watershed Protection [CWP], 2000a). Typical responses in streams exposed to high flows for longer periods of time include: excessive streambed and stream bank instability (May, Horner, Karr, Mar, and Welch, 1997); increased stream channel cross-sectional area (typically, cross sectional area is enlarged 2 to 5 times depending on the amount of total impervious area and other development factors (CWP, 2000a and March 2000); and overall loss of habitat structure, and hydraulic diversity (Booth, 1991). While water quality conditions (as defined by dissolved oxygen, temperature, sediment, various pollutant concentrations, and other parameters) are critical considerations for managing stream health, altered watershed hydrologic regimes and associated channel instability are a leading cause for in-stream physical habitat degradation and initial loss of **biotic integrity** (May et al., 1997).

Altered watershed hydrologic regimes and associated channel instability are a leading cause for in-stream physical habitat degradation and initial loss of biotic integrity.

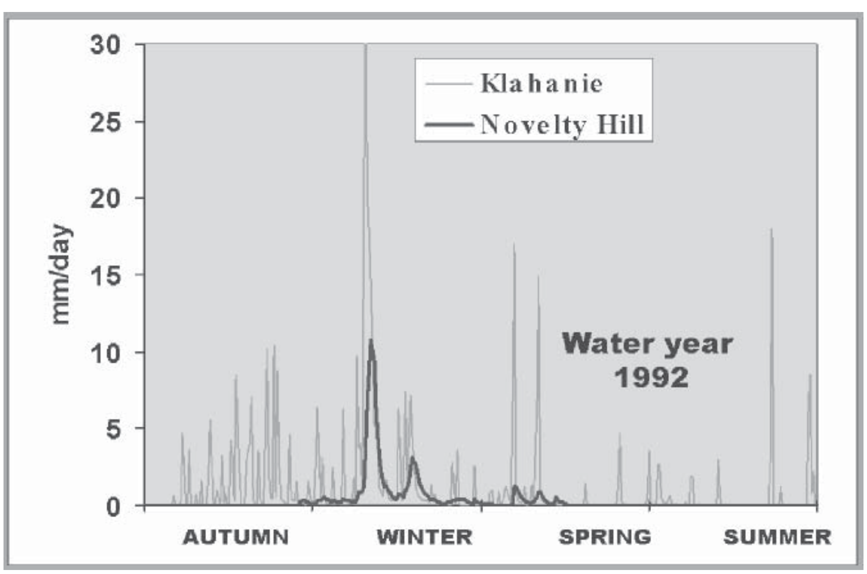


Figure 1.4 Hydrograph for an urban (Klahanie) and a rural watershed (Novelty Hill) in the Puget Sound lowlands. Storm flows increase in magnitude and frequency in the urban watershed.

Source: 'Hydrological Effects of Land-use Change in a Zero-order Catchment.'

Burges, Wigmosta and Meema, 1998. Journal of Hydrologic Engineering. *Material reproduced with permission from the American Society of Civil Engineers.*

Figure 1.5 Down-cut stream channel resulting from increased storm flow generated by nearby development (Gig Harbor Peninsula).

Photo courtesy of Hans Hunger

Streams respond to watershed urbanization through several other important mechanisms as outlined in Table 1.1 (MacCoy and Black, 1998; May et al., 1997; Staubitz, Bortleson, Semans, Tesoriero, and Black 1997; and Washington Department of Ecology [Ecology], 1999).

Table 1.1 Degradation of watershed conditions and stream response.

Change in watershed condition	**Response**
Increased drainage density due to road networks, road crossings and stormwater outfalls	Increased storm flow volume and frequency, and channel erosion Increased fine sediment and urban water pollutant loads Increased fish passage barriers
Increased fine sediment deposition	Reduced intergravel dissolved oxygen levels in streambed Loss of salmonid spawning and macroinvertebrate habitat
Loss or fragmentation of riparian areas	Reduced delivery of large woody debris Reduced bank stability and loss of bank habitat structure and complexity Reduced shading and temperature control
Reduced quantity and quality of large woody debris	Reduced channel stability, sediment storage, instream cover for fish and insects, loss of pool quality and quantity
Increased pollutant loads	Synthetic organic compounds and trace elements: some acutely toxic; tumors in fish; salmon and trout will alter spawning and migration behavior in presence of metals as low as <1% of lethal concentration; **endocrine disruptors** (18 of 45 suspected endocrine disrupting trace elements found in Puget Sound fish tissue) Nutrients: excessive aquatic plant growth; excessive **diurnal oxygen fluctuations** Synergistic influence of multiple pollutants unknown

The cumulative impact of hydrologic alteration and the various other changes in watershed conditions can result in channel instability and degraded biotic integrity at low or typically rural levels of watershed development. Studies conducting empirical stream assessments observed physical degradation of channels with **effective impervious area** (EIA) percentages of less than 10 percent within the contributing watersheds (Booth et al., 2002). While impervious surface coverage generally is low at this density, forest clearing for pasture, lawns and hobby farms can be extensive across the rural landscape. Hydrologic analysis of the same watersheds (see Figure 1.6) observed the same relationship between low levels of imperviousness, changes in modeled stream flows (recurrence of pre-developed forest and developed flows), and stream channel stability. Booth, Hartley and Jackson (2002) note that observed channel instability is a relatively insensitive evaluation tool and the lack of observed degradation does not guarantee the absence of subtle, but important consequences for the physical or biologic health of streams.

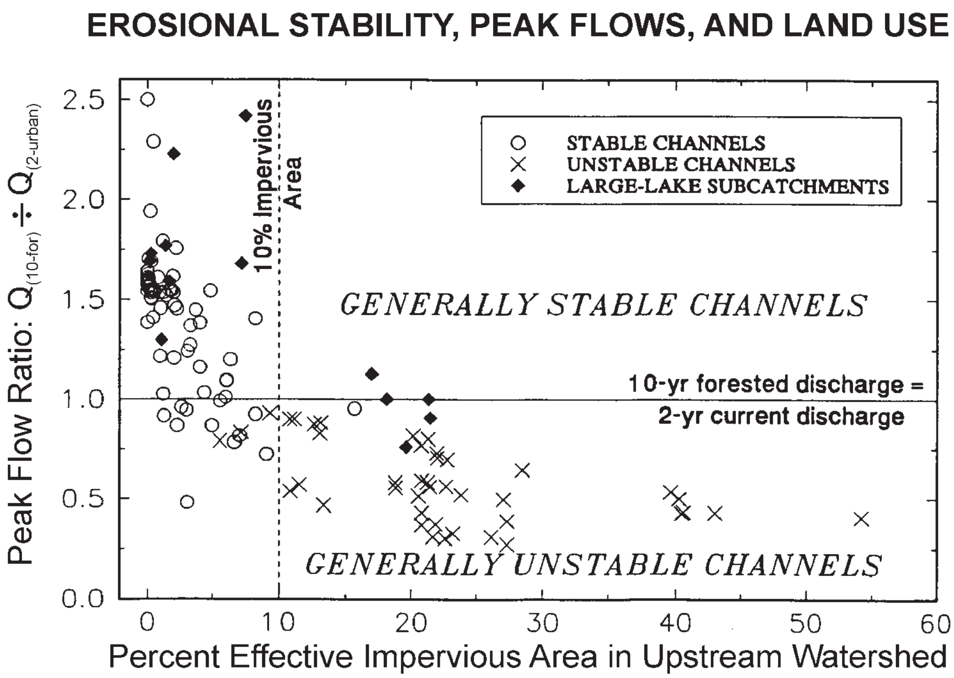


Figure 1.6 Observed stable and unstable stream channels in the Puget Sound lowlands plotted by percent EIA and ratio of modeled 10-year forested and 2-year urbanized discharges. Stable channels in this study consistently meet the apparent thresholds of EIA <10% and $Q_{(2\text{-urban})} \leq Q_{(10\text{-forest})}$ (Booth et al., 2002).

Graph courtesy of Booth and Jackson, 1997

The physical and chemical composition of wetlands and lakes are altered in response to land development as well. Typically, water levels in wetlands gradually rise in the beginning of the wet season and then subside slowly as the wet season ends. Wetland plant species have adapted to this fairly narrow and stable range of water depths and soil saturation (CWP, January 2000c). As development proceeds and impervious surfaces replace native vegetation and soils, water levels can rise rapidly in response to individual storms. A major finding in the Puget Sound Wetlands and Stormwater Management Program was that "hydrologic changes were having more immediate and measurable effects on composition of vegetation and amphibian communities than other conditions [monitored]" (Azous and Horner, 2001). Decline in wetland plant and amphibian species richness are likely when:

- Mean annual water level fluctuations exceed 20 centimeters per year.
- The frequency of **stage excursions** of 15 cm above or below pre-development condition exceeds an annual average of six.
- The duration of stage excursions of 15 cm above or below pre-development condition exceeds 72 hours per excursion.

- The total dry period (when pools dry down to the soil surface everywhere in the wetland) increases or decreases by more than two weeks in any year (Azous and Horner, 2001).
- Increased water level fluctuations occur early in the growing season (CWP, January 2000c).

Increased water level fluctuations of this nature are observed when total impervious area within the drainage area exceeds 10 to 15 percent (Taylor, 1993).

Lakes and estuaries, while not as prone to morphological change due to altered hydrology, are highly susceptible to shoreline modifications and water quality degradation from urbanization. Phosphorus, bacteria and sediment are typical urban stormwater pollutants impacting lakes. Phosphorus is often a limiting nutrient in fresh water systems, and contributes to increased plant growth and diurnal oxygen level fluctuations that degrade wildlife habitat, recreational opportunities and other beneficial uses.

Bacteria can restrict or close shellfish growing areas in Puget Sound to harvest. Nonpoint source pollution (including stormwater runoff) is now "the most common cause of shellfish classification downgrades in Puget Sound, reducing the region's commercially approved acreage by approximately 25 percent since 1980" (PSAT, 2004). Toxic pollutants associated with stormwater sediments (e.g., heavy metals and polycyclic aromatic hydrocarbons) that settle in urban estuaries and near shore areas have contributed to the listing of several urban bays as Superfund (federal) or Model Toxic Control Act (state) clean-up sites.

1.3 Current Stormwater Management

Conventional tools to manage stormwater are mitigation-based and flood-control focused. This strategy emphasizes the efficient collection and rapid conveyance of runoff from residential and commercial development to central control ponds. Several factors have led to the implementation and continuation of this approach: stormwater has been perceived as a liability and applications have evolved from wastewater technology; hard conveyance structures and central control ponds are considered reliable and relatively simple to maintain; the conveyance and collection approach is relatively simple to model for regulatory requirements; and construction costs are readily estimated.

Conventional tools to manage stormwater are mitigation-based and flood-control focused.

Newer conveyance and pond strategies, if properly designed and maintained, can match modeled pre-development peak flows and runoff rates discharged from development sites; however, a number of problems will continue to challenge current management strategies. These include:

- *Peak and volume control*. Typical residential and commercial development practice in the Puget Sound removes most, if not all, vegetation and topsoil. Suburban development in the region is estimated to have 90 percent less stormwater storage than the native forested condition, and BMP applications (circa 1994) are estimated to recover approximately 25 percent of that storage (May et al., 1997). Without infiltration, excess volume generated above the onsite storage capacity is released to receiving waters. If flows exceed **critical shear stresses,** stream channels are exposed to excessive erosion over prolonged periods (Booth et al., 2002). (See Figure 1.7 for graphic representation of actual storage needed to replace loss of native soil and vegetation.)

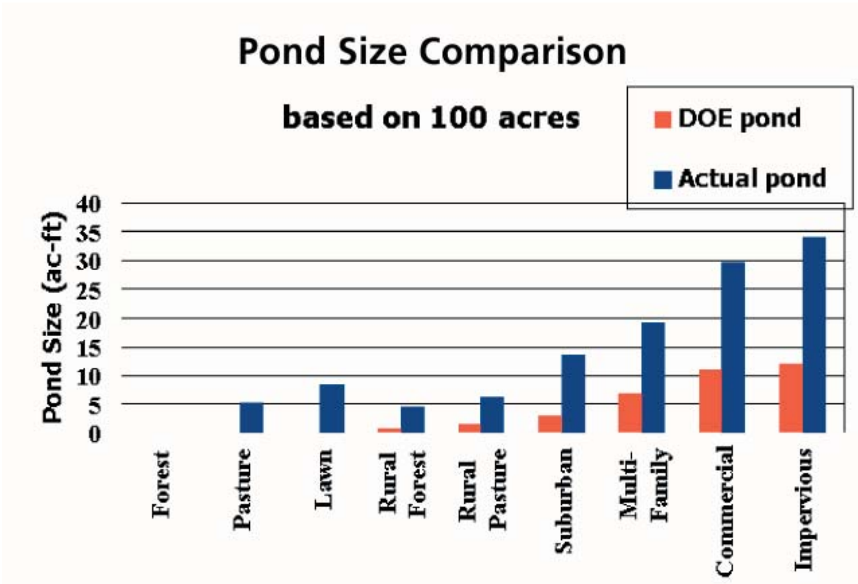


Figure 1.7 Storage required to meet Washington State Department of Ecology's stormwater management requirement (DOE Pond) and actual storage needed (actual pond) to replace loss of native soil and vegetation storage on a 100-acre site.

Source: Beyerlein, 1999.

- *Spatial Distribution*. Conventional management converts spatially distributed subsurface flows to point discharges. No analysis is currently available that focuses on the larger hydrologic impacts of this transition; however, locally severe erosion, disturbed riparian habitat, and degraded in-stream habitat can result at point discharge locations (Booth et al., 2002).
- *Density and Market Implications*. Duration-control design standards in Washington Department of Ecology's (Ecology) 2005 *Stormwater Management Manual for Western Washington* will require larger ponds. As a larger percentage of land is designated for stormwater management within the development, stormwater infrastructure costs will increase and the number of buildable lots will likely decrease.

1.4 Low Impact Development

The conventional, purely structural approach to manage stormwater runoff has limitations for recovering adequate storage and spatially distributed flow paths necessary to more closely approximate pre-development hydrologic function and protect aquatic resources from adverse effects of development. Low impact development (LID) principles and applications present a significant conceptual shift from a purely structural approach. LID is primarily a source reduction approach. Site planning and stormwater management are integrated at the initial design phases of a project to maintain a more **hydrologically functional landscape**. Hydrology and natural site features that influence water movement guide road, structure, and other infrastructure layout. Native soil and vegetation protection areas and landscaping that are strategically distributed throughout the project to slow, store, and infiltrate storm flows are designed into the project as amenities, as well as hydrologic controls.

Pre-development or natural hydrologic function is the relationship among the overland and subsurface flow, infiltration, storage, and evapotranspiration characteristics of the forested landscape predominant in the Puget Sound lowland (see Section 1.1). Low impact development strategies focus on evaporating, transpiring, and infiltrating stormwater on-site through native soils, vegetation, and bioengineering applications to reduce and treat overland flow that is characteristically negligible in the forested setting.

Low Impact Development defined

Low impact development is a stormwater management and land development strategy applied at the parcel and subdivision scale that emphasizes conservation and use of on-site natural features integrated with engineered, small-scale hydrologic controls to more closely mimic pre-development hydrologic functions.

1.4.1 The Goal of Low Impact Development

The goal of LID is to prevent measurable harm to streams, lakes, wetlands, and other natural aquatic systems from commercial, residential, or industrial development sites. The impact to receiving waters (and determining if a project has achieved the above goal) is estimated by hydrologic models and measured by monitoring surface and ground water quality and quantity, and biological health.

1.4.2 Flow Control Objective

The primary stormwater management objective for LID is to match pre-development forested hydrologic condition (or prairie condition if historic records indicate that as the native setting) over the full range of rainfall intensities and durations.

1.4.3 Flow Control Objective Discussion

Maintaining the pre-development hydrologic regime cannot be achieved everywhere or at all times given current development practices. The hydrologic system of our region evolved from, and is dependent on, the characteristics of undisturbed Pacific Northwest watersheds—mature forest canopy, uncompacted soils, ungullied hillslopes—and cannot be expected to have the same hydrologic regime when significant portions of a site are disturbed. The objectives of any given low impact development, therefore, must be strategically chosen, recognizing both the opportunities and the limitations of any given site. Regulatory requirements, typical zoning and housing types, and costs of sophisticated control technology required on sites with poor soils and higher densities, as well as site topography, soil permeability and depth, and groundwater movement create significant challenges for reducing or eliminating hydrologic impacts from development sites. These challenges are likely to be most prominent during periods of extended rainfall, where the distributed on-site infiltration reservoirs common to most LID designs will experience their highest water levels and approach, or reach, full saturation.

Initial monitoring in the Puget Sound region suggests that LID strategies can be effective for maintaining pre-development hydrologic condition for light to moderate storm events typical of a maritime climate (Horner, Lim and Burges, 2002). Effectiveness in mimicking pre-development hydrology for large storms and during extended wet periods is not well documented. On difficult sites with low infiltration rates and higher densities, additional storage using conventional retention or detention pond facilities may be necessary in concert with LID strategies. Properly designed and implemented LID applications will, however, significantly reduce pond size requirements (Derry, Butchart and Graham, 2004 and Horner et al., 2002).

Properly designed and implemented LID applications will significantly reduce the size requirements of ponds.

1.4.3.1 Rural setting

Empirical data coupled with hydrologic modeling analysis, at the watershed scale, suggest that retaining 65 percent mature forest cover is necessary to mimic pre-development hydrologic conditions and maintain stable stream channels on moderately sloping till soils and typical rural development settings (EIA 3 to 5 percent). While this is an estimate of complex hydrologic processes, the 65 percent cover is a defensible target for forest protection in rural densities (see Figure 1.8) (Booth et al., 2002).

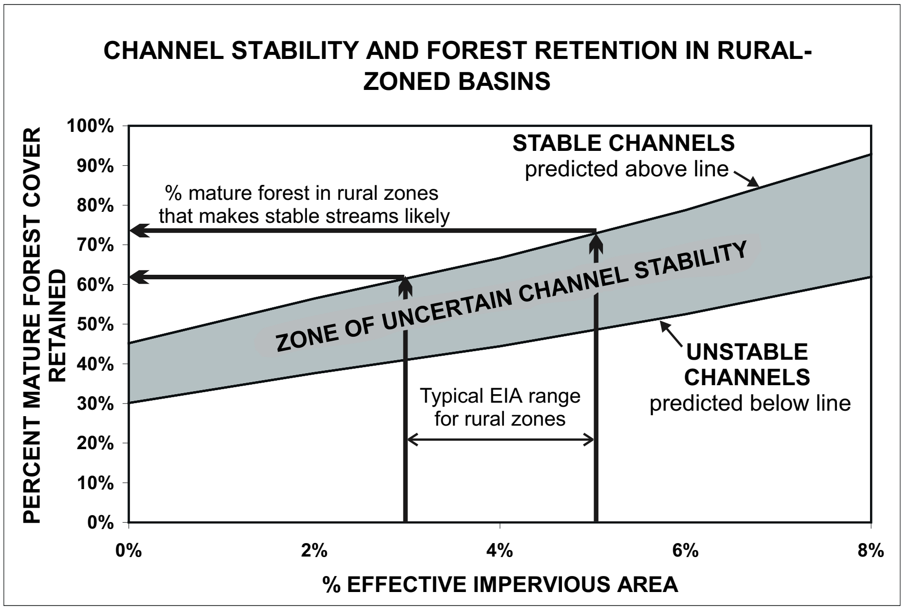


Figure 1.8 Modeled channel stablity plotted by percent forest cover retained and percent EIA (Booth et al., 2002).

Forested glacial outwash soils produce less overland flow than forested till soil conditions during storm events. As a result, forest clearing and increased impervious surface coverage can produce relatively larger peak-flows and increases in volume on outwash soils without adequate infiltration practices (Booth et al., 2002). The impact of concentrating infiltration facilities at a single location on outwash soils is not known; however, shallow subsurface flows may alter hydrologic characteristics if the development and facility are located proximate to a headwater stream.

Stormwater pollutant treatment is required when infiltrating stormwater on outwash soils from pollution generating surfaces (Washington Department of Ecology [Ecology], 2001). Processing pollutants in a facility that collects storm flows from an entire development can significantly increase infrastructure requirements and costs. Accordingly, 65 percent native soil and vegetation protection and *application of dispersed LID infiltration practices* is recommended for protecting stream and wetland habitat in the forested outwash soil and the rural setting.

1.4.3.2 Medium and high-density settings (6 or more dwelling units per acre)

The 65 percent target for mature native vegetation coverage may be achievable in medium and high-density settings by applying multifamily, cottage, or condominium type development. Sixty-five percent native vegetation and soil protection is not feasible with conventional single family detached housing at such densities. In the higher density setting, *comprehensive application of LID practices* is necessary to reduce the hydrologic changes and pollutant loads to surface and ground waters where less forest protection area is possible (see Chapter 3: Site Planning and Layout for design strategies).

Initial research modeling experimental, medium-density, residential LID designs indicates that pre-development hydrologic conditions may be approximated on soils with low infiltration rates when using the full suite of LID practices and 40 to 50 percent open space protection (CH2M HILL, 2001). In this difficult type of development scenario it is essential to apply a full complement of LID practices. Soil enhancement, bioretention, open conveyance, dispersion to open space, minimal excavation foundation systems, aggregate storage under paving, and roof water harvesting techniques must be integrated into the design to minimize hydrologic impacts. Eliminating the roof water contribution through roof water harvesting systems is essential for achieving the LID flow objective where higher density projects are located on soils with low infiltration rates.

1.4.4 Flow Control Objective and Department of Ecology's *Stormwater Management Manual for Western Washington*

This document or the flow control objective recommended in this manual does not supercede Ecology's 2005 *Stormwater Management Manual for Western Washington*. Where the Ecology manual is adopted, the minimum flow control standard for new development will be required to match 50 percent of the two-year event up to the full 50-year peak flows for a pre-developed forested condition (or prairie conditions if historic records indicate that as the native setting).

1.4.5 Site Design and Management Strategies to Meet Flow Control Objectives

The goal and flow control objective for LID are achieved through the following site design objectives. The objectives are grouped into four basic elements that constitute a complete LID design.

Conservation measures

- Maximize retention of native forest cover and restore disturbed vegetation to intercept, evaporate, and transpire precipitation.
- Preserve permeable, native soil and enhance disturbed soils to store and infiltrate storm flows.
- Retain and incorporate topographic site features that slow, store, and infiltrate stormwater.
- Retain and incorporate natural drainage features and patterns.

Site planning and minimization techniques

- Utilize a multidisciplinary approach that includes planners, engineers, landscape architects and architects at the initial phases of the project.
- Locate buildings and roads away from critical areas and soils that provide effective infiltration.
- Minimize total impervious surface area and eliminate effective impervious surfaces.

Distributed and integrated management practices

- Manage stormwater as close to its origin as possible by utilizing small scale, distributed hydrologic controls.
- Create a hydrologically rough landscape that slows storm flows and increases **time of concentration.**
- Increase reliability of the stormwater management system by providing multiple or redundant LID flow control practices.
- Integrate stormwater controls into the development design and utilize the controls as amenities—create a multifunctional landscape.
- Reduce the reliance on traditional conveyance and pond technologies.

Maintenance and Education

- Develop reliable and long-term maintenance programs with clear and enforceable guidelines.

- Educate LID project homeowners and landscape management personnel on the operation and maintenance of LID systems and promote community participation in the protection of those systems and receiving waters.

Subsequent sections of the manual–Chapter 3: Site Planning and Layout; Chapter 4: Vegetation Protection, Reforestation and Maintenance; Chapter 5: Site Clearing and Grading; Chapter 6: Integrated Management Practices; and Chapter 7: Flow Modeling Guidance–will provide information on low impact development tools and techniques that can be used to meet the objectives and strategies listed above. The manual outlines many of the tools available for designing a low impact development system, but it does not provide an exhaustive list of practices. The LID approach is creative and designers must consider the attributes of individual sites in the context of the local jurisdiction and community setting. Designers should apply sound science, an interdisciplinary approach and, at times, unique applications to meet LID goals and objectives. See Table 1.2 for a list of some LID techniques.

Table 1.2 LID techniques (checked items are examined in this manual).

X	Site assessment	X	Maintenance		Downspout dispersion
X	Site planning and design	X	Amending construction site soils	X	Roof stormwater harvesting systems
X	Site phasing and fingerprinting	X	Permeable asphalt		Filter strips
X	Preserving native soils and vegetation	X	Permeable concrete		Media filtration
X	Clearing and grading	X	Permeable gravel pave systems		
X	Bioretention cells	X	Permeable pavers		
X	Sloped biodetention	X	Vegetated roofs		
X	Bioretention swales	X	Minimal excavation foundations		
	Tree box filters		Homeowner education		

While the focus of low impact development and this manual is to more effectively manage stormwater, LID can and should address other livability issues including:

- Residential road design that reduces traffic speeds and promotes walking and biking as alternative transportation methods.
- Development at appropriate densities that meets Growth Management Act goals, and increases access to, and connection between, public transportation modes.
- Subdivision layout and building design that promote interaction between neighbors and the connection to open space and recreation areas.

1.4.6 Low Impact Development in the Watershed Context

LID is a tool for retrofitting existing or constructing new commercial and residential development at the parcel and subdivision scale. Maintaining aquatic habitat, water quality, species of special concern, and healthy aquatic systems in general requires protection or restoration of processes (for example the movement of water and recruitment of large woody debris) and structures (forest canopy, soils, etc.) at the sub-watershed, watershed or regional scale.

To protect high quality, sensitive stream systems the following critical area designations and associated land use controls are necessary:

- Extensive and near continuous riparian buffer protection.
- Floodplain protection.
- Aggressive native forest and soil protection.
- Limit EIA to approximately 10 percent.

(Horner, May, Livingston, Blaha, Scoggins, Tims, Maxted, 2001 and May et al., 1997)

Where higher levels of EIA and development exist or are proposed and ecological function is good or impaired (but not entirely lost), several strategies can be employed for protection and enhancement including, but not limited to: forest and soil restoration; comprehensive drainage design addressing cumulative impacts and implementing regional stormwater control facilities; and other mitigation and enhancement measures (May et al., 1997).

To improve sub-watershed or regional scale ecosystem functions, basin assessments must evaluate the quality and sensitivity of resources, and the cumulative impacts of existing development, future growth and other activities in sub-watersheds. Through the assessment and planning process, managers should set priorities for resource protection for sub-watersheds based on resource sensitivity and growth pressures. Various landscape analysis tools are available that allow managers to assign appropriate densities and types of development based on the projected cumulative impacts of different land use scenarios.

1.4.7 Low Impact Development and Comprehensive Stormwater Management

LID does not compensate for the cumulative and adverse effects from road networks and other land clearing activities that occur outside the development site. Low impact development can, however, be used in the various sub-basin development scenarios to help achieve larger-scale, sub-watershed protection goals. Implemented comprehensively, native soil and vegetation protection, soil improvement, and increased on-site storage and infiltration capacity at the site level are necessary to protect or enhance larger-scale hydrologic function and other watershed attributes.

While LID works with and supports the effective implementation of regional stormwater management plans and land use planning under the Growth Management Act, it is not a substitute for these local government responsibilities. The use of LID techniques should be part of a local, comprehensive stormwater management program that includes:

- Adoption and use of Ecology’s 2005 *Stormwater Management Manual for Western Washington* (or an alternative manual that is technically equivalent).
- Regular inspections of construction sites.
- Maintenance of temporary and permanent facilities.
- Source control.
- Elimination of illicit discharges.
- Identification and ranking of existing stormwater problems.
- Public education and involvement.
- Watershed or basin planning.
- Stable funding.
- Programmatic and environmental monitoring.

(Puget Sound Action Team, 2000)

2 Site Assessment

In this chapter...

Inventory and assessment of:

- *Soil analysis*
- *Hydrologic patterns and features*
- *Native forest and soil conservation areas*
- *Wetlands*
- *Riparian areas*
- *Floodplains*

Comprehensive inventory and assessment of on-site and adjacent off-site conditions are the initial steps for implementing low impact development (LID). The inventory and assessment process provides information necessary to implement the site planning and layout activities (examined in the next chapter) by identifying the current and estimating the pre-disturbance conditions. Specifically, the site assessment process should evaluate hydrology, topography, soils, vegetation, and water features to identify how stormwater moves through the site prior to development. The site design should align roads, lots, and structures and implement construction practices to preserve and utilize these features to retain natural hydrologic functions. In almost all cases, low impact development requires on-site inventory and assessment and cannot be properly planned and implemented through map reconnaissance alone.

> *The site assessment process should evaluate hydrology, topography, soils, vegetation, and water features to identify how stormwater moves through the site prior to development.*

Jurisdictions in the Puget Sound region have various requirements for identification and assessment of site characteristics and site plan development. Some or all of the following existing conditions are included by most local governments for identification and evaluation:

Geotechnical/soils	Streams	Wetlands
Floodplains	Lakes	Closed depressions
Springs/seeps	Other minor drainage features	Groundwater
Existing hydrologic patterns	Slope stability and protection	Geology
Habitat conservation areas	Aquifer recharge areas	Topography
Vegetation/forest cover	Anadromous fisheries impacts	Existing development
Erosion hazard areas	Offsite basin and drainage	Down-stream analysis

(King County, 1998; Washington State Department of Community, Trade and Economic Development, 2003; and Washington State Department of Ecology, 2001)

Inventory and evaluation to successfully implement an LID project will include some or all of the above existing conditions depending on the physical setting and regulatory requirements; however, the objective of the analysis and the level of detail necessary may vary. This section presents six steps in the LID site evaluation process that are essential and will likely require more focused attention than in a conventional project. Management recommendations for wetlands, riparian management areas, and floodplains are provided at the end of each evaluation step. Management recommendations for soils, hydrologic features, and native soil and vegetation protection areas are provided in subsequent chapters focusing on those issues.

2.1 Soil Analysis

LID requires detailed understanding of site soils. In-depth soil analyses in appropriate locations are often necessary to determine operating infiltration rates for two primary reasons: (1) LID emphasizes evaporation, storage, and infiltration of stormwater in smaller-scale facilities distributed throughout the site; and (2) on sites with mixed soil types, the LID site plan should locate impervious areas over less permeable soils and preserve and utilize permeable soils for infiltration.

2.1.1 Inventory and Assessment

Methods recommended for determining infiltration rates fall into two categories:

- Texture or grain size analysis using U.S. Department of Agriculture (USDA) Soil Textural Classification (Rawls survey) or ASTM D422 Gradation Testing at Full Scale Infiltration Facilities.
- In-situ infiltration measurements using a Pilot Infiltration Test, small-scale test infiltration pits (septic test pits), and groundwater monitoring wells.

Grain size analysis and infiltration tests present important but incomplete information. Soil stratigraphy should also be assessed for low permeability layers, highly permeable sand/gravel layers, depth to groundwater, and other soil structure variability necessary to assess subsurface flow patterns. Soil characterization for each soil unit (soil strata with the same texture, color, density, compaction, consolidation and permeability) should include:

- Grain size distribution.
- Textural class.
- Percent clay content.
- Cation exchange capacity.
- Color/mottling.
- Variations and nature of stratification.

(Ecology, 2001)

A few strategically placed soil test pits are generally adequate for initial site assessment. Pit locations are determined by topography, estimated soil type, hydrologic characteristics, and other site features. Consult a geotechnical engineer or soil scientist for initial assessment and soil pit recommendations.

A more detailed soil pit assessment is necessary once the preliminary site layout with location of LID stormwater controls is determined. Specific recommendations for assessing infiltration rates for bioretention areas and permeable paving installations are located in sections 6.1: Bioretention Areas and 6.3: Permeable Paving.

For management of on-site soils, see Section 6.2: Amending Construction Site Soils.

Assessing highly permeable gravel conditions

Special considerations are necessary for areas with highly permeable gravel. Signs of high groundwater will likely not be present in gravel lacking finer grain material such as sand and silt. Test pit and monitoring wells may not show high groundwater levels during low precipitation years. Accordingly, sound professional judgment, considering these factors and water quality treatment needs, is required to design multiple and dispersed infiltration facilities on sites with gravel deposits *(personal communication, Larry West, January 2004).*

2.2 Hydrologic Patterns and Features

Hydrology is a central design element that is integrated into the LID process at the initial site assessment and planning phase. Using hydrology as a design element begins by identifying and maintaining on-site hydrologic processes, patterns, and physical features (streams, wetlands, native soils and vegetation, etc.) that influence those patterns.

2.2.1 Inventory and Assessment

In addition to identifying prominent hydrologic features, additional analysis will likely be required to adequately assess water movement over and through the site including:

- Identify and map minor hydrologic features including seeps, springs, closed depression areas, and drainage swales.
- Identify and map surface flow patterns during wet periods, and identify signs of duration and energy of storm flows including vegetation composition, and erosion and deposition patterns.
- If seasonally high groundwater is suspected and if soil test pits do not provide sufficient information to determine depth to groundwater, map groundwater table height and subsurface flow patterns in infiltration and dispersion areas using shallow monitoring wells. Note: in many sites, shallow hand-augured monitoring wells can be installed at low cost.

The conservation and use of on-site native soil and vegetation for stormwater management is a central principle for an LID design.

For management of on-site hydrologic features see Section 1.4.5: Site Design and Management Strategies, Section 2.5: Riparian Management Areas, Chapter 3: Site Planning and Layout, and Chapter 5: Clearing and Grading.

2.3 Native Forest and Soil Conservation Areas

The conservation and use of on-site native soil and vegetation for stormwater management is a central principle of LID design. Protecting these features accomplishes three objectives: (1) reducing total impervious area; (2) increasing stormwater storage, infiltration, and evaporation; and (3) providing potential dispersion areas for stormwater. In addition to maintaining natural hydrologic processes, forest protection can provide other benefits including critical habitat buffers, open space, and recreation opportunity.

2.3.1 Inventory and Assessment

The following are steps to conduct a basic inventory and assessment of the function and value of on-site native vegetation:

- Identify any forest areas on the site and identify species and condition of ground cover and shrub layer, as well as tree species, **seral stage**, and canopy cover.
- Identify underlying soils utilizing soil pits and soil grain analysis to assess infiltration capacity. See Soil Analysis section above and consult a geotechnical engineer for site-specific analysis recommendations.

Soil surveys and vegetation surveys are necessary to determine baseline conditions, establish long-term management strategies, and determine appropriate application of dispersion techniques if stormwater is directed to the protection area.

For management of native vegetation and soil protection areas see Chapter 4: Vegetation Protection, Reforestation and Maintenance.

2.4 Wetlands

Determining appropriate assessment and management protocols for wetlands requires clear goals and objectives, as well as estimates of pre-development and evaluation of current conditions. Appropriate goals and objectives are determined through

Steep slope and shoreline bluff considerations

Special care must be taken when developing on or near steep slopes, including coastal bluffs, especially those composed of layers of unconsolidated glacial sediment that occur in many areas of Puget Sound. Clearing of vegetation, increasing surface runoff, and hydraulic loading through infiltration of surface runoff can destabilize these areas, and in some cases lead to dramatic slope failures. A detailed analysis of the site's geology and hydrology should be prepared by a qualified professional prior to site clearing and development.

the development application process and involve government permitting entities, consultants, and the developer. Core assessment and management objectives for a project that is in a drainage basin with a wetland designated as high quality and sensitive should include: (1) protect native riparian vegetation and soils; (2) protect diverse native wetland habitat characteristics to support the native assemblage of wetland biota; and (3) maintain or approximate pre-development hydrology and **hydroperiod** within the wetland. Note: Washington State Department of Ecology (Ecology) guidance includes Category 1 or 2 wetlands and Category 3 wetlands that meet most of the criteria in Appendix 1-D of Ecology's 2005 *Stormwater Management Manual for Western Washington* (SMMWW) as high quality and sensitive. If the project is within the drainage area for a wetland that can be considered for structural or hydrological modification then the development may incorporate use of the wetland into the stormwater management strategy. Ecology recommends use of criteria in the 2005 SMMWW Appendix 1-D page D-10 for wetland assessment guidelines.

2.4.1 Inventory and Assessment

The following steps should be used as a starting point to adequately inventory and provide an assessment of wetlands:

- Identify wetland category using local jurisdiction regulations and/or Ecology's *Washington State Wetlands Rating System for Western Washington.*
- If the wetland qualifies for protection:
    - o Measure existing hydroperiods and estimate future hydroperiods resulting from the proposed development.
    - o Identify hydrologic pathways into and out of wetland.
    - o Determine whether the wetland has breeding, native amphibians (conduct survey in spring).

2.4.2 Management

- If the wetland qualifies for protection, utilize LID strategies to increase stormwater infiltration and storage on the project site in order to meet the following guidelines (Azous and Horner, 2001):
    - o The increase or decrease of the pre-development mean monthly water level fluctuations should be maintained to less than 5 inches.
    - o The increase or decrease of 6 inches or more to the pre-development water level fluctuation should be restricted to less than 6 times during an average year.
    - o The duration of stage excursions of 6 inches or more above or below the pre-development water level fluctuations should not exceed 72 hours per excursion.
    - o Total dry period (when pools dry down to the soil surface everywhere in the wetland) should not increase or decrease by more than two weeks in any year.
    - o For priority peat wetlands, the duration of stage excursions above or below the pre-development water level fluctuations should not exceed 24 hours in a year.
    - o For wetlands inhabited by breeding amphibians, increases or decreases in pre-development water level fluctuations should not exceed 3 inches for more than 24 hours in any 30-day period.

- o See Guidesheets 2A through 2D in Appendix 1-D of the 2005 SMMWW for additional criteria.
- Designate buffer widths consistent with best available science (see Washington State Department of Community, Trade and Economic Development *Critical Areas Assistance Handbook*, 2003 and *Citations of Recommended Sources of Best Available Science*, 2002).
- Map wetlands and wetland buffer areas on all plans and delineate these areas on the site with fencing to protect soils and vegetation from construction damage. Fencing should provide a strong physical and visual barrier of high strength plastic or metal and be a minimum of 3 to 4 feet high (see Ecology 2001 SMMWW BMP C103 and C104). Silt fencing, or preferably a compost berm, is necessary in addition to, or incorporated with, the barrier for erosion control.
- Install signs to identify and explain the use and management of the natural resource protection areas.
- See Riparian Management Areas section for additional management strategies within buffer areas.

2.5 Riparian Management Areas

The riparian zones are defined as areas adjacent to streams, lakes, and wetlands that support native vegetation adapted to saturated or moderately saturated soil conditions. When there is adequate mature vegetation, stable land-form, and large woody debris, riparian areas perform the following functions:

- Dissipate stream energy and erosion associated with high flow events.
- Filter sediment, capture bedload, and aid in floodplain development.
- Improve flood water retention and groundwater recharge.
- Develop diverse ponding and channel characteristics that provide habitat necessary for fish and other aquatic life to spawn, feed, and find refuge from flood events.
- Provide vegetation litter and nutrients to the aquatic food web.
- Provide habitat for a high diversity of terrestrial and aquatic biota.
- Provide shade and temperature regulation.
- Provide adequate soil structure, vegetation, and surface roughness to slow and infiltrate stormwater delivered as precipitation or low velocity sheet flow from adjacent areas (Prichard et al., 1998).

2.5.1 Inventory and Assessment

The objective for riparian area assessment and management is to protect, maintain, and restore mature native vegetation cover that provide the above functions and structures. See sections 2.4: Wetlands, 2.6: Floodplains, and Chapter 4: Vegetation Protection, Reforestation, and Maintenance for assessing the extent and quality of riparian management areas (RMA) in various settings.

Riparian Management Areas

Adequately sized and maintained riparian management areas are necessary for protecting streams, lakes, and wetlands from many of the impacts of surrounding urbanization.

2.5.2 Management

RMAs are used to buffer streams, lakes, wetlands and other aquatic resources from adjacent land disturbance. While managing RMAs to maintain vegetation cover, soils, and stable land-form to buffer aquatic resources is standard practice, managing overland stormwater flows from adjacent developed is not the primary function of riparian management areas. However, if the riparian area will receive storm flow, the following minimum riparian buffer design criteria are recommended to dissipate, infiltrate, and remove pollutants from overland flow:

- Maintain overland flow as sheet flow and do not allow stormwater entering or within buffers to concentrate.
- Maintain (and restore if necessary) mature, native plant community and soils within the buffer.
- Designate buffer widths consistent with best available science (see Washington State Department of Community, Trade and Economic Development *Critical Areas Assistance Handbook,* 2003 and *Citations of Recommended Sources of Best Available Science,* 2002).
- If buffer averaging is used, the following minimum site features and objectives should be considered when determining the extent of the buffer: soils, slope, vegetation, pollutant loads, water quantity and quality targets, and sensitivity of resource.
- Map RMAs on all plans, and delineate with fencing to protect soils and vegetation from construction damage. Fencing should provide a strong physical and visual barrier of high strength plastic or metal and be a minimum of 3 to 4 feet high (see Ecology 2005 SMMWW BMP C103 and C104). Silt fencing, or preferably a compost berm, is necessary in addition to, or incorporated with, the barrier for erosion control.
- Install signs to identify and explain the use and management of the natural resource protection areas.
- Buffers should include 100-year floodplain, wetlands and steep slopes adjacent to streams, and the channel migration zone.
- Flow velocities reaching and within buffer areas should not exceed 1 ft/second.
- Unrestricted overland flow distance should not exceed 150 ft for pervious areas and 75 ft for impervious areas before reaching buffers (Schueler, 1995).
- See Chapter 7: Flow Modeling Guidance for detailed dispersion guidelines.
- Do not allow effective impervious surface within the buffer.
- Activity within the RMA should be limited to:
    - passive, confined recreation (i.e., walking and biking trails) constructed from pervious surfaces.
    - platforms for viewing streams, lakes, and wetlands constructed with techniques to minimize disturbance to soils and vegetation.
- Establish a long-term management entity and strategy to maintain or enhance the structural integrity and capacity of the buffer to protect water quality and habitat.

2.6 Floodplains

The objective for floodplain area assessment and management is to maintain or restore: (1) the connection between the stream channel, floodplain, and off channel habitat; (2) mature native vegetation cover and soils; and (3) pre-development hydrology that supports the above functions, structures, and flood storage.

2.6.1 Inventory and Assessment

The following steps, at a minimum, should be used to inventory and provide baseline conditions of the floodplain area:

- Identify the 100-year floodplain and channel migration zone.
- Identify active channel.
- Inventory composition and structure of vegetation within the floodplain area.

2.6.2 Management

- Map the extent of the 100-year floodplain or channel migration zone on all plans and delineate these areas on the site with fencing to protect soils and vegetation from construction damage. Fencing should provide a strong physical and visual barrier of high strength plastic or metal and be a minimum of 3 to 4 feet high (see Ecology 2005 SMMWW BMP C103 and C104). Silt fencing, or preferably a compost berm, is necessary in addition to, or incorporated with, the barrier for erosion control.
- See Section 2.5: Riparian Management Areas for additional management strategies.
- Install signs to identify and explain the use and management of the natural resource protection areas.

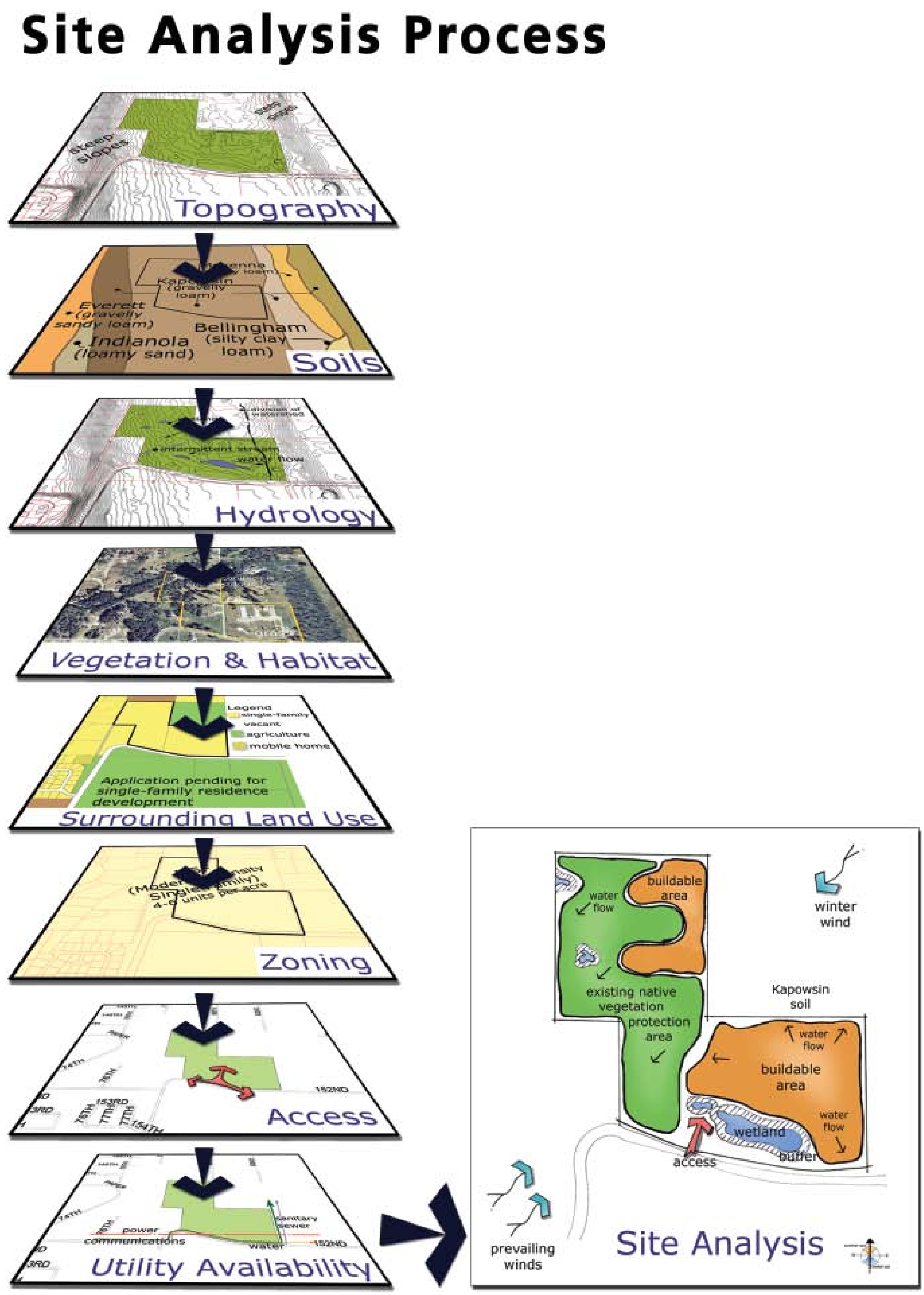
A project should not be considered low impact development if it is located within the 100-year floodplain or channel migration zone.

2.7 Site Mapping Process

Through the assessment process, map layers are produced to delineate important site features. The map layers are combined to provide a composite site analysis that guides the road layout and overall location and configuration of the development envelopes (see figures 2.1 and 2.2, following pages). See Chapter 3: Site Planning and Layout for details on utilizing assessment information for site design.

Figure 2.1 Composite site analysis for a residential subdivision.

Graphic by AHBL Engineering



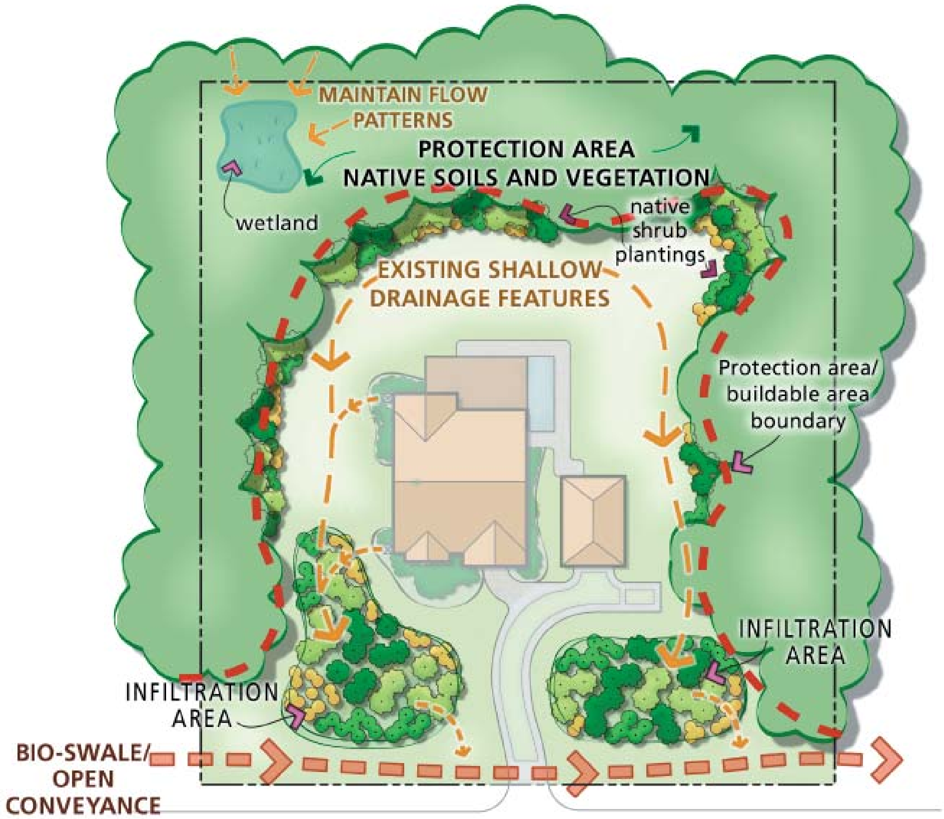


Figure 2.2 Large lot composite site analysis.

Graphic by AHBL Engineering

3 Site Planning and Layout

In this chapter...

- *Road, driveway, and parking layouts for medium to high density subdivisions, large lots, and commercial sites*
- *Road crossings*
- *Street trees*
- *Lot layout for medium to high density clusters, large lots, and rural clusters*
- *Building design*

Site assessment and site planning are iterative processes. Existing and native environmental conditions strongly influence the extent and location of the development envelope for a low impact development (LID) project. The regulatory, market, and architectural context of the location are integrated with the site assessment findings to produce a road and lot configuration that strategically uses site features for isolating impervious surface and dispersing and infiltrating storm flows. As site planning progresses and details for roads, structures, and LID practices are considered, additional evaluation of site conditions may be necessary.

Context is essential for developing any successful residential or commercial project. The designer must consider the appropriate plat design and housing type given the existing character and possible future conditions of the area when developed. Architectural considerations influence how the project integrates with the surroundings while at the same time creating neighborhood identity (personal communication Len Zickler, January 2004). A low impact development project incorporates these same design considerations; however, the following stormwater and other environmental management elements are elevated to equal standing:

> *Hydrology is an organizing principle that is integrated into the initial site assessment and planning phases.*

- Hydrology is an organizing principle that is integrated into the initial site assessment and planning phases.
- Individual LID practices are distributed throughout the project site and influence the configuration of roads, house lots, and other infrastructure.
- LID practices are amenities that provide multiple functions, including aesthetic landscaping, visual breaks that increase a sense of privacy within a variety of housing densities, and a design element (of equal importance to architectural and plat design) that promotes neighborhood identity.

Assessment of natural resources outlined in the previous section will produce a series of maps identifying streams, lakes, wetlands, buffers, steep slopes, and other hazard areas, significant wildlife habitat areas, and permeable soils offering the best available infiltration potential. Maps can be combined as GIS or CAD layers to delineate the best areas to direct development. Building sites, road layout, and stormwater infrastructure should be configured within these development areas to minimize soil and vegetation disturbance and take advantage of a site's natural stormwater processing capabilities.

Initial site management strategies include:

- Establish limits of disturbance to the minimum area required for roads, utilities, building pads, landscape areas, and the smallest additional area needed to maneuver equipment.
- Map and delineate natural resource protection areas with appropriate fencing and signage to provide protection from construction activities.
- Meet and walk the property with the owner, engineers, landscape architects, and others directing project design to identify problems and concerns that should be evaluated for developing the site plans.
- Meet and walk the property with equipment operators prior to clearing and grading to clarify construction boundaries and limits of disturbance (see Chapter 4: Vegetation Protection, Reforestation, and Maintenance and Chapter 5: Site Clearing and Grading for more detailed information).

The following section is organized under two main categories: (1) Roads, Driveways and Parking; and (2) Lot Layout. The first category is examined by medium to high density, individual large lot, and commercial type development, and the second by medium to high density cluster, rural cluster, and large lot development.

3.1 Roads, Driveways and Parking

Residential roads in the early 1900s were primarily laid out in grid patterns to allow efficient access to services and transit, and were dominated by a mix of uses including pedestrian, bicycle, and vehicle transportation. The grid configuration has evolved over the past century to modified grids and the current prevailing designs that use curvilinear layouts with relatively disconnected loops and cul-de-sacs. The transition has been driven primarily by the increased mobility offered by the automobile and the perceived safety and privacy of dead end roads (Canadian Mortgage and Housing Corporation [CMHC], 2002).

An analysis in south Puget Sound found that the transportation component of the suburban watershed accounts for approximately 60 percent of the total impervious area (City of Olympia, 1995). At the national level, the American Association of State Highway and Transportation Officials (AASHTO) estimates that the urban and rural local access roads typically account for 65 to 80 percent of the total road network (AASHTO, 2001). Design standards for roads in residential areas focus on efficient and safe movement of traffic and rapid conveyance of stormwater. As a result, streets contribute higher storm flow volumes and pollutant loads to urban stormwater than any other source area in residential developments (City of Olympia, 1995 and Bannerman, Owens, Dodds and Hornewer, 1993).

Streets contribute higher storm flow volumes and pollutant loads to urban stormwater than any other source area in residential developments.

The overall objectives for low impact development road designs are:

- Reduce **total impervious area** (TIA) by reducing the overall road network coverage.
- Minimize or eliminate effective impervious area (EIA) and concentrated surface flows on impervious surfaces by reducing or eliminating hardened conveyance structures (pipes or curbs and gutters).
- Infiltrate and slowly convey storm flows in roadside bioretention cells and swales, and through permeable paving and aggregate storage systems under the pavement.

- Design the road network to minimize site disturbance, avoid sensitive areas, and reduce fragmentation of landscape.
- Create connected street patterns and utilize open space areas to promote walking, biking and access to transit and services.
- Provide efficient fire and safety vehicle access.

Local access and small-collector road design is influenced at the individual parcel and subdivision scale and is the focus of this section. Road design is site specific; accordingly, this section does not recommended specific road designs. Instead, the strengths and weaknesses of different road layouts are examined in the context of LID to assist designers in the process of providing adequate transportation systems while reducing impervious surface coverage.

3.1.1 Medium to High Density Subdivision and Planned Community

Road layout

The Urban Land Institute (ULI), Institute of Transportation Engineers (ITE), National Association of Home Builders, and American Society of Civil Engineers state in a 2001 collaborative publication that: "The movement of vehicles is only one of a residential street's many functions. A residential street is also part of its neighborhood and provides a visual setting for the homes as well as a meeting place for residents." Additionally, ULI recommends that the land area devoted to streets should be minimized (National Association of Home Builders [NAHB], American Society of Civil Engineers, Institute of Transportation Engineers, and Urban Land Institute, 2001). These recommendations are derived primarily from a livability and safety perspective; however, the guidelines also integrate well with the low impact development design approach.

Designs for residential roads generally fall into three categories: grid, curvilinear and hybrids. Figure 3.1 illustrates the grid and curvilinear road layouts and Table 3.1 summarizes the strengths and weaknesses of the grid and curvilinear approaches.

Table 3.1 Strengths and weaknesses of the grid and curvilinear approaches.

Road Pattern	Impervious Coverage	Site Disturbance	*Biking, Walking, Transit	Safety	Auto Efficiency
Grid	27-36% (Center for Housing Innovation, 2000 and CMHC, 2002)	less adaptive to site features and topography	promotes by more direct access to services and transit	may decrease by increasing traffic throughout residential area	more efficient—disperses traffic through multiple access points
Curvilinear	15-29% (Center for Housing Innovation, 2000 and CMHC, 2002)	more adaptive for avoiding natural features, and reducing cut and fill	generally discourages through longer, more confusing, and less connected system	may increase by reducing through traffic in dead end streets	less efficient—concentrates traffic through fewer access points and intersections

** Note: biking, walking and transit are included for livability issues and to reduce auto trips and associated pollutant contribution to receiving waters.*

Figure 3.1
Top: Typical grid road layout with alleys.
Lower: Typical curvilinear road layout with cul-de-sacs.

Graphic by AHBL Engineering

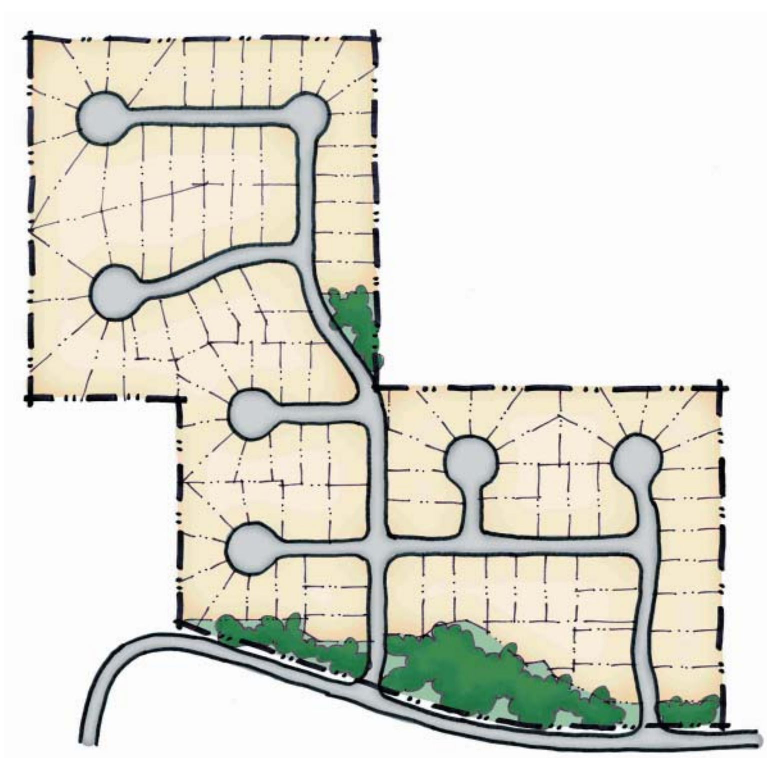


Figure 3.2 Hybrid, or open space, road layout.

Graphic by AHBL Engineering

The grid and curvilinear systems both have advantages and disadvantages. However, grid street patterns with alleys have one large drawback in the LID context: grids typically require 20 to 30 percent more total street length than curvilinear patterns (CWP, 1998 and Table 3.1). Recently, planners have integrated the two prevalent models to incorporate the strengths of both. These street networks have several names including open space, hybrid, and headwater street plans (Figure 3.2).

The following are strategies used to create road layouts in medium to higher density low impact residential developments that provide effective transportation networks and minimize impervious surface coverage:

- Cluster homes to reduce overall development envelope and road length (Schueler, 1995).
- Narrow lot frontages to reduce overall road length per home (see Figure 3.2) (Schueler, 1995).
- For grid or modified grid layouts, lengthen street blocks to reduce the number of cross streets and overall road network per home, and provide mid-block pedestrian and bike paths to reduce distances to access transit and other services (Center for Housing Innovation [CHI], 2000).
- Where cul-de-sacs are used, provide pedestrian paths to connect the end of the street with other pathways, transit or open space (Ewing, 1996).
- Provide paths in open space areas to increase connection and access for pedestrians and bicyclists (Ewing, 1996).
- Create pedestrian routes to neighborhood destinations that are direct, safe and aesthetically pleasing (CHI, 2000).

- Reduce road widths and turn around area coverage (see road widths, parking and driveway sections).
- Reduce front yard set backs to reduce driveway length.
- Minimize residential access road right-of-way to only accommodate needed infrastructure next to road (residential access roads are rarely widened) (Schueler, 1995).
- Eliminate, or reduce to an absolute minimum, all stream crossings.

The road and pedestrian pathway networks in figures 3.3 and 3.4 illustrate multifunctional road layout designs.

Figure 3.3 Loop road design.

Graphic by AHBL Engineering

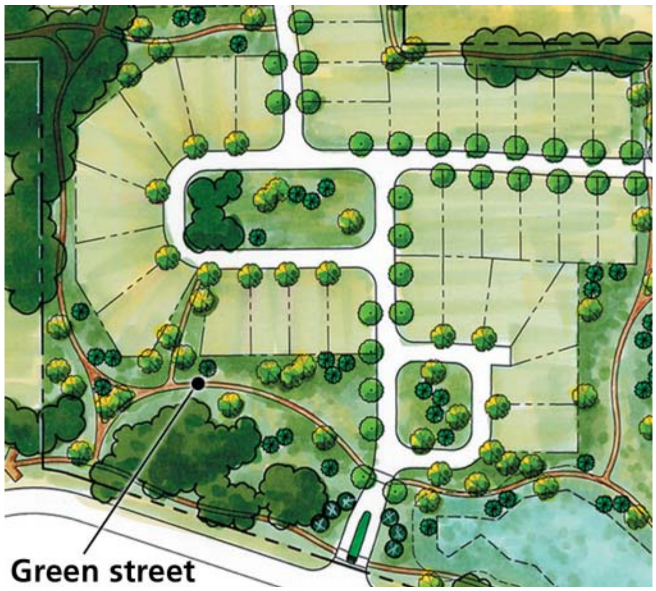
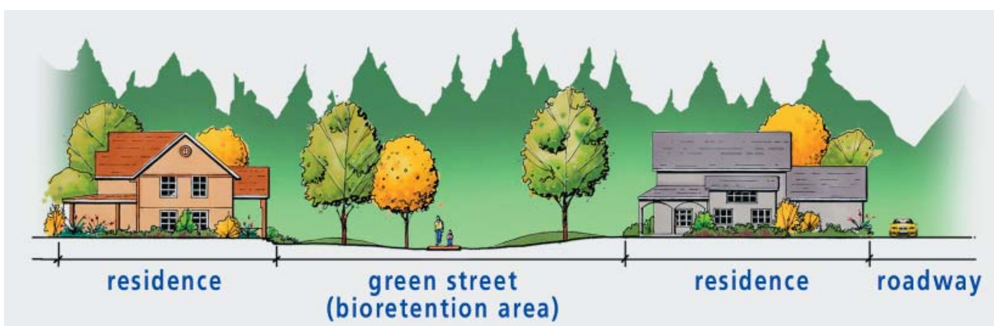


Figure 3.4 Green street section.

Graphic by AHBL Engineering



The loop road design:

- Minimizes impervious road coverage per dwelling unit.
- Provides adequate turning radius for fire and safety vehicles.
- Provides through traffic flow with two points of access.
- Provides a large bioretention area in the center of the loop and a visual landscape break for homes facing the road.

The open space pathways between homes (green streets):

- Provide a connected pedestrian system that takes advantage of open space amenities.

- Provide additional stormwater conveyance and infiltration for infrequent, large storm events.

The Sherbourne project in figures 3.5 and 3.6 is designed with one access to the development; however, ample traffic flow through the subdivision is provided by the loop and along home frontages, allowing for easier movement of fire and safety vehicles. Open space in the center of the loop provides stormwater storage, a visual landscape break for homes facing the road, and a creative example of integrating a regulatory requirement with a site amenity.

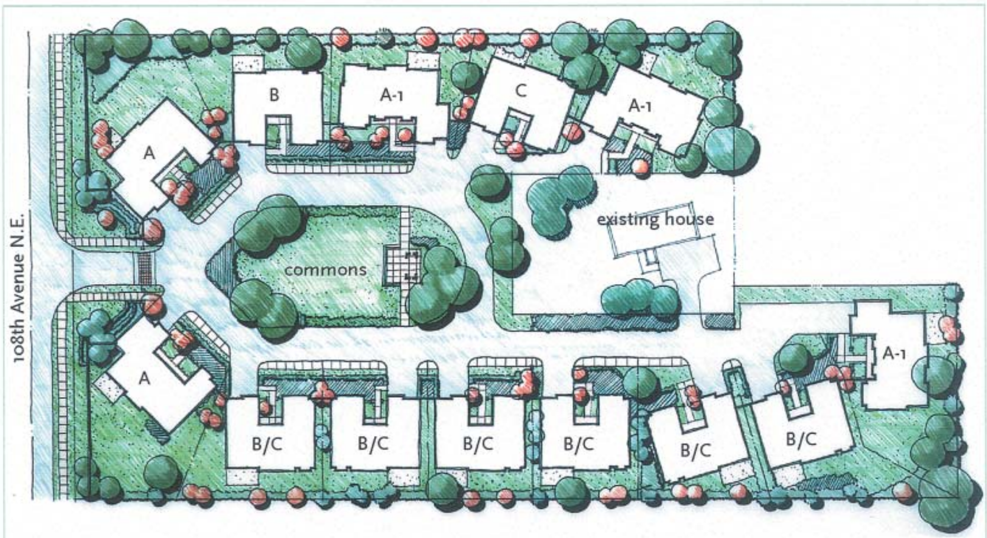


Figure 3.5 Sherbourne plan view.

Graphic courtesy of Mithun

Figure 3.6 Combined commons and stormwater facility at Sherbourne.

Photo by Colleen Owen

Road width

Residential road widths and associated impervious surface have, for various reasons, increased by over 50 percent since the mid-1900's (Schueler, 1995). Road geometry, including road widths, are derived primarily from two sources: American Association of State Highway Transportation Officials (AASHTO) and ITE (Schueler, 1995). A standardized guideline for residential roads that responds to general safety, traffic flow, emergency access, and parking needs is often adopted from these sources to fit various development scenarios. For example, AASHTO recommends 26-foot pavement widths and 50-foot right of way for residential roads across various density and traffic load demands. Additionally, many communities continue to equate wider streets with better and safer streets. Studies indicate, however, that residential accidents may increase exponentially as the street gets wider, and narrower roads that reduce traffic speeds are safer (CHI, 2000; NAHB et al., 2001; and Schueler, 1995).

Total and effective impervious area can be significantly reduced by determining specific traffic, parking, and emergency vehicle access needs and designing for the narrowest width capable of meeting those requirements. Examples of narrow street widths tailored to traffic need from different U.S. locations and from ULI are provided in Table 3.2. Reducing the street width from 26 to 20 feet reduces TIA by 30 percent. In the road network represented in Figure 3.2, the 30 percent reduction represents a storm flow reduction from 15,600 cubic feet to 12,000 cubic feet for a 2 inch 24-hour storm.

Table 3.2 Examples of narrow street widths from various jurisdictions.

Location or Source	Street Type	Width	Volume (ADT*)	Parking
Buck's County, PA	local access	18 ft	200	none
Buck's County, PA	residential collector	20 ft	200-1,000	none
Portland, OR	queuing	26 ft	not reported	both sides
ULI	shared driveway (5-6 homes)	16 ft	not reported	not reported
ULI	local	18 ft	not reported	one side only
ULI	local	22-26 ft	not reported	both sides
ULI	alley	12 ft	not reported	none
City of Seattle	local access	14 ft	125 (from traffic counts)	none
City of Seattle	local access	20 ft	250 (from traffic counts)	one side
City of Olympia	local access (2-way)	18 ft	0-500	none
City of Olympia	local access (queuing)	18 ft	0-500	one side alternating
City of Olympia	neighborhood collector	25 ft	500-3000	one side alternating

** ADT: Average daily traffic*

Turnarounds

Dead end streets with excessive turn around area (particularly cul-de-sacs) can needlessly increase impervious area. In general, dead end or cul-de-sac streets should be discouraged; however, a number of alternatives are available where topography, soils or other site specific conditions suggest this road design. Thirty-foot radius turnarounds are adequate for low volume residential roads servicing primarily passenger vehicles (AASHTO, 2001 and NAHB et al., 2001). A 40-foot radius with a landscaped center will accommodate most service and safety vehicle needs when a minimum 20-foot internal turning radius is maintained (Schueler, 1995). The turning area in a cul-de-sac can be enhanced by slightly enlarging the rear width of the radius. A hammerhead turnaround requires vehicles to make a backing maneuver, but this inconvenience can be justified for low volume residential roads servicing 10 or fewer homes (NAHB et al., 2001). A 10-foot reduction in radius can reduce impervious coverage by 44 percent and the hammerhead configuration generates approximately 76 percent less impervious surface than the 40-foot cul-de-sac. Four turnaround options and associated impervious surface coverage are presented in Figure 3.7.

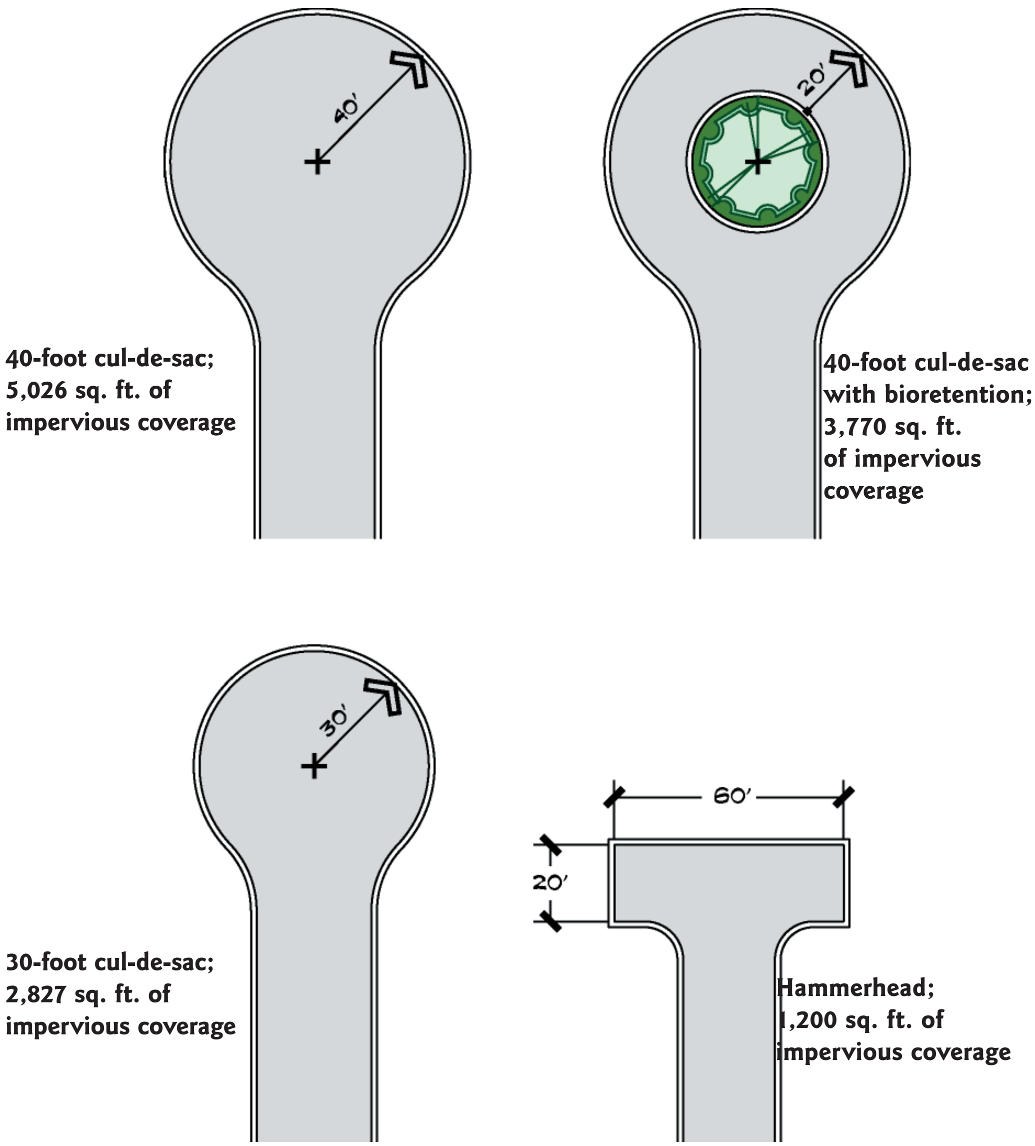


Figure 3.7 Turnaround areas and associated impervious coverage.

Graphic by AHBL Engineering

Islands in cul-de-sacs should be designed as bioretention or detention facilities. Either a flat concrete reinforcing strip or curb-cuts can be utilized to allow water into the facility (see Section 6.3: Permeable Paving for details).

The loop road configuration is an alternative to the dead end street and provides multiple access points for emergency vehicles and residents (see figures 3.3 and 3.5). For similar impervious surface coverage, the loop road has the additional advantage of increasing available storm flow storage within the loop compared to the cul-de-sac design.

Parking

Many communities require 2 to 2.5 parking spaces per dwelling. Driveways and garages can accommodate this need in most cases, and providing curb side parking on both sides of the street and two travel lanes (i.e., the 36-foot wide local residential street) creates excess impervious surface. Parking needs and traffic movement can be met on narrowed roads where one or two on-street parking lanes serve as a traffic lane (queuing street) (CWP, 1998). Figure 3.8 provides two examples of queuing streets for local residential streets.

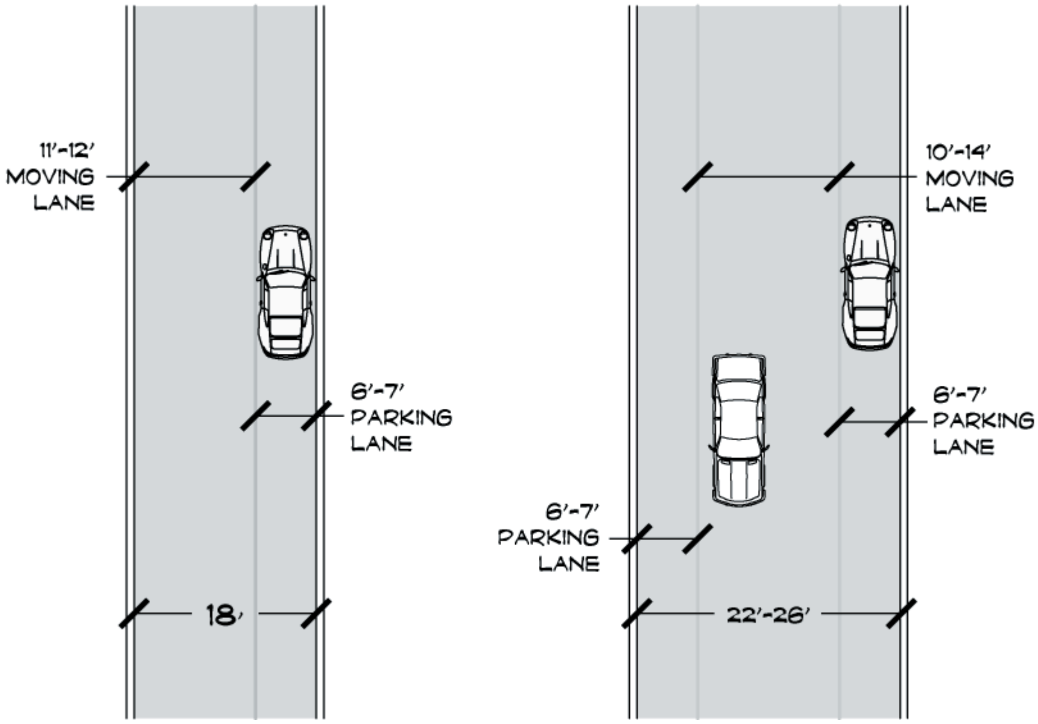


Figure 3.8
Left: 18-ft street with parking on one side.
Right: 22 to 26-ft street with parking on both sides.
(Adapted from National Association of Home Builders et al., 2001)

In higher density residential neighborhoods with narrow roads and where no on-street parking is allowed, pullout parking can be utilized. Pullouts (often designed in clusters of 2 to 4 stalls) should be strategically distributed throughout the area to minimize walking distances to residences. Depending on the street design, the parking areas may be more easily isolated and the impervious surface rendered ineffective by slightly sloping the pavement to adjacent bioretention swales or bioretention cells (Figure 3.9).

All or part of pullout parking areas, queuing lanes or dedicated on-street parking lanes can be designed using permeable paving (see Figure 3.10 for an example design). Permeable asphalt, concrete, pavers, and gravel pave systems can support the load requirements for residential use, reduce or eliminate storm flows from the surface, and may be more readily acceptable for use on lower-load parking areas by jurisdictions hesitant to use permeable systems in the travel way. Particular design and management strategies for subgrade preparation and sediment control must be implemented where pullout parking or queuing lanes receive storm flows from adjacent impervious areas (see Section 6.3: Permeable Paving for details).

Traffic calming strategies

Several types of traffic calming strategies are used on residential roadways to reduce vehicle speeds and increase safety. These design features also offer an opportunity for storm flow infiltration and/or slow conveyance to additional LID facilities downstream (figures 3.11 and 3.12).

Figure 3.9 Pullout parking adjacent to a 14-foot residential access road, Seattle.

Photo by Colleen Owen

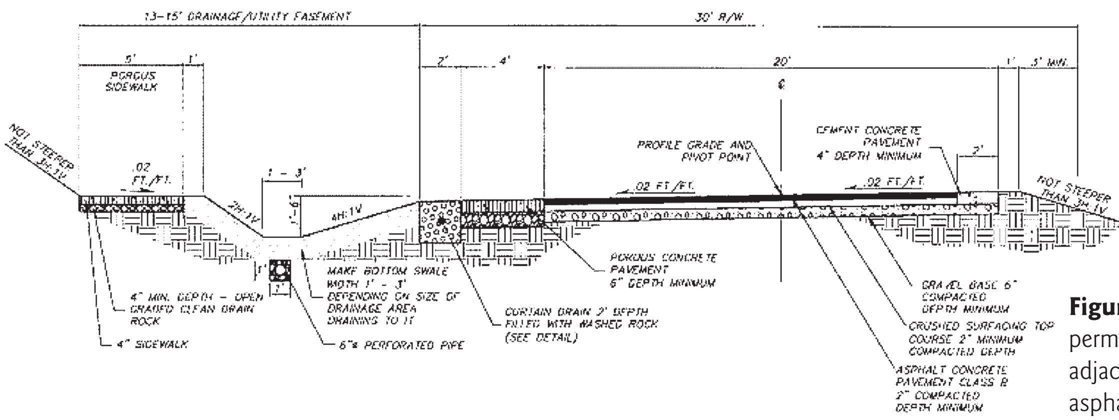


Figure 3.10 Four-foot permeable paving section adjacent to conventional asphalt roadway.

Courtesy of Pierce County Department of Public Works and Utilities

Alleys

Alleys should be the minimum width required for service vehicles, constructed of permeable paving materials, and allow any surface flows to disperse and infiltrate to adjacent bioretention swales, shoulders or yards (Figure 3.13). Strategies to reduce TIA associated with alleys include:

Maximum alley width should be 10 to 12 feet with 14- to 16-foot right-of-ways respectively.

Several permeable paving materials are applicable for low speeds and high service vehicle weights typically found in alleys including:

- Gravel pave systems.
- Permeable concrete.
- Permeable pavers.
- Systems integrating multiple permeable paving materials.

See Section 6.3: Permeable Paving for details.

Figure 3.11 Combination stormwater management and traffic calming. (Note: These areas are slightly lower than road surface.)

Graphic by AHBL Engineering

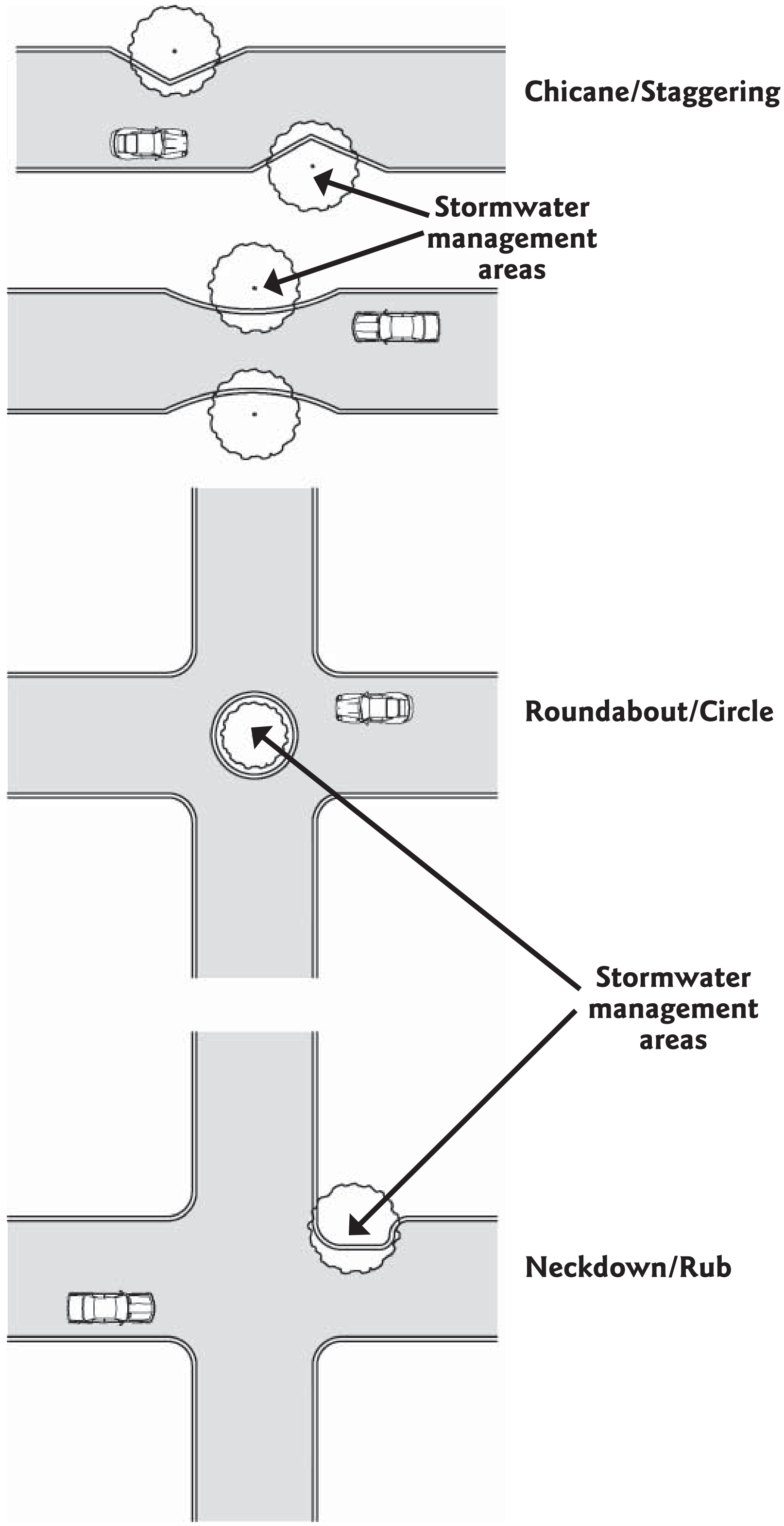


Figure 3.12 Siskiyou project in Portland, Oregon uses traffic calming designs to manage stormwater. Note curb cuts that allow stormwater to enter bioretention area in narrow section of road.

Photo by Erica Guttman

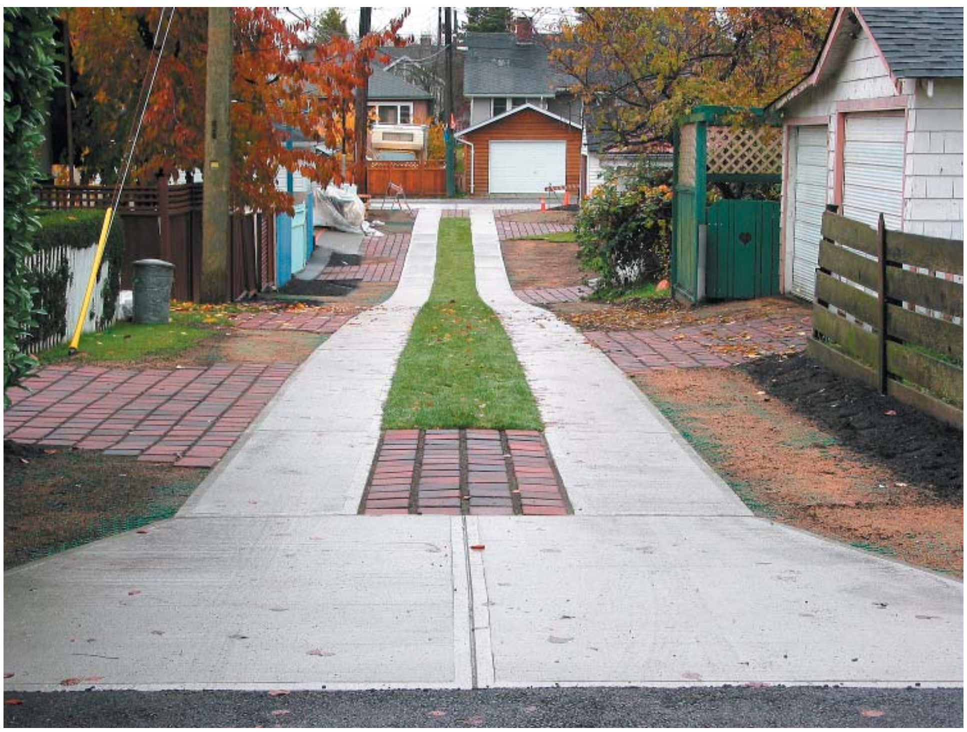


Figure 3.13 Vancouver, BC Country Lane alley uses a combination of concrete wheel strips, permeable pavers, reinforced plastic grid with grass, and under-drains to attenuate storm flows and create an aesthetic design objective.

Photo by Curtis Hinman

Driveways

As much as 20 percent of the impervious cover in a residential subdivision can be attributed to driveways (CWP, 1998). Several techniques can be used to reduce impervious coverage associated with driveways including:

- Shared driveways provide access to several homes and may not have to be designed as wide as local residential roads (Figure 3.14). Recommendations range from 9 to 16 feet in width serving 3 to 6 homes (NAHB et al., 2001 and Prince George's County, Maryland, 2000). A hammerhead or other configuration that generates minimal impervious surface may be necessary for turnaround and parking area.
- Minimize front yard setbacks to reduce driveway length.
- Reduce minimum driveway width from 20 (common standard) to 18 feet. Driveways can be reduced further to 10 feet with a bulb-out at the garage.

Figure 3.14 Issaquah Highlands shared driveway.
Photo by Curtis Hinman

- Use permeable paving materials and aggregate storage under wearing surface.
- Limit impervious surface to two tracks with remainder in reinforced grass or other pervious surface (California strips).
- Direct surface flow from driveways to compost-amended soils, bioretention areas or other dispersion and infiltration areas (see Section 6.2: Amending Construction Site Soils and Section 6.1: Bioretention Areas for details).

Sidewalks

Many jurisdictions require sidewalks on both sides of residential roads for safety and perceived consumer demand. Studies indicate that pedestrian accident rates are similar in areas with sidewalks on one or both sides of the street (CWP, 1998). Limited assessments suggest that there is no appreciable market difference between homes with sidewalks on the same side of the street and homes with sidewalks on the opposite side of the road (CWP, 1998). The Americans with Disabilities Act (ADA) does not require sidewalks on both sides, but rather at least one accessible route from public streets (WAC 51-40-1100, 2003). Impervious surface coverage generated by sidewalks can be reduced using the following strategies:

- Reduce sidewalk to a minimum of 44 inches (ADA recommended minimum) or 48 inches (AASHTO, 2001 and NAHB et al., 2001 recommended minimum).
- For low speed local access roads eliminate sidewalks or provide sidewalks on one side of the road. A walking and biking lane, delineated by a paint stripe, can be included along the roadway edge.
- Design a bioretention swale or bioretention cell between the sidewalk and the street to provide a visual break and increase the distance of the sidewalk from the road for safety (NAHB et al., 2001).
- Install sidewalks at a two percent slope to direct storm flow to bioretention swales or bioretention cells—do not direct sidewalk water to curb and gutter or other hardened roadside conveyance structures.
- Use permeable paving material to infiltrate or increase time of concentration of storm flows (see Section 6.3: Permeable Paving for details).

Figure 3.15 Permeable concrete walkway and parking area on Whidbey Island.

Courtesy of Greg McKinnon

3.1.2 Low Density/Large Lots

Dispersion

Low density or large lot development offer increased opportunities or land area to integrate LID dispersion, storage, and infiltration strategies. The greater distances between residences can, however, increase the overall road network and total impervious coverage per dwelling (Schueler, 1995). Preserving or restoring native soils and vegetation along low density road networks and driveways, and dispersing storm flows to those areas offers a low cost and effective LID strategy. Designs for dispersion should minimize surface flow velocities and not concentrate storm flows.

The strategies for road, driveway, parking and other LID designs appropriate in medium to high density settings (see Section 3.1.1) can be applied in large lot settings as well.

Dispersion flow control credit

See Chapter 7 for design of dispersion techniques and flow control guidelines when using the Western Washington Hydrologic Model.

Driveways

Shared driveways are applicable in large lot as well as higher density settings. Figure 3.16 is a large lot conservation design for protecting open space and uses shared driveways to access homes.

Figure 3.16 Large lot cluster design with shared driveway.

Graphic by AHBL Engineering

3.1.3 Commercial

Parking

Parking lots and roof tops are the largest contributors to impervious surface coverage in commercial areas. Typical parking stall dimensions are approximately 9 to 9.5 feet by 18.5 to 19 feet, totaling 166.5 and 180.5 square feet respectively (Schueler, 1995 and City of Olympia, 1995). Considering the total space associated with each stall including overhangs, access isle, curbs, and median islands, a parking lot can require up to 400-square feet per vehicle or approximately one acre per 100 cars (CHI, 2000). The large effective impervious coverage associated with parking areas accumulates high pollutant loads from atmospheric deposition and vehicle use (auto pollutant contributions can be particularly heavy during stopping and starting a vehicle). As a result, commercial parking lots can produce greater levels of petroleum hydrocarbons and trace metals (cadmium, copper, zinc, lead) than many other urban land uses (Schueler, 1995 and Bannerman et al., 1993).

Many jurisdictions specify parking demand ratios as a minimum number of spaces that must be provided for the development type, number of employees, gross floor area or other parking need indicator. While parking infrastructure is a significant expense for commercial development, providing excess parking is often perceived as necessary to attract (or not discourage) customers. As a result, minimum standards are often exceeded in various regions of the U.S. by 30 to 50 percent (Schueler, 1995). In a local study, the city of Olympia found that 70 percent of all parking lots surveyed had at least 25 percent additional capacity during normal and peak hours (City of Olympia, 1995). The same study concluded that a 20 percent reduction in parking stalls was feasible without significantly impacting business activity.

The city of Olympia found that 70 percent of all parking lots surveyed had at least 25 percent additional capacity during normal and peak hours.

Capping parking demand ratios to reflect actual need is the most effective of several methods used to reduce impervious coverage in parking areas. In a commercial parking area selected in the Olympia study (526 stalls), a 20 percent reduction (105 stalls) would reduce surface flows by approximately 4,000 cubic feet for a typical two-year event (City of Olympia, 1995).

To reduce impervious coverage, storm flows, and pollutant loads from commercial parking areas, several LID strategies can be employed including:

- Assess parking demand ratios to determine if ratios are within national or, if available, actual local ranges (Schueler, 1995).
- Establish minimum and maximum or median parking demand ratios and allow additional spaces above the maximum ratio only if parking studies indicate a need for added capacity.
- Dedicate 20 to 30 percent of parking to compact spaces (typically 7.5 by 15 feet).
- Use a diagonal parking stall configuration with a single lane between stalls (reduces width of parking isle from 24 to 18 feet and overall lot coverage by 5 to 10 percent) (Schueler, 1995).
- Where density and land value warrant, or where necessary to reduce TIA below a maximum allowed by land use plans, construct underground, under building or multi-story parking structures.
- Use permeable paving materials for the entire parking area or, at a minimum, for spillover parking that is used primarily for peak demand periods (Figure 3.17).

- Integrate bioretention into parking lot islands or planter strips distributed throughout the parking area to infiltrate, store, and/or slowly convey storm flows to additional facilities.
- Encourage cooperative parking agreements to coordinate use of adjacent or nearby parking areas that serve land uses with non-competing hours of operation—for example a cooperative agreement between a church and an office or retail store (City of Olympia, 1995).

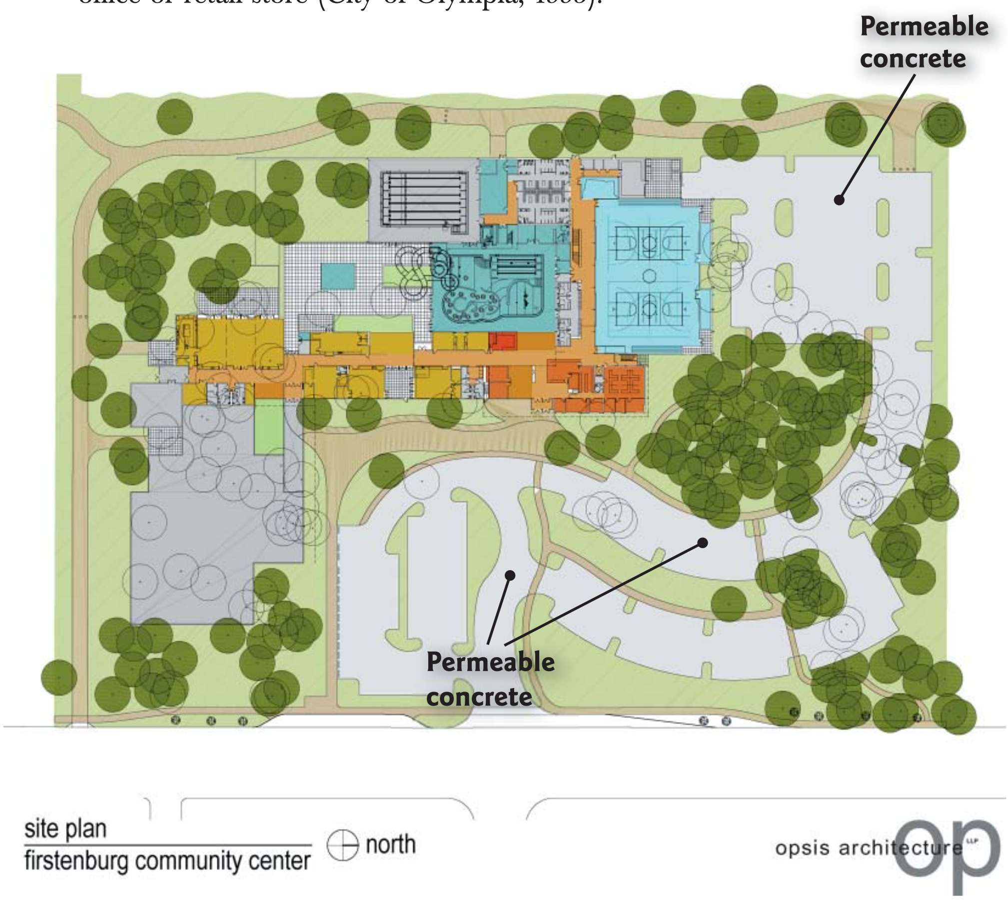


Figure 3.17 Firstenburg project in Vancouver, Washington includes 100,000 square feet of permeable concrete.

Courtesy of 2020 Engineering

3.2 Road Crossings

Numerous studies have correlated increased total impervious area with declining stream and wetland conditions (Azous and Horner, 2001; Booth et al., 2002; May et al., 1997). Recent research in the Puget Sound region suggests that the number of stream crossings per stream length may be a relatively stronger indicator of stream health (expressed through Benthic Index of Biotic Integrity) than TIA (Avolio, 2003). In general, crossings place significant stress on stream ecological health by concentrating and directing storm flows and contaminants to receiving waters through associated outfall pipes, fragmenting riparian buffers, altering hydraulics, and disrupting in-channel processes such as meander migration and wood recruitment (Avolio, 2003 and May, 1997). Culvert and bridge design that place supporting structures in the floodplain or active channel confine stream flows. The confined flow often increases bank and bed erosion resulting in channel enlargement downstream of the structure (Avolio, 2003). Bank armoring associated with crossings further disrupts hydraulics and channel processes and can increase the impacts of all crossing types including less damaging bridge designs (Avolio, 2003).

Road crossings place significant stress on stream ecological health by directing concentrated storm flows and contaminants to receiving waters, fragmenting riparian buffers, altering hydraulics, and disrupting in-channel processes.

Improperly designed crossings using culverts can also inhibit or completely block fish passage. Design considerations for minimizing road crossing impacts include:

- Eliminate, or reduce to an absolute minimum, all stream crossings.
- Where stream crossings are unavoidable, bridges are preferable to culverts.
- Locate bridge piers or abutments outside of the active channel or channel migration zone.
- If culverts are utilized, install slab, arch or box type culverts, preferably using bottomless designs that more closely mimic stream bottom habitat.
- Utilize the widest possible culvert design to reduce channel confinement.
- Minimize stream bank armoring and establish native riparian vegetation and large woody debris to enhance bank stability and diffuse increased stream power created by road crossing structures. (Note: consult a qualified fluvial geomorphologist and/or hydrologist for recommendations.)
- All crossings should be designed to pass the 100-year flood event.
- Cross at approximately 90 degrees to the channel to minimize disturbance.
- Do not discharge storm flows directly from impervious surfaces associated with road crossing directly to the stream—disperse and infiltrate stormwater or detain and treat flows.

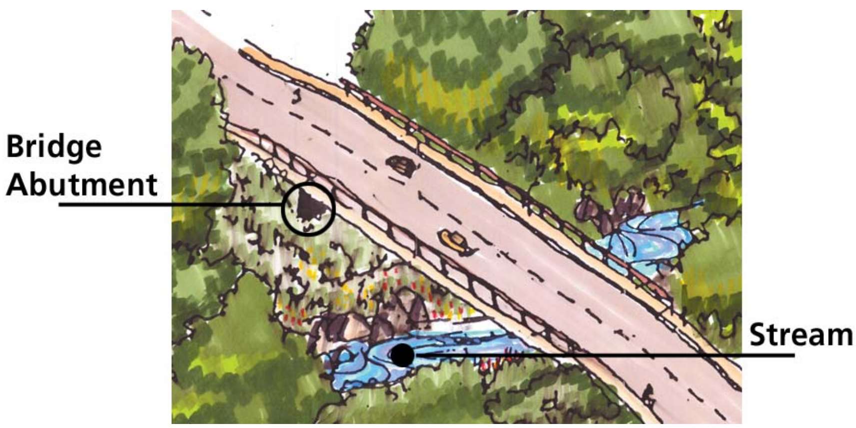


Figure 3.18 Minimal impact stream crossing. Locate abutments outside of active channel or channel migration zone. Cross at approximately 90° to channel to minimize shading and other disturbances.

Courtesy of Portland Metro Green Streets Program

3.3 Street Trees

Trees can be used as a stormwater management tool in addition to providing more commonly recognized benefits such as energy conservation, air quality improvement, and aesthetic enhancement. Tree surfaces (foliage, bark, and branches) intercept, evaporate, store or convey precipitation to the soil before it reaches surrounding impervious surfaces. In bioretention cells or swales, tree roots build soil structure that enhances infiltration capacity and reduces erosion (Metro, 2003).

Appropriate placement and selection of tree species is important to achieve desired benefits and reduce potential problems such as pavement damage by surface roots and poor growth performance. When selecting species, consider the following site characteristics:

- Available growing space.
- Type of soil and availability of water.
- Overhead wires.
- Vehicle and pedestrian sight lines.
- Proximity to paved areas and underground structures.

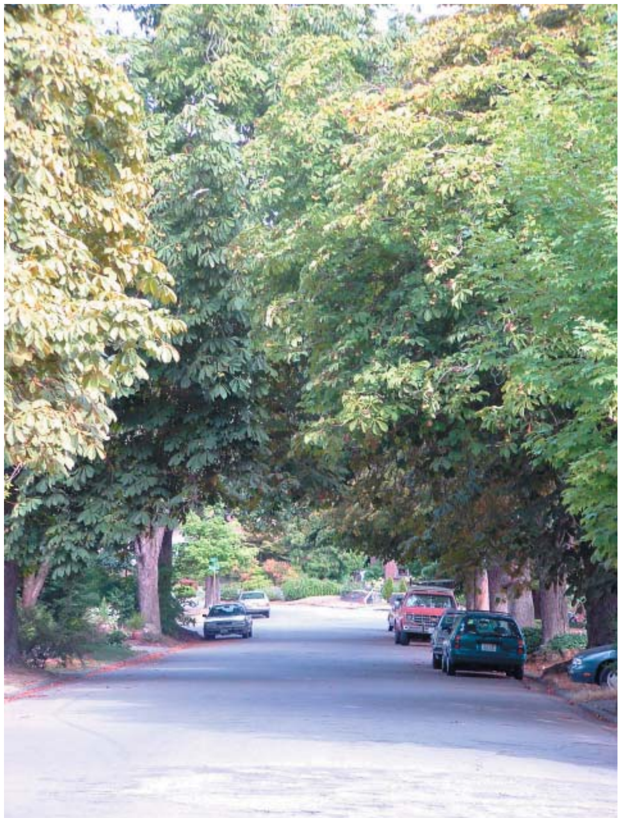


Figure 3.19 Street trees—Queen Anne neighborhood, Seattle.
Photo by Colleen Owen

- Proximity to neighbors, buildings, and other vegetation.
- Prevailing wind direction and sun exposure.
- Additional functions desired, such as shade, aesthetics, windbreak, privacy screening, etc.

Local jurisdictions often have specific guidelines for the types and location of trees planted along public streets or rights-of-way. The extent and growth pattern of the root structure must be considered when trees are planted in bioretention areas or other stormwater facilities with under-drain structures or near paved areas such as driveways, sidewalks or streets. Other important tree characteristics to consider when making a selection include:

- Longevity or life-span (ideally a street tree will be "long-lived", meaning it has a life span of 100 years or more. However, the longevity of a tree will need to be balanced with other selection priorities).
- Tolerance for urban pollutants.
- Growth rate.
- Tolerance to drought, seasonally saturated soils, and poor soils.
- Canopy spread and density (trees that provide a closed street canopy maximize interception and evapotranspiration).
- Foliage texture and persistence.

Appendix 1 lists the growth pattern and appropriate site characteristics for a variety of trees appropriate for street, parking lot, residential yard, and bioretention applications.

3.4 Lot Layout

Typical residential development determines lot size by dividing the total plat acreage, minus the roads and regulated sensitive areas, by the number of lots allowed under the applicable zoning. Most, if not all, of the site is cleared and graded. In contrast, LID projects employ clustering and other planning strategies to minimize site disturbance, maximize protection of native soil and vegetation, and permanently set aside the open tracts for multiple objectives including stormwater management. Four general objectives should guide the placement and orientation of lots for LID projects:

- Minimize site disturbance.
- Strategically locate lots for dispersing stormwater to open space areas.
- Orient lots and buildings to maximize opportunities for on-lot infiltration or open conveyance through bioretention swales or cells to downstream LID facilities.
- Locate lots adjacent to, or with views of, open space to improve aesthetics and privacy.

The following examines three prevalent development strategies applied in a low impact development context–medium to high density cluster, rural cluster, and large lot development.

3.4.1 Medium to High Density Cluster (4 or More Dwelling Units Per Acre)

Clustering is a type of development where buildings are organized together into compact groupings that allow for portions of the development site to remain in open space (Maryland Office of Planning, 1994). In the U.S., the primary focus of cluster development has been to preserve natural and cultural features, provide recreation, preserve rural character, and produce more affordable housing (Schueler, 1995).

The LID cluster may include the above objectives; however, the primary purpose of the low impact development cluster is to minimize the development envelope, reduce impervious coverage, and maximize native soil and forest protection or restoration areas. Natural resource protection areas (the preferred strategy) are undisturbed conservation areas. Restoration areas (appropriate where land is or will be disturbed) can be enhanced through soil amendments and native planting to improve the hydrologic function of the site. Both can provide dispersion for overland flows generated in developed areas. Demonstration projects indicate that significant open space protection can still be achieved over conventional development projects designed with relatively small lot sizes when using cluster strategies (Figure 3.20).

Objectives for medium to high density clustering:

- Medium density (4 to 6 dwelling units per acre): reduce the development envelope in order to retain a minimum of 50 percent open space.
- High density (more than 6 dwelling units per acre): protect or restore to the greatest extent possible. Note: in medium to high density settings, reducing the development envelope and protecting native forest and soil areas will often require multifamily, cottage, condominium or mixed attached and detached single family homes.

Techniques to meet objectives for medium to high density clustering include:

- Minimize individual lot size (3,000 to 4,000 square-foot lots can support a medium sized home designed to occupy a compact building footprint).

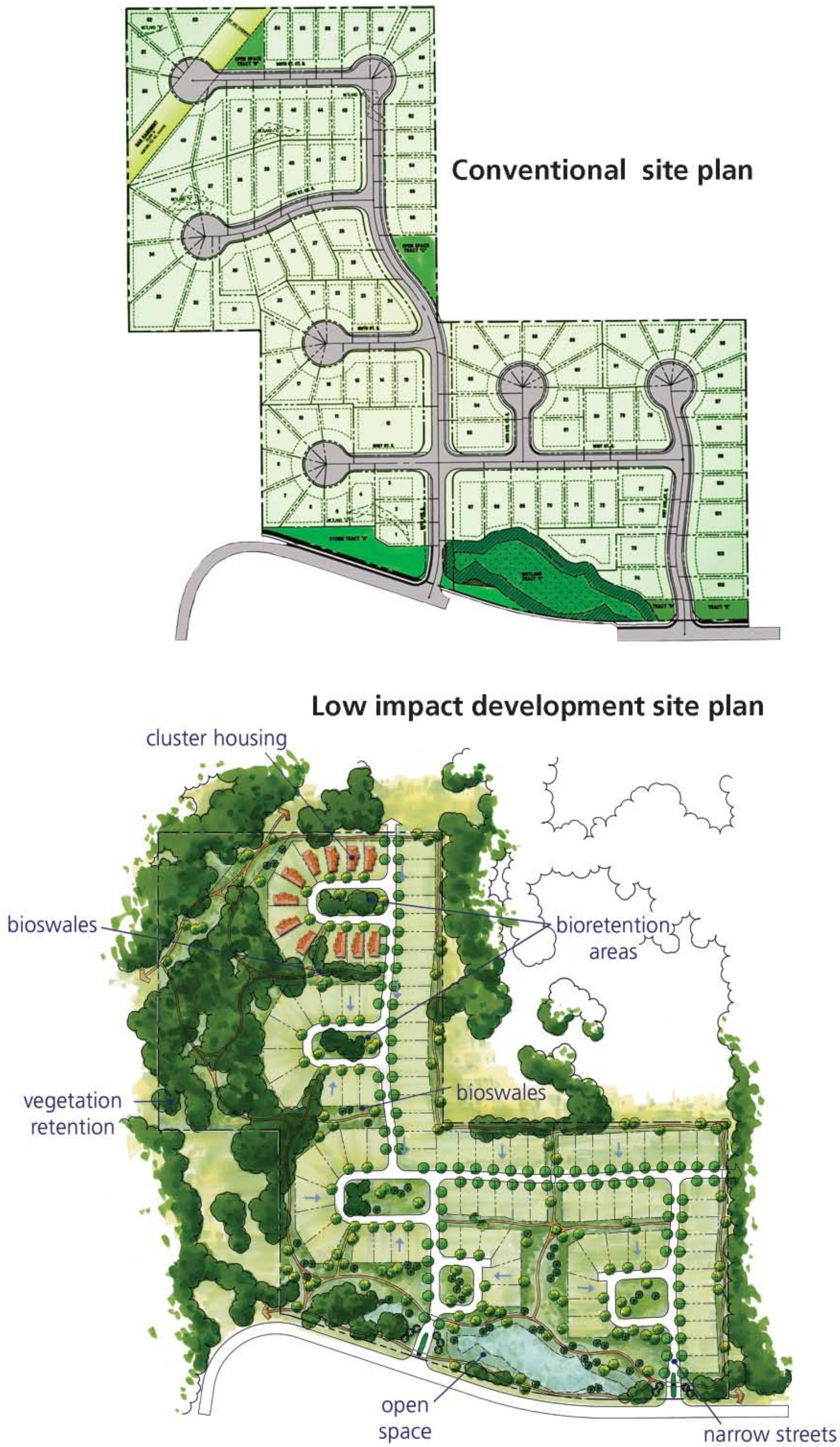


Figure 3.20 Conventional small lot development compared to LID cluster design.

Graphic by AHBL Engineering

Figure 3.21 Example of medium- to high-density lot using low impact development practices.

Graphic by AHBL Engineering

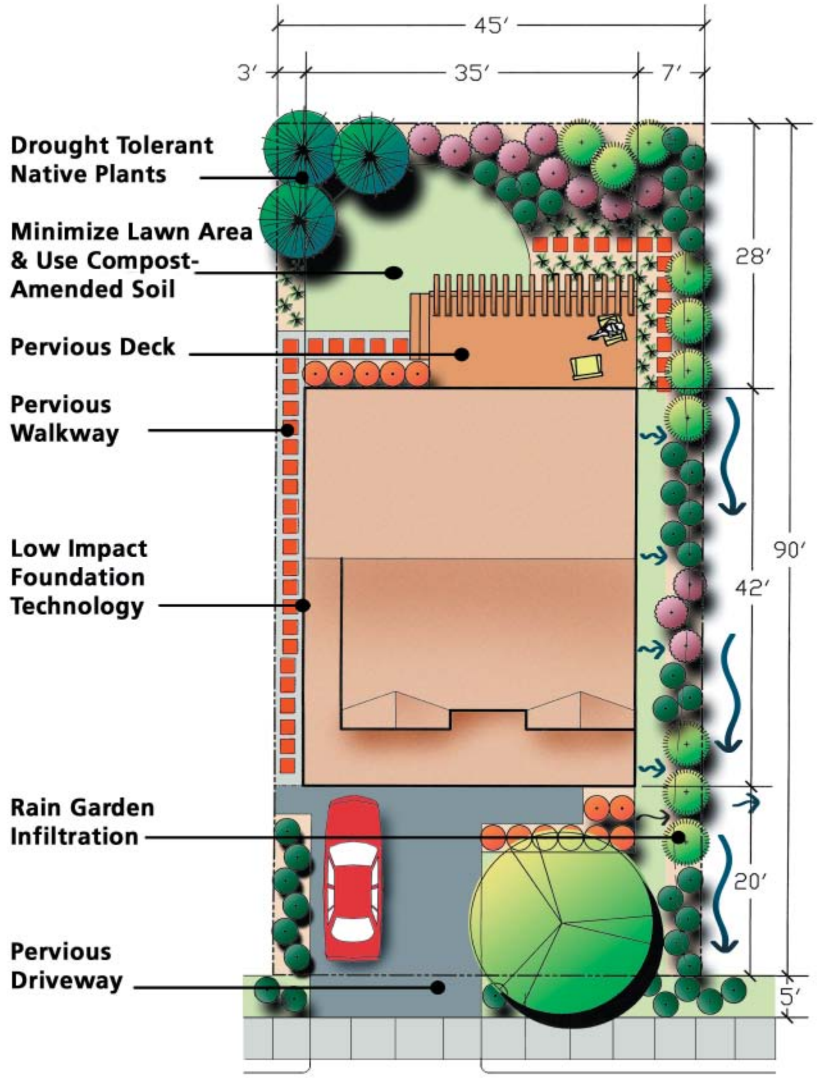


Figure 3.22 Zero lot line configuration.

Graphic by AHBL Engineering

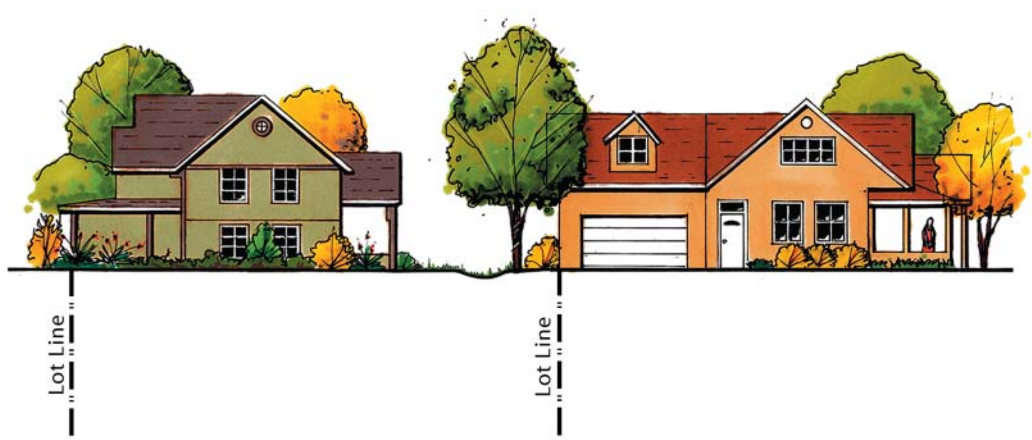


Figure 3.23 Shared courtyard in a cottage development in Seattle.
Photo by Curtis Hinman

Figure 3.24 Cluster of homes designed with vegetated roofs in Berlin, Germany.
Photo courtesy of Patrick Carey

- Minimize setbacks. Examples of minimum setbacks include:
  - o 25-foot front yard.
  - o 3-foot side yard (minimum side yard set backs should allow for fire protection ladder access, and structures with narrow side yards should use fire resistant siding materials).
- Use zero lot line set back to increase side yard area (Figure 3.22).
- Use cottage designs for a highly compact development envelope.
- Amend disturbed soils to regain stormwater storage capacity (see Section 6.2: Amending Construction Site Soils).
- Drain rooftops to cisterns for non-potable reuse within the house or garden (see Section 6.6: Roof Rainwater Collection Systems).
- Utilize vegetated roof systems to evaporate and transpire stormwater (see Section 6.4: Vegetated Roofs).
- Lay out roads and lots to minimize grading to the greatest extent possible.
- Stormwater from lots not adjacent to forested/open space infiltration areas can be conveyed in swales or dispersed as low velocity (< 1fps) sheet flow to the infiltration areas.
- Orient lots to use shared driveways to access houses along common lot lines.
- To maximize privacy and livability within cluster developments, locate as many lots as possible adjacent to open space, orient lots to capture views of open space, and design bioretention swales and rain gardens as visual buffers.
- Set natural resource protection areas aside as a permanent tract or tracts of open space with clear management guidelines.

A little known, but effective, cluster strategy is Air Space Condominium design. In this design scenario (applicable for most single family residential development), the property is not divided into separate lots. Instead, designated areas, or air space, that include the dwelling and some additional yard space (optional) are available for purchase with the remaining property held in common and managed by a homeowners association. The stormwater management practices are held within an easement for local jurisdiction access and require a long-term management agreement followed by the homeowners. The advantage of the condominium classification is increased design flexibility including:

- The entire road network can be considered as driveway reducing design standards for road widths, curb and gutter, etc.
- No minimum lot size.
- Reduced overall development envelope.

Note: fire and vehicle safety requirements must still be satisfied.

3.4.2 Rural Cluster and Large Lot Development

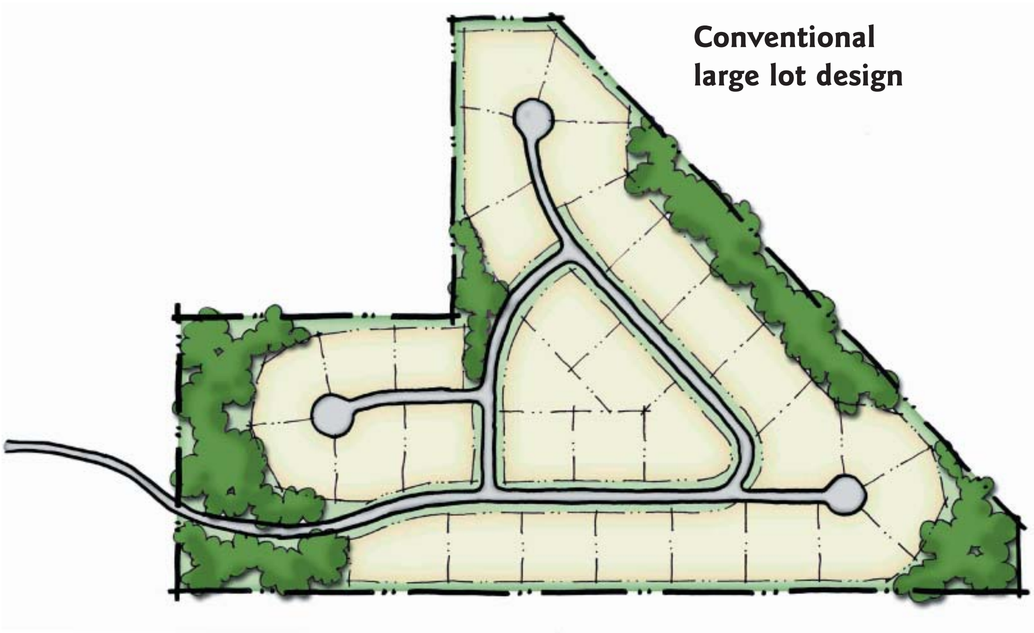
Substantial reduction of impervious surfaces can be realized through clustering large lot development. In a study comparing 100-lot subdivision designs, the Maryland Office of State Planning found a 30 percent reduction in impervious surface when lot size was reduced from a typical rural density of 1.4 to 0.25 acres. Additional road network and driveway lengths are the primary reasons for increased imperviousness associated with large lot development (Delaware Department of Natural Resources and Environmental Control and the Environmental Management Center of the Brandywine Conservancy, 1997). The increased storm flows from the additional road network required to serve rural cluster and large lot designs should be dispersed to bioretention swales, adjacent open space, and/or lawn areas amended with compost (figures 3.25 and 3.26).

Objectives for rural clustering and large lots:

- Reduce the development envelope in order to retain a minimum of 65 percent of the site in native soil and vegetation.
- Reduce EIA to zero (fully disperse stormwater).

Medium to high density cluster guidelines can be used in large lot settings. The increased land area in the rural cluster and large lot scenarios offer additional opportunities including:

- Integrate bioretention and open bioretention swale systems into the landscaping to store, infiltrate, slowly convey, and/or disperse stormwater on the lot.
- Disperse road and driveway stormwater to adjacent open space and lawn areas (see Chapter 7: Flow Modeling Guidance for dispersion details).
- Maintain pre-development flow path lengths in natural drainage patterns.
- Preserve or enhance native vegetation and soil to disperse, store, and infiltrate stormwater.
- Disperse roof water across the yard and to open space areas or infiltrate roof water in infiltration trenches.
- Lots may be organized into cluster units separated by open space buffers as long as road networks and driveways are not increased significantly, and the open space tract is not fragmented.
- Place clusters on the site and use native vegetation to screen or buffer higher density clusters from adjacent rural land uses.



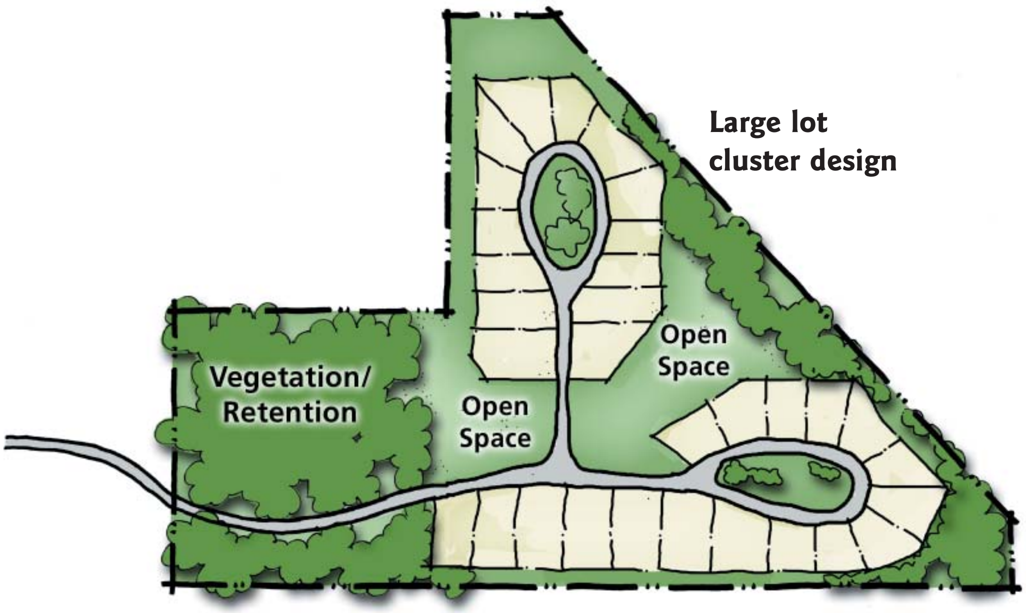


Figure 3.25 Conventional and large lot cluster designs.

Graphic by AHBL Engineering

3.5 Building Design

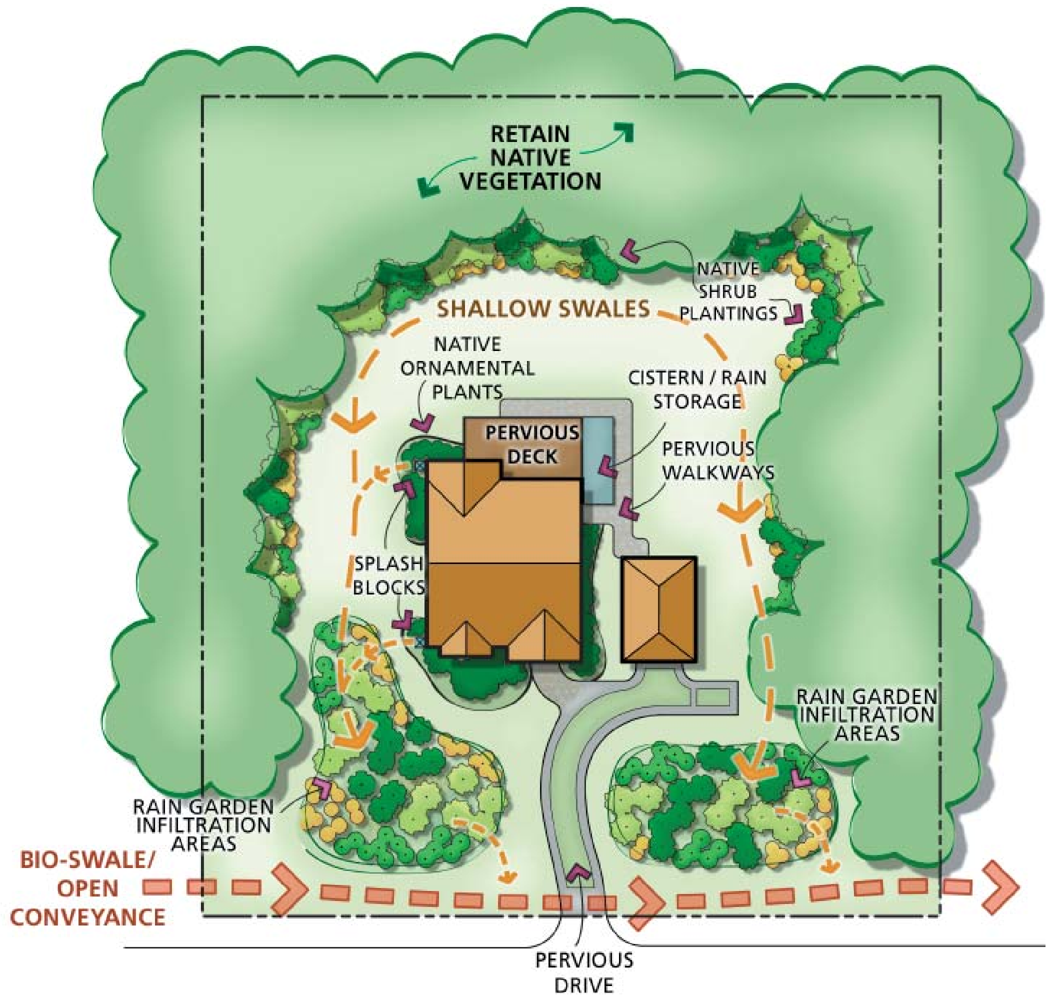
Impervious surface associated with roofs ranges from approximately 15 percent for single family residential, 17 percent for multifamily residential, and 26 percent for commercial development (City of Olympia, 1995). As densities increase for detached single-family residential development, opportunities for infiltrating roof stormwater decrease; however, other strategies to process this water can be applied.

Objectives for building design strategies are to disconnect roof stormwater from stormwater conveyance and pond systems (i.e., eliminate roofs as effective impervious surface), and reduce site disturbance from the building footprint. Strategies for minimizing storm flows and disturbance include:

- Reduce building footprint. Designing taller structures can reduce building footprints and associated impervious surface by one-half or more in comparison to a single story configuration. Proposals to construct taller buildings can also

Figure 3.26 Large lot LID design example.

Graphic by AHBL Engineering



present specific fire, safety, and health issues that may need to be addressed. For example, any residence over two stories requires a fire escape and a sprinkler system. These additional costs may be partially reduced by a reduction in stormwater conveyance and pond systems and stormwater utility fees.

- Orient the long axis of the building along topographic contours to reduce cutting and filling.
- Control roof water onsite (see Section 6.4 Vegetated Roofs and Section 6.6 Roof Rainwater Collection Systems for design guidelines).
- Use low impact foundations (see Section 6.5: Minimal Excavation Foundations).
- Limit clearing and grading to road, utility, building pad, landscape areas, and the minimum amount of extra land necessary to maneuver machinery. All other land should be delineated and protected from compaction with construction fencing. (see Chapter 4: Vegetation Protection, Reforestation, and Maintenance, and Chapter 5: Clearing and Grading).

LID in Green Cove Basin

The city of Olympia is using low impact development strategies and other environmental protection measures to preserve high quality forest and aquatic resources in Green Cove basin. One measure includes setting a maximum total impervious surface coverage of 2,500 square feet per lot (Title 18 Unified Development Code: Article II. Land Use Districts).

4 Vegetation Protection, Reforestation, and Maintenance

In this chapter...

- *Native vegetation protection*
- *Reforestation:*
  Plant evaluation and selection
  Plantings
- *Maintenance*

Mature native vegetation and soil are necessary to maintain watershed hydrology, stable stream channels, wetland hydroperiods, and healthy aquatic systems (Booth et al., 2002). While necessary to maintain aquatic systems, native vegetation and soils are also the most cost-effective and efficient tools for managing stormwater quantity and quality. Hydrologic modeling comparing conventional development and low impact development (LID) designs suggests that of the various LID applications, reducing the development envelope and increasing vegetation and soil conservation areas can provide the single largest reduction of storm flows (Table 4.1) (AHBL, 2002).

Table 4.1 Hydrologic modeling comparing a conventional development and the flow reduction benefits from individual practices for a low impact development design. The 24-acre till-mantled site in southern Puget Sound has 103 lots and was modeled with the Western Washington Hydrologic Model (adapted from AHBL, 2000).

	Detention storage reduced (ft^3)	Detention storage required (ft^3)
Conventional development	0	**270,000**
Low impact development		
Reduce development envelope, 24' wide road	- 149,019	
And use bioretention swales and cells	- 40,061	
And use minimal excavation foundations	- 7,432	
And use 20' wide permeable paving road	-29,988	
Total	-226,500	**43,500**

Retaining native soil and vegetation protection areas is a primary objective for low impact development in order to: (1) reduce total impervious surface coverage; (2) provide infiltration areas for overland flows generated in adjacent developed portions of the project; and (3) maintain or more closely mimic the natural hydrologic function of the site. The protection areas provide additional benefits, including critical area and habitat protection, open space corridors for passive recreation, visual buffers, and erosion and sediment control.

While necessary to maintain aquatic systems, native vegetation and soils are also the most cost-effective and efficient tools for managing stormwater quantity and quality.

Objectives for on-site native vegetation coverage:

- Rural and large lot development: 65 percent minimum.
- Medium density (4 to 6 dwelling units per acre): 50 percent minimum.

- High density (more than 6 dwelling units per acre): protect or restore to the greatest extent practical. Note: in medium to high density settings, reducing the development envelope and protecting native forest and soil areas will often require multifamily, condominium, cottage or mixed attached and detached single family homes (see Chapter 3: Site Planning and Layout).
- Riparian Management Areas can be included as a part of the native vegetation retention area and are the highest priority for native vegetation retention.

The 65 percent forest retention objective is a watershed level target based on best available science for maintaining watershed hydrologic functions (Booth et. al, 2002). Not all projects can achieve 65 percent protection at the project site. However, projects attaining 40, 50 or 60 percent native vegetation protection and using a full complement of LID practices still play a critical role in achieving overall watershed protection objectives when part of a larger planning process that strategically conserves riparian and other sensitive resources at a regional scale.

The following sections provide guidelines for native vegetation protection during the construction phase, enhancement or rehabilitation of impacted areas, and strategies for long-term maintenance.

4.1 Native Vegetation Protection

Native vegetation and soil protection areas in today's urban, suburban, and rural settings are fragments of pre-European contact forests and prairie. Natural successional forces have been altered and active management is required to compensate for the loss of natural processes and the addition of new stressors (Matheny and Clark, 1998). Vegetation protection areas not directly adjacent to structures (or located where they may potentially impact a structure) should be managed to encourage natural successional patterns and develop diverse multilayer canopy structure, snags, large woody debris, understory vegetation, and forest duff. The protection, reforestation, and management strategies provided below are designed to maintain vegetation cover, adequate soil building, and plant regeneration processes necessary for retaining these areas for the long term.

Assessment of natural resources and the site planning process will identify and delineate critical areas and native vegetation offering the best suite of benefits, including greatest infiltration potential. The final delineation and details of the management program for the vegetation protection areas requires assessment by a qualified urban forester or landscape architect that considers size of the area, type of soil, exposure, vegetation type and structure, invasive species impacts, human use, condition of existing vegetation, and existing and post-development hydrologic patterns in the area.

Selection of dispersed individual trees and tracks of native vegetation may be necessary to meet native forest and soil protection objectives. Individual trees selected for protection should have developed as individuals with well-tapered trunks and good live crown ratios (total tree height in relation to the height of the live crown). Trees from dense stands with tall, poorly tapered trunks and high irregular shaped crowns generally do not adapt to wind and sun exposure and are not good candidates to preserve as single trees (Figure 4.1) (Matheny and Clark, 1998). As a general guideline, conifers with live crown ratios of less than 30 percent tend to break in winds while trees with ratios greater than 50 percent tend to be more stable (Matheny and Clark, 1998).

LID in Green Cove Basin

To protect sensitive aquatic resources, the city of Olympia requires all development in the Green Cove basin to have approximately 55 percent tree cover.

Figure 4.1 These native trees that were retained during clearing have low live crown ratios.
Photo by Curtis Hinman

Trees and other native vegetation that developed in forests or woodlands are best retained in groups of sufficient size to maintain adequate growing space characteristics and the integrity of the unit. Growing space characteristics include soil moisture, sunlight, humidity, wind, competition among adjacent plants, and other growth factors. Retaining small fragments of mature, single species trees adapted to the interior of a forest stand is seldom successful (Matheny and Clark, 1998). Additional stressors along newly exposed edges of larger preserved vegetation tracts can affect unit integrity and result in high initial plant mortality on the perimeter. Replacement of unhealthy trees and other vegetation with material adapted to edge environments, as well as invasive species control, may be necessary (Matheny and Clark, 1998).

Delineation and management of larger tracts and smaller scale, dispersed protection areas are necessary to meet retention objectives on most sites. Larger contiguous tracts are more likely to sustain healthy soils, retain diverse and dense vegetation coverage, and have less area affected by edge stress factors (increased sunlight, wind, and invasive species). Small-scale dispersed protection areas can be located to intercept storm flows at the source, reduce flow volumes within small contributing areas, and maintain time of concentration. Specific site and design requirements will influence the type and distribution of protection areas; however, the location and type of area can influence the extent of benefit and long-term viability.

The following provides a list of native vegetation and soil protection areas prioritized by location and type of area:

1. Large tracts of riparian areas that connect and create contiguous riparian protection areas.
2. Large tracts of critical and wildlife habitat area that connect and create contiguous protection areas.
3. Tracts that create common open space areas among and/or within developed sites.
4. Protection areas on individual lots that connect to areas on adjacent lots or common protection areas.
5. Protection areas on individual lots.

4.1.1 Protection During the Construction Phase

Soil compaction is a leading cause of death or decline of mature trees in developed areas (World Forestry Center, 1989). Most tree roots are located within 3 feet of the ground surface and the majority of the fine roots active in water and nutrient absorption are within 18 inches. Root systems can extend 2 to 3 times beyond the diameter of the crown (World Forestry Center and Morgan, 1993 and Matheny and Clark, 1998). Equipment activity on construction sites can severely compact soil, essentially eliminating soil pore structure at 6 to 8 inches below the ground surface. Compaction can extend as deep as 3 feet depending on soil type, soil moisture, and total axle load of the equipment. Foot traffic can exert per unit area pressure similar to that of a vehicle and significantly compact soil as well (Corish, 1995 and World Forestry Center and Morgan, 1989). Soil compaction results in a reduction of soil oxygen and an increase in **soil bulk density**. In response to soil compaction, tree root penetration, root respiration, and associated uptake of nutrients and minerals decline, **mycorrhizal** activity is reduced, and susceptibility to root disease increases (Matheny and Clark, 1998).

Soil compaction is a leading cause of death or decline of mature trees in developed areas.

Several other direct and indirect impacts can influence vegetation health during land development including:

- Direct loss of roots from trenching, foundation construction, and other grade changes.
- Application of fill material that can compact soil, reduce oxygen levels in existing grade, and change soil chemistry.
- Damage to trunks or branches from construction equipment and activities.
- Exposure of forest interior areas to new stresses of forest edges as land is cleared.
- Changes in surface and subsurface water flow patterns.

Detrimental impacts to native vegetation and soil protection areas can be minimized through the following strategies:

- Map native soil and vegetation protection areas on all plans and delineate these areas on the site with appropriate fencing to protect soils and vegetation from construction damage. Fencing for forest protection areas should be located at a minimum of 3 feet beyond the existing tree canopy along the outer edge of the tree stand. Fencing should provide a strong physical and visual barrier of high strength plastic or metal and be a minimum of 3 to 4 feet high (see Ecology 2005 SMMWW BMP C103 and C104). Silt fencing, or preferably a compost berm, is necessary in addition to, or incorporated with, the barrier for erosion control.
- Install signs to identify and explain the use and management of the natural resource protection areas.
- Meet and walk property with equipment operators to clarify construction boundaries and limits of disturbance.
- Protect drainage areas during construction. Channel or drainage swales that provide a hydrologic connection to vegetation protection area(s) should be protected throughout the construction phase by fencing and erosion control measures to prevent untreated construction site runoff from entering the channel.

- Protect trees and tree root systems utilizing the following methods:
  - o Minimize soil compaction by protecting critical tree root zones. The network of shallow tree roots, active in nutrient and water uptake, extends beyond the **tree canopy dripline**. Several methods can be used to assess the area necessary to protect tree roots. The dripline method may be applicable for broad-canopy trees; however, this method will likely underestimate the extent of roots and lead to extensive root damage for narrow-canopied trees and leaning trees with canopies extending to one side more than the other. As a general guideline, the trunk diameter method provides more design flexibility for variable growth patterns. This method provides a protection area with a 1-foot radius for every 1 inch of trunk diameter at chest height (DBH ~ 4.5ft). Factors that influence the specific distance calculated include the tree's tolerance to disturbance, age, and vigor (Matheny and Clark, 1998).
  - o Limit to an absolute minimum any excavation within the critical root zone. Tree species and soils will influence the ability of a tree to withstand disturbance. If the tree(s) are to be preserved and excavation in the critical root zone is unavoidable, consult a certified arborist for recommendations.
  - o Prohibit the stockpiling or disposal of excavated or construction materials in the vegetation retention areas to prevent contaminants from damaging vegetation and soils.
  - o Avoid excavation or changing the grade near trees that have been designated for protection. If the grade level around a tree is to be raised, a retaining wall (preferably with a discontinuous foundation to minimize excavation) should be constructed around the tree. The diameter of the wall should be at least equal to the diameter of the tree canopy plus five feet. If fill is not structural, compact soil to a minimum (usually 85 percent proctor) (World Forestry Center and Morgan, 1993). Some trees can tolerate limited fill if proper soils and application methods are used. Subsoil irrigation may be required. Consult a certified arborist for recommendations.
  - o Tree root systems tend to tangle and fuse among adjacent trees. Trees or woody vegetation that will be removed and that are next to preserved trees should be cut rather than pushed over with equipment (World Forestry Center and Morgan, 1993). Stumps can be ground if necessary.
  - o Restrict trenching in critical tree root zone areas. Consider boring under or digging a shallow trench through the roots with an air spade if trenching is unavoidable.
  - o Prevent wounds to tree trunks and limbs during the construction phase.
  - o Prohibit the installation of impervious surfaces in critical root zone areas. Where road or sidewalk surfaces are needed under a tree canopy, non-mortared porous pavers or flagstone (rather than concrete or asphalt) or bridging techniques should be used.
  - o Prepare tree conservation areas to better withstand the stresses of the construction phase by watering, fertilizing, pruning, and mulching around them well in advance of construction activities.

4.2 Reforestation

Soil and vegetation protection areas that have been disturbed and do not have vegetation of sufficient size, quantity, and quality to achieve the necessary coverage may require soil enhancement and replanting with native trees and vegetation in order to achieve the full hydrologic benefits of the site (see Section 6.2: Amending Construction Site Soils for soil guidelines). Consult with a qualified urban forester or landscape architect to develop a long-term vegetation and soil management plan.

4.2.1 Existing Plant Evaluation and Site Preparation

Trees remaining in the protection area should have the following characteristics:

- No major pest or pathological problems.
- No extensive crown damage.
- No weakly attached co-dominant trunks if located in areas where failure could cause damage or safety problems.
- Relatively sound trunks without extensive decay or damage.
- Wind-firm in the post development condition.

(Matheny and Clark, 1998).

Trees identified as having significant wildlife value such as snags and nesting sites should be retained regardless of the health of the tree, unless the tree poses an imminent safety threat as determined by a qualified arborist or urban forester (Pierce County Ordinance No 2003-66, 18H.40.040, Tree Conservation Standards).

Intensive inventories and individual tree health evaluation is generally limited to areas where trees can damage existing or proposed structures. Depending on the physical setting, regulatory requirements, aesthetics, and other specific management needs, inventories and subsequent evaluations may be necessary in portions or all of the protection area's interior. If inventories and management plans indicate deficiencies in protected area vegetation structure, removing unhealthy trees may be desirable to free growing space, encourage new seedlings and create age and species diversity. The site should be prepared for planting by removing invasive species, stabilizing erosion areas, and enhancing soil with compost amendment where necessary.

4.2.2 Plant Selection

The native vegetation species should be selected based on the underlying soils and the historic, native indigenous plant community type for the site (Pierce County Ordinance No 2003-66, Exhibit B, Chapter 10, Low Impact Development). Coniferous trees provide greater interception, storage, and evaporation potential in the wet months and should be the major component of the protection area if ecologically compatible with the site. A single species of vegetation should not be used for replacement purposes.

Coniferous trees provide greater interception, storage, and evaporation potential in the wet months and should be the major component of the protection area if ecologically compatible with the site.

The following general guidelines are recommended for installing a self-sustaining native plant community that is compatible with the site and minimizes long-term maintenance requirements:

- The plantings should provide a multilayer canopy structure of large trees, small trees, and shrubs.
- Emphasize climax species, for example Douglas fir (*psuedotsuga menziesii*), on drier sites with more sun exposure, and western red cedar (*thuja plicata*),

western hemlock *(tsuga heterophylla)*, or sitka spruce (*picea sitchensis*) on wetter sites with less sun exposure.

- For many sites, a ratio of 2 evergreens to 1 deciduous tree will provide a mix similar to native forests.
- To create a multilayer canopy, install 50 percent large structure trees to 50 percent small trees and shrubs.
- Space large trees at 15 to 20 feet and shrubs at 4 feet on center.
- The installation should be designed to develop to a dense closed canopy (when compatible with the site) to provide interception and evaporation of precipitation in the wet months and shade the site to exclude invasive vegetation species.

(Personal communication, Bill Barnes August, 2004)

Plants should conform to the standards of the current edition of *American Standard for Nursery Stock* as approved by the American Standards Institute, Inc. All plant grades should be those established in the current edition of *American Standards for Nursery Stock* (current edition: ANSI Z60.1-2004). All plant materials for installation should:

- Have normal, well-developed branches and a vigorous root system.
- Be healthy and free from physical defects, diseases, and insect pests.
- Not have weakly attached co-dominant trunks.

4.2.3 Plant Size

Selecting the optimum size of plant material for installation includes several factors. In general, small plant material requires less careful handling, less initial irrigation, experiences less transplant shock, is less expensive, adapts more quickly to a site, and transplants more successfully than larger material (Sound Native Plants, 2000). Smaller plant material is, however, more easily overgrown by weeds and invasive species such as reed canary grass, is more susceptible to browse damage, and is more easily damaged by maintenance personnel or landowners (Kantz, 2002). Accordingly, the following recommendations are provided:

- Where invasive species are not well established, weeds and browsing are controlled regularly, and maintenance personnel and landowners are trained in proper maintenance procedures, smaller material will likely have a lower mortality rate, is less expensive, and is recommended. Small trees and shrubs are generally supplied in pots of 3 gallons or less.
- Where invasive species are prevalent and weed and browse control is not ensured, larger plant material is recommended. Larger plants will require additional watering during the establishment period.
- For larger tree stock, coniferous and broadleaf evergreen material should be a minimum of 3 feet in height and deciduous trees should have a minimum caliper size of 1 inch (Kantz, 2002).

Native species should be used for vegetation and soil protection areas not adjacent to residential lots or commercial development. Depending on aesthetic needs, cultivars adapted to the region for hardiness may be used in transition areas between protection areas and structures. For growth characteristics and site suitability of trees and shrubs native or adapted to the Pacific Northwest see Appendix 1: Street Trees and Appendix 3: Bioretention Area Plants.

4.2.4 Reference Documents for Planting

Vegetation restoration/planting methods should conform to published standards. The following guidance documents are examples:

- *Restoring the Watershed: A Citizen's Guide to Riparian Restoration in Western Washington,* Washington Department of Fish and Wildlife, 1995.
- *Plant It Right Restoring Our Streams,* Washington State University Extension http://wawater.wsu.edu
- *Integrated Streambank Protection Guidelines*, Washington Department of Fish and Wildlife, 2000.
- *Surface Water and Groundwater on Coastal Bluffs: A Guide for Puget Sound Property Owners*, Washington Department of Ecology, Shorelands and Coastal Zone Management Program Publication No. 95-107, 1995.
- *Vegetation Management: A Guide for Puget Sound Bluff Property Owners*, Washington Department of Ecology, Shorelands and Coastal Zone Management Program Publication No. 93-31, 1993.
- *Relative Success of Transplanted/Outplanted Plants*, Sound Native Plants, 2000.

Plants installed in the fall generally outperform late winter or spring plantings. In fall, the soil is warmer and more aerated than in the spring and transpiration requirements are less than in the spring and summer months. During the fall and winter, plants can develop sufficient root systems, recover from transplant shock, and prepare for the top growth and water demands of the growing season (Sound Native Plants, 2000).

4.3 Maintenance

In a low impact development, native vegetation and soil protection areas serve as stormwater management facilities. Clearly written management plans and protection mechanisms are necessary for maintaining the benefits of these areas over time. Some mechanisms for protection include dedicated tracts, conservation and utility easements, transfer to local land trusts (large areas), and homeowner association covenants. Property owner education should be part of all these strategies.

Ongoing maintenance should include weeding, watering, erosion and sediment control, and replacement of dead plant material for a minimum of three years from installation in order to achieve a minimum 80 percent survival of all plantings. If during the three-year period survival of planted vegetation falls below 80 percent, additional vegetation should be installed to achieve the required survival percentage. Additionally, the likely cause of the plant mortality should be determined (often poor soils and compaction) and corrected. If it is determined that the original plant choices are not well suited to site conditions, these plants should be replaced with plant species better suited to the site.

In a low impact development, native vegetation and soil protection areas serve as stormwater management facilities. Clearly written management plans and protection mechanisms are necessary for maintaining the benefits of these areas over time.

Permanent signs should be installed explaining the purpose of the area, the importance of vegetation and soils for managing stormwater, and that removal of trees or vegetation and compaction of soil is prohibited within the protected area. Permanent fencing, rock barriers, bollards or other access restriction at select locations or around the perimeter of protection areas may be required to limit encroachment.

5 Clearing and Grading

In this chapter...

- *Techniques to minimize site disturbance*

Protecting native soil and vegetation and retaining hydrologic function during the clearing and grading phase presents one of the most significant challenges within the development process. Upper soil layers contain organic material, soil biota, and a structure favorable for storing and slowly conducting stormwater down gradient. Clearing and grading exposes and compacts underlying subsoil, producing a site with significantly different hydrologic characteristics. On till soil, precipitation is rapidly converted to overland flow. Surface and interflow are usually less on sites with native outwash soils and vegetation compared to native till conditions. Accordingly, the increase in overland flow from pre- to post-construction conditions can be greater on outwash than till sites if impervious areas are not minimized and soil structure is not protected for infiltration.

In addition to hydrologic modifications, sediment yield from clearing, grading and other construction activities can significantly affect receiving waters. Gammon found that stream biota was significantly reduced at suspended solids levels of 50 to 80mg/L (Corish, 1995). Schueler reported a median total suspended solids concentration of 4,145 mg/L leaving construction sites without erosion and sediment control and 283 mg/L at sites with controls (the range of concentrations with controls—11 to 2,070 mg/L in the study—was highly variable) (Corish, 1995). Typically, sediment and erosion is managed through structural practices; however, reliance on structural approaches alone to compensate for widespread vegetation loss can add unnecessary construction costs and may not provide adequate protection for aquatic habitat and biota. Minimizing site disturbance as a primary strategy to control erosion reduces the extent of grading, retains vegetation cover, and is the most cost-efficient and effective method for controlling sediment yield (Corish, 1995).

> *Minimizing site disturbance as a primary strategy to control erosion reduces the extent of grading, retains vegetation cover, and is the most cost-efficient and effective method for controlling sediment yield.*

Several factors including topography, hydrology, zoning density and plat design, and housing type influence the timing and extent of clearing and grading activities. The scope of this section does not include the regulatory and market structure influencing clearing and grading, but rather focuses on planning and implementation techniques to reduce impacts to native soils, vegetation, and hydrology on the site.

Proper installation and maintenance of erosion and sediment control **best management practices** (BMPs) are required during the clearing, grading, and construction phases of a project. For detailed guidelines and specifications for erosion and sediment control BMPs see Washington State Department of Ecology 2005 *Stormwater Management Manual for Western Washington* Volume II chapter 4.

5.1 Techniques to Minimize Site Disturbance

Planning and implementation techniques to minimize site disturbance fall into four categories:

- **Site design**
- **Construction planning**
- **Training**
- **Equipment**

5.1.1 Efficient Site Design

- Reduce the overall development envelope and maximize protection of native soils and vegetation with efficient road layout and cluster design (see Chapter 3: Site Planning and Layout).
- Retain natural topographic features that slow and store storm flows.
- Do not increase steep continuous slopes.
- Limit overall project cut and fill through efficient road design and lot layout.
- Minimize cut and fill by orienting the long axis of buildings along contours or staggering floor levels for buildings to adjust to gradient changes.
- Use minimal excavation foundation systems to reduce grading (see Section 6.5 Minimal Excavation Foundations for details).
- Limit clearing and grading disturbance to road, utility, building pad, landscape areas, and the minimum additional area needed to maneuver equipment (a 10-foot perimeter around the building site can provide adequate work space for most activities).
- Limit the construction access to one route if feasible, and locate access where future roads and utility corridors will be placed.

5.1.2 Coordinated Planning and Activities among Construction Entities

- Begin clearing, grading and heavy construction activity during the driest months and conclude by late fall when rainfall and associated soil compaction, erosion, and sediment yield from equipment activity increases. Late fall is also when conditions are most favorable for establishing vegetation.
- Plan efficient sequencing of construction phases to reduce equipment activity and potential damage to soil and vegetation protection areas.
- Establish and maintain erosion and sediment controls before or immediately after clearing and grading activity begins.
- Phase project to complete operations in one section of the site before clearing and grading the next. Project phasing is challenging when coordinating utility, road, and other activities (Corish, 1995). The greatest potential to implement and benefit from phasing will be on large projects where extensive exposed areas are difficult to stabilize over long periods.
- Map native soil and vegetation protection areas on all plans and delineate these areas on the site with appropriate fencing to protect soils and vegetation from clearing, grading, and construction damage. Fencing should provide a strong physical and visual barrier of high strength plastic or metal and be a minimum of 3 to 4 feet high (see Ecology 2005 SMMWW BMP C103 and

C104). Silt fencing, or preferably a compost berm, is necessary in addition to, or incorporated with, the barrier for erosion control.

- Stockpile materials in areas designated for clearing and grading (avoid areas within the development envelope that are designated for bioretention or other bioretention areas).
- Stockpile and reuse excavated topsoil to amend disturbed areas (see Section 6.2: Amending Construction Site Soils for details).
- Small stockpiles of soil should be covered and larger piles seeded for erosion control during wet months.
- Inspections (Corish, 1995):
    - Conduct a pre-construction inspection to determine that adequate barriers have been placed around vegetation protection areas and structural controls are implemented properly.
    - Routine inspections should be conducted to verify that structural controls are maintained and operating effectively throughout construction, and that soil structure and vegetation are maintained within protection areas.
    - Conduct a final inspection to verify that re-vegetated areas are stabilized and that stormwater management systems are in place and functioning properly.

5.1.3 Training Personnel Implementing Project Activities

- Install signs to identify limits of clearing and grading, and explain the use and management of the natural resource protection areas.
- Meet and walk the property with equipment operators regularly to clarify construction boundaries, limits of disturbance, and construction activities.
- Require erosion and sediment control training for operators.

5.1.4 Proper Equipment

Research in the agricultural setting indicates that ground contact pressure generally determines the potential for compaction in the upper 6 to 8 inches of soil while total axle load can influence compaction in the deeper subsoil layers. Vehicles with tracks or tires with axle loads exceeding 10 tons per axle can compact soils as deep as 3 feet (Delong-Hughes, Moncrief, Voorhees and Swan, 2001). A majority of the total soil compaction (70 to 90 percent) can occur in the first pass with equipment (Balousek, 2003).

To minimize the degree and depth of compaction, use equipment with the least ground pressure to accomplish tasks. For smaller projects, many activities can be completed with mini-track loaders that are more precise, require less area to operate, exert less contact pressure than equipment with deep lugged tires, and have lower total axle weight (personal communication, James Lux, August 2004).

6 Integrated Management Practices

In this chapter...

Specifications for:
- *Bioretention areas*
- *Amending construction site soils*
- *Permeable paving*
- *Vegetated roofs*
- *Minimal excavation foundations*
- *Roof rainwater collection systems*

Integrated management practices (IMPs) are the tools used in a low impact development (LID) project for water quality treatment and flow control. The term IMP is used instead of best management practice or BMP (used in a conventional development) because the controls are integrated throughout the project and provide a landscape amenity in the LID design.

6.1 Bioretention Areas

The bioretention concept originated in Prince George's County, Maryland in the early 1990s and is a principal tool for applying the LID design approach. The term bioretention was created to describe an integrated stormwater management practice that uses the chemical, biological, and physical properties of plants, microbes, and soils to remove, or retain, pollutants from stormwater runoff. Numerous designs have evolved from the original application; however, there are fundamental design characteristics that define bioretention across various settings.

Bioretention areas (also known as rain gardens) are:

- Shallow landscaped depressions with a designed soil mix and plants adapted to the local climate and soil moisture conditions that receive stormwater from a small contributing area.
- Facilities designed to more closely mimic natural conditions, where healthy soil structure and vegetation promote the infiltration, storage, and slow release of stormwater flows.
- Small-scale, dispersed facilities that are integrated into the site as a landscape amenity.
- An IMP designed as part of a larger LID approach. Bioretention can be used as a stand-alone practice on an individual lot, for example; however, best performance is achieved when integrated with other LID practices.

> *Bioretention is an integrated stormwater management practice that uses the chemical, biological, and physical properties of plants, microbes, and soils to remove, or retain, pollutants from stormwater.*

The term bioretention is used to describe various designs using soil and plant complexes to manage stormwater. The following terminology is used in this manual:

- Bioretention cells: Shallow depressions with a designed planting soil mix and a variety of plant material, including trees, shrubs, grasses, and/or other herbaceous plants. Bioretention cells may or may not have an under-drain and are not designed as a conveyance system.

- Bioretention swales: Incorporate the same design features as bioretention cells; however, bioretention swales are designed as part of a conveyance system and have relatively gentle side slopes and flow depths that are generally less than 12 inches.
- Bio*detention:* A design that uses vegetative barriers arranged in hedgerows across a slope to disperse, infiltrate, and treat stormwater (see sloped biodetention description in this chapter).

The following section outlines various applications and general design guidelines, as well as specifications, for individual bioretention components. Design examples are also included in Appendix 2 to provide designers with a pool of concepts and specifications useful for developing bioretention facilities specific to local needs. This section draws information from numerous sources; however, many of the specifications and guidelines are from extensive work and experience developed in Prince George's County, Maryland and the city of Seattle.

6.1.1 Applications

While the original concept of bioretention focused on stormwater pollutant removal, the practice is also used for water quantity control. Where the surrounding native soils have adequate infiltration rates, bioretention can be used as a retention facility. Under-drain systems can be installed and the facility used to filter pollutants and detain flows that exceed infiltration capacity of the surrounding soil. However, designs utilizing under-drains provide less flow control benefits.

Rain gardens are a landscape amenity and a stormwater control practice that can be applied in various settings, including:

- Individual lots for rooftop, driveway, and other on-lot impervious surface infiltration.
- Shared facilities located in common areas for individual lots.
- Areas within loop roads or cul-de-sacs.
- Landscaped parking lot islands.
- Within right-of-ways along roads (linear bioretention swales and cells).
- Common landscaped areas in apartment complexes or other multifamily housing designs.

Figure 6.1.1 Bioretention area in center of apartment building courtyard, Portland, Oregon.
Photo by Curtis Hinman

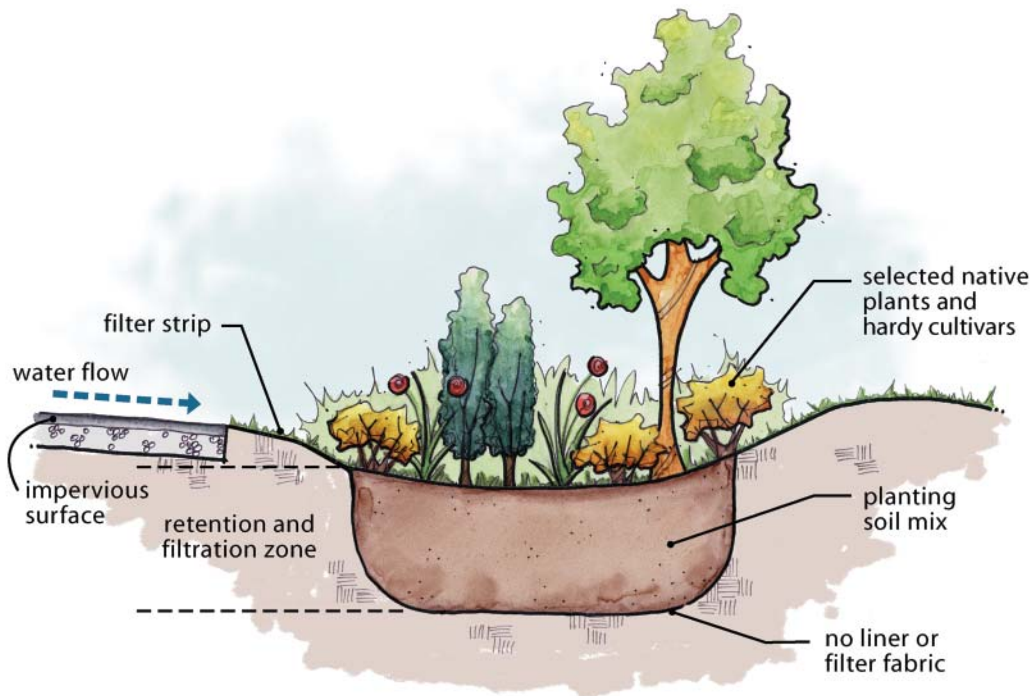


Figure 6.1.2 Cross-section of a basic bioretention cell with no under-drain.

Graphic by AHBL Engineering

6.1.2 Design

Bioretention systems are placed in a variety of residential and commercial settings, and are a visible and accessible component of the site. Design objectives and site context are, therefore, important factors for successful application.

The central design considerations include:

- *Soils:* The soils underlying and surrounding bioretention facilities are a principal design element for determining infiltration capacity, sizing, and rain garden type. The planting soil placed in the cell or swale is highly permeable and high in organic matter (e.g., loamy sand, USDA soil texture classification, mixed thoroughly with compost amendment) and a surface mulch layer. See Section 6.1.2.3: Bioretention Components for details.
- *Site topography:* For slopes greater than 10 percent, sloped biodetention and weep garden designs can be used. See Section 6.1.2.1: Types of bioretention areas.
- *Depth-to-water table:*
  - o A minimum separation of 1 foot from the seasonal high water mark to the bottom of the bioretention area is recommended where the contributing area of the bioretention has less than 5,000 square feet of pollution-generating impervious surface; and less than 10,000 square feet of impervious surface; and less than ¾ acres of lawn. Recommended separation distances for bioretention areas with small contributing areas are less than the new Department of Ecology (Ecology) recommendation of 3 feet for two reasons: (1) bioretention soil mixes provide effective pollutant capture; and (2) hydrologic loading and potential for groundwater mounding is reduced when managing flows from small contributing areas.
  - o A minimum separation of 3 feet from the seasonal high water mark to the bottom of the bioretention area is recommended where the contributing

area of the bioretention area is equal to or exceeds any of the following limitations: 5,000 square feet of pollution-generating impervious surface; or 10,000 square feet of impervious surface; or ¾ acres of lawn and landscape. See Bioretention Areas in Chapter 7 for flow modeling guidance.

- *Expected pollutant loading:* See sections 6.1.2.3: Bioretention components and 6.1.4: Performance for recommended designs by pollutant type.
- *Site growing characteristics and plant selection:* Appropriate plants should be selected for sun exposure, soil moisture, and adjacent plant communities. Invasive species control may also be necessary.
- *Transportation safety:* The design configuration and selected plant types should provide adequate sight distances, clear spaces, and appropriate setbacks for roadway applications.
- *Visual buffering:* Bioretention facilities can be used to buffer structures from roads, enhance privacy among residences, and for an aesthetic site feature.
- *Ponding depth and surface water draw-down:* Flow control needs, as well as location in the development, will determine draw-down timing. For example, front yards and entrances to residential or commercial developments may require rapid surface dewatering for aesthetics. See Section 6.1.2.3: Bioretention components for details.
- *Impacts of surrounding activities:* Human activity influences the location of the facility in the development. For example, locate bioretention areas away from traveled areas on individual lots to prevent soil compaction and damage to vegetation, and provide barriers to restrict vehicle access in roadside applications.
- *Setbacks:* Local jurisdiction guidelines should be consulted for appropriate bioretention area setbacks from wellheads, on-site sewage systems, basements, foundations, and utilities.

6.1.2.1 Types of bioretention areas

Numerous designs have evolved from the original bioretention concept as designers have adopted the practice to different physical settings. Types of bioretention designs include:

- Bioretention cells integrated into gardens on individual lots.

Figure 6.1.3 Bioretention cell integrated into landscaping.
Photo by Larry Coffman

- Curb or curbless bioretention in landscaped parking lot islands.

Figure 6.1.4 Bioretention landscaped island with curb cut to allow flows to enter.
Photo by Larry Coffman

- **Off-line bioretention** areas (Figure 6.1.5) are placed next to a swale with a common flow entrance and flow exit, and the bioretention invert placed below the swale **invert** to provide the proper ponding depth (often 6 to 12 inches).

Figure 6.1.5 (left) Off-line bioretention area adjacent to roadside swale.
Photo by Larry Coffman

Figure 6.1.6 (right) Bioretention swale in Seattle.
Photo courtesy of Seattle Public Utilities

- **In-line bioretention** swales are hybrid facilities usually installed along roadways that incorporate bioretention cell and swale characteristics (see Figure 6.1.6 and Appendix 2: Bioretention Examples for design details).

- Sloped or weep garden bioretention areas (Figure 6.1.7) are used for steeper gradients where a retaining wall is used for structural support and for allowing storm flows, directed to the facility, to seep out.

- Sloped biodetention-use vegetative barriers, designed for a specific hydraulic capacity, placed along slope contours (see Figure 6.1.8 and Appendix 2: Bioretention Examples for design details).

Figure 6.1.7 Sloped or weep garden bioretention area.

Photo courtesy of LID Center

Figure 6.1.8 Sloped biodetention area.

Photo courtesy of Murphee Engineering

- Tree box filters are street tree plantings with an enlarged planting pit for additional storage, a storm flow inlet from the street or sidewalk, and an underdrain system.

Figure 6.1.9 Tree box filter.

Photo by Puget Sound Action Team

6.1.2.2 Determining infiltration rates

Infiltration rates are necessary to determine flow reduction benefits for bioretention areas when using the Western Washington Hydrologic Model (WWHM) or MGS Flood. See Figure 6.1.10 for a graphic representation of the process to determine infiltration rates.

The assumed infiltration rate for determining the flow reduction benefits of bioretention areas should be the lower of the estimated long-term rate of the planting soil mix or the initial (short-termed or measured) infiltration rate of the underlying soil profile. The overlying planting soil mix protects the underlying native soil from sedimentation; accordingly, the underlying soil does not require a correction factor. See Chapter 7 for more detail on flow control modeling for bioretention areas.

The following provides recommended tests for the soils underlying and planting soil mixes within bioretention areas.

1. Underlying native soils:

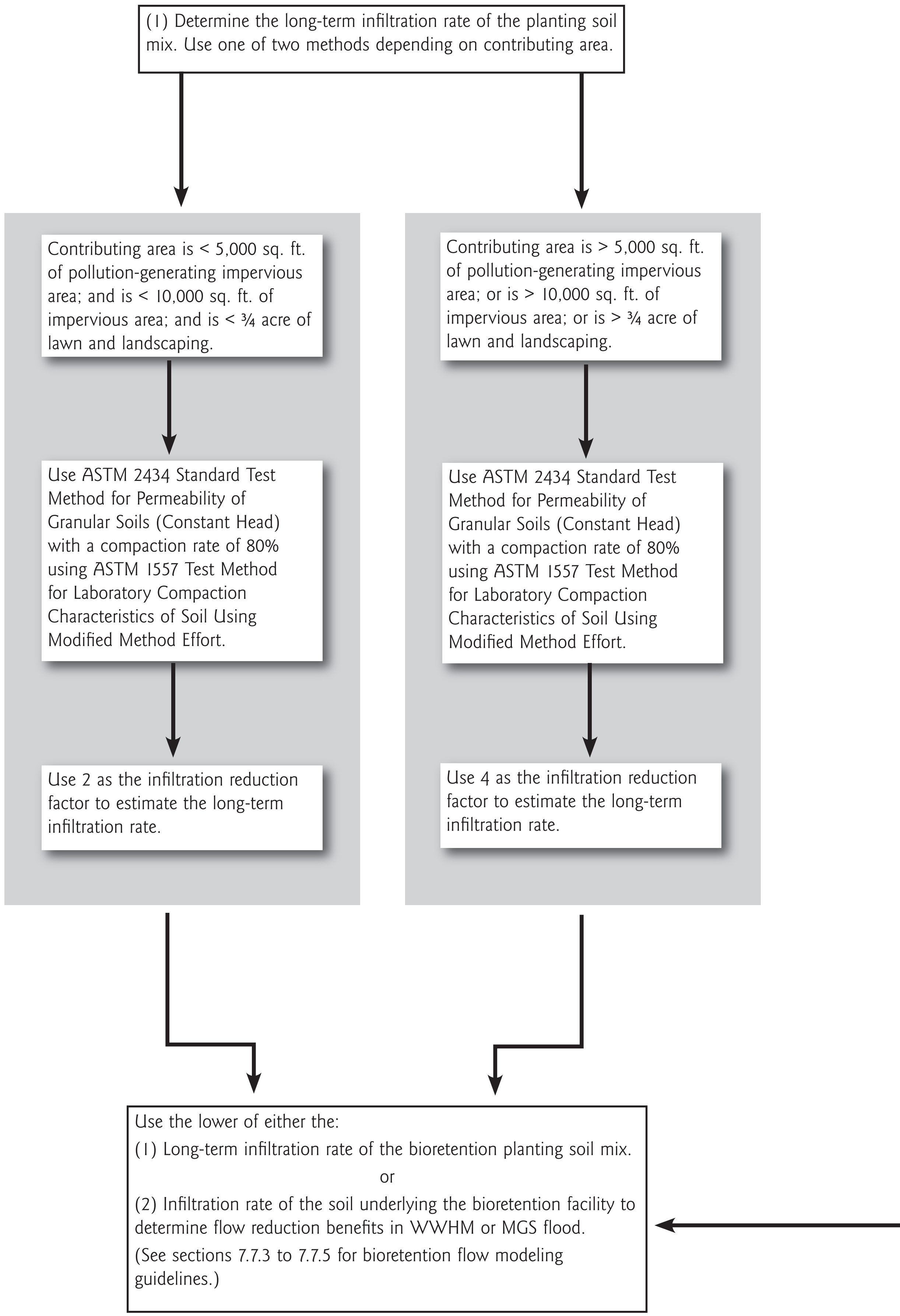
- Method 1: Use Table 3.7 of the Ecology 2005 *Stormwater Management Manual for Western Washington* (SMMWW) to determine the short-term infiltration rate of the underlying soil. Soils not listed in the table cannot use this approach. Use 1 as the infiltration reduction factor.
- Method 2: Determine the D_{10} size of the underlying soil. Use the upperbound line in Figure 4-17 of the Washington State Department of Transportation (WSDOT) 2004 *Highway Runoff Manual* to determine the corresponding infiltration rate. Use 1 as the infiltration reduction factor.
- See the 2005 SMMWW Volume III for details on methods 1 and 2.
- Method 3: Field infiltration tests (the specific test depends on scale of the project).
    - Small bioretention cells (bioretention facilities receiving water from 1 or 2 individual lots or < 1/4 acre of pavement or other impervious surface): Small-scale infiltration tests such as the U.S. Environmental Protection Agency (USEPA Falling Head or double ring infiltrometer tests, ASTM 3385-88). Small-scale infiltration tests, such as a double ring infiltrometer, may not adequately measure variability of conditions in test areas and, if used, measurements should be taken at several locations within the area of interest. Soil pit excavation may still be necessary if highly variable soil conditions or seasonal high water tables are suspected. Use 1 as an infiltration correction factor.
    - Large bioretention cells (bioretention facilities receiving water from several lots or 1/4 to 1/2-acre of pavement or other impervious surface): Pilot Infiltration Test (PIT) or small-scale test infiltration pits (septic test pits) at a rate of 1 pit/cell excavated to a depth of at least 5 feet and preferably 6 to 8 feet. See 2005 SMMWW Appendix III-D (formerly V-B) for PIT method description. Use 1 as an infiltration correction factor.
    - Bioretention swales: approximately 1 pit/50 feet of swale to a depth of at least 5 feet (personal communication, Larry West, Ed O'Brien, 2004).
    - Consult a geotechnical engineer for site-specific analysis recommendations.
- Use the measured infiltration rate of the underlying native soil as the assumed infiltration rate of the bioretention area if it is lower than the planting soil mix.

2. Compost-amended planting mix soils: Depending on the size of contributing area use one of the following two recommended test protocols.

Flow Modeling Guidance

See Chapter 7 for guidelines for applying infiltration rates when using the WWHM to determine flow control credits for bioretention areas.

Figure 6.1.10
Recommendations for determining infiltration rates of soils in bioretention areas.
(See sections 7.7.3 to 7.7.5 for using infiltration rates and bioretention flow modeling guidelines.)



(2) Determine the short-term (measured) infiltration rate of the soils underlying the bioretention facility. Use one of the methods below depending on the soil grain size characteristics.

Soil underlying the bioretention area has a D_{10} larger than the smallest size in table 3.8 of the SMMWW.

Use table 3.8 of the SMMWW to determine long-term infiltration rate (based on ASTM gradation testing).

or

Use Table 3.7 of the SMMWW to determine long-term infiltration rate (based on soil type, USDA textural classification).

Soil underlying the bioretention area has a D_{10} smaller than the smallest size in Table 3.8 or is not soil type listed in table 3.7 of the 2005 SMMWW.

Perform 1 of 3 tests to determine long-term infiltration rate.

(1) Perform PIT test in Appendix III-D and assign appropriate correction factors from Table 3.9 in the SMMWW.

or

(2) Determine D_{10} of soil beneath storage volume and use infiltration rate predicted by the "lowerbound" line in Figure 4-17 of the 2004 WSDOT Highway Runoff Manual (lowerbound line ends at a D_{10} of approximately 0.0015 mm and an infiltration rate of 0.1 in/hr).

or

(3) Use detailed procedure in Section 4-5.2.1 of the 2004 WSDOT Highway Runoff Manual.

Use an infiltration reduction correction factor of 1.

- Test 1: If the contributing area of the bioretention cell or swale has less than 5,000 square feet of pollution-generating impervious surface; and less than 10,000 square feet of impervious surface; and less than ¾ acre of lawn and landscape:
  - o Use ASTM D 2434 Standard Test Method for Permeability of granular Soils (Constant Head) with a compaction rate of 80 percent using ASTM D1557 Test Method for Laboratory Compaction Characteristics of Soil Using Modified Effort.
  - o Use 2 as the infiltration reduction factor.
- Test 2: If the contributing area of the bioretention cell or swale is equal to or exceeds any of the following limitations: 5,000 square feet of pollution-generating impervious surface; or 10,000 square feet of impervious surface; or ¾ acre of lawn and landscape:
  - o Use ASTM D 2434 Standard Test Method for Permeability of granular Soils (Constant Head) with a compaction rate of 80 percent using ASTM D1557 Test Method for Laboratory Compaction Characteristics of Soil Using Modified Effort.
  - o Use 4 as the infiltration reduction factor.
- Use the long-term infiltration rate of the planting soil mix as the assumed infiltration rate of the bioretention area if it is lower than the underlying native soil.

6.1.2.3 Bioretention components

The following provides a description and suggested specifications for the components of bioretention cells and swales. Some or all of the components may be used for a given application depending on the site characteristics and restrictions, pollutant loading, and design objectives. Also see Appendix 2 for various bioretention design examples.

Pretreatment

Vegetated buffer strips slow incoming flows and provide an initial settling of particulates. Design will depend on topography, flow velocities, volume entering the buffer, and site constraints. Flows entering a rain garden should be less than 1.0 ft/second to minimize erosion potential. Engineered flow dissipation (e.g., rock pad) should be incorporated into curb-cut or piped (concentrated) flow entrances.

Flow entrance

Five primary types of flow entrances can be used for bioretention cells:

- *Dispersed, low velocity flow across a landscape area:* This is the preferred method of delivering flows to the rain garden cell. Dispersed flow may not be possible given space limitations or if the facility is controlling roadway or parking lot flows where curbs are mandatory.
- *Dispersed flow across pavement or gravel and past wheel stops for parking areas.*
- *Curb cuts for roadside or parking lot areas:* Curb cuts should include rock or other erosion protection material in the channel entrance to dissipate energy. Flow entrance should drop 2 to 3 inches from curb line and provide an area for settling and periodic removal of sediment and coarse material before flow dissipates to the remainder of the cell (Prince George's County, Maryland, 2002, and U.S. Army Environmental Center and Fort Lewis, 2003).
- *Pipe flow entrance:* Piped entrances should include rock or other erosion protection material in the channel entrance to dissipate energy and/or flow dispersion.

- *Catch basin:* Catch basins can be used to slowly release water to the bioretention area through a grate for filtering coarse material.

Woody plants can restrict or concentrate flows and can be damaged by erosion around the root ball and should not be placed directly in the entrance flow path (Prince George's County, 2002).

Figure 6.1.11 Bioretention with curb cuts in parking lot islands.

Photo by Larry Coffman

Ponding area

The ponding area provides surface storage for storm flows, particulate settling, and the first stages of pollutant treatment within the cell. Pool depth and draw-down rate are recommended to provide surface storage, adequate infiltration capability, and soil moisture conditions that allow for a range of appropriate plant species (Prince George's County, 2002).

- Maximum ponding depth: 12 inches recommended.
- Surface pool drawdown time: 24 hours recommended.
- Soils must be allowed to dry out periodically in order to:
  - Restore hydraulic capacity to receive flows from subsequent storms.
  - Maintain infiltration rates.
  - Maintain adequate soil oxygen levels for healthy soil biota and vegetation.
  - Provide proper soil conditions for biodegradation and retention of pollutants. (Ecology, 2001)

Under-drain

The area above an under-drain pipe in a bioretention area provides detention and pollutant filtering; however, only the area below the under-drain invert and the bottom of the bioretention facility can be used in the WWHM for flow control benefit (see Chapter 7 for bioretention area flow control credits). Under-drain systems (see Figure 6.1.12) should be installed only when the bioretention area is:

- Located near sensitive infrastructure (e.g., unsealed basements) and potential for flooding is likely.
- Used for filtering storm flows from gas stations or other pollutant hotspots (requires impermeable liner).
- In soils with infiltration rates that are not adequate to meet maximum pool and system dewater rates.

The under-drain can be connected to a downstream open conveyance (bioretention swale), to another bioretention cell as part of a connected treatment system, daylight to a dispersion area using an effective flow dispersion practice, or to a storm drain.

The pipe diameter will depend on hydraulic capacity required (4 to 8 inches is common). The preferred material is slotted 6-inch, thick-walled plastic pipe. The slot opening should be smaller than the smallest aggregate gradation for the gravel blanket to prevent migration of material into the drain. This configuration allows for pressurized water cleaning and root cutting if necessary (personal communication, Tracy Tackett, 2004). Example specification:

- Slotted subsurface drain PVC per ASTM D1785 SCH 40.
- Slots should be cut perpendicular to the long axis of the pipe and be 0.04 to 0.069 inches by 1 inch long and be spaced 0.25 inches apart (spaced longitudinally). Slots should be arranged in four rows spaced on 45-degree centers and cover ½ of the circumference of the pipe. See Filter Materials section for aggregate gradation appropriate for this slot size.

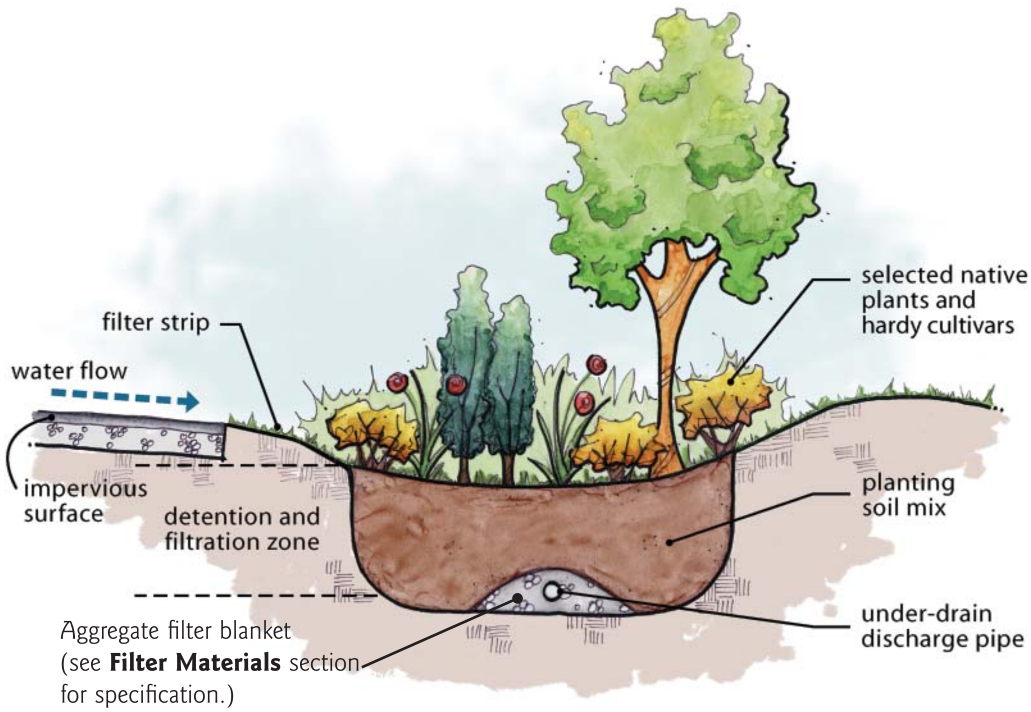


Figure 6.1.12 Bioretention with under-drain.

Graphic by AHBL Engineering

Perforated PVC or flexible slotted HDPE pipe can be used; however, cleaning operations, if necessary, can be more difficult or not possible. Under-drains should be sloped at a minimum of 0.5 percent unless otherwise specified by an engineer (Low Impact Development Center, 2004). Wrapping the under-drain pipe in filter fabric increases chances of clogging and is not recommended (Low Impact Development Center, 2004). A 6-inch rigid non-perforated observation pipe or other maintenance access should be connected to the under-drain every 250 to 300 feet to provide a clean-out port, as well as an observation well to monitor dewatering rates (Prince George's County, 2002 and personal communication, Tracey Tackett, 2004).

Bioretention areas do not effectively remove nitrate. Where nitrate is a concern, the under-drain can be elevated from the bottom of the bioretention facility and within the gravel blanket to create a fluctuating anaerobic/aerobic zone below the drain pipe (Figure 6.1.13). **Denitrification** within the anaerobic zone is facilitated by microbes using forms of nitrogen (NO_2 and NO_3) instead of oxygen for respiration. Adding a suitable carbon source (e.g., wood chips) to the gravel layer provides a nutrition source for the microbes, enables anaerobic respiration, and can enhance the denitrification process (Kim, Seagren and Davis, 2003).

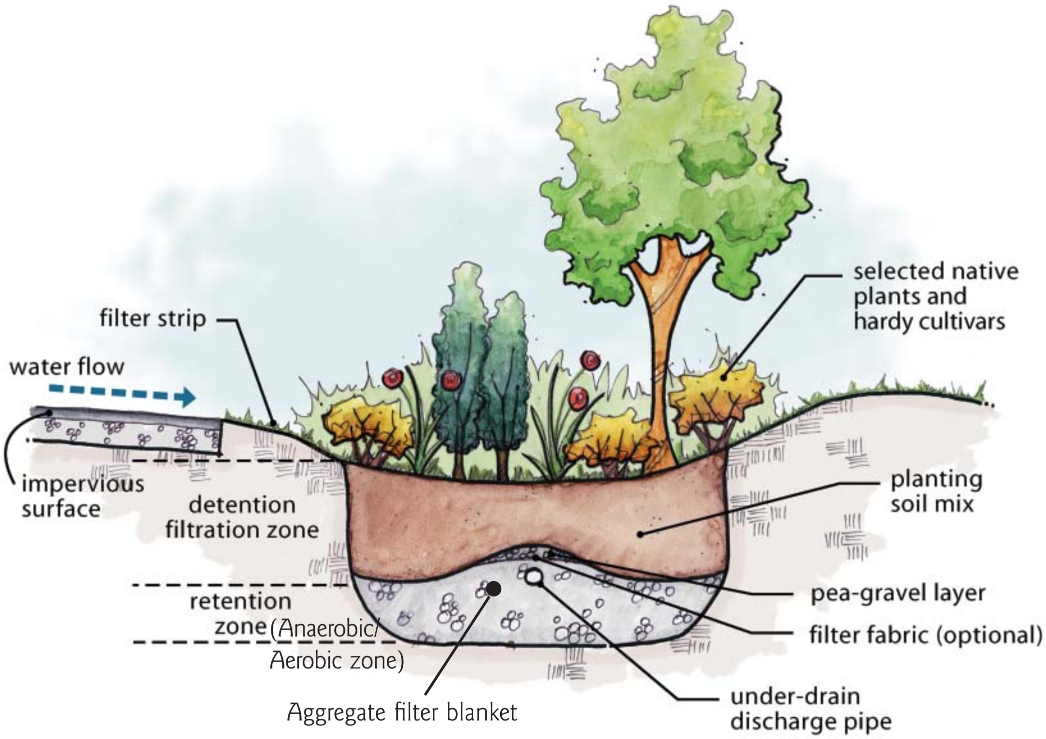


Figure 6.1.13 Bioretention with elevated under-drain.

Graphic by AHBL Engineering

Filter materials

Gravel blankets and filter fabrics buffer the under-drain system from sediment input and clogging. Properly selected for the soil gradation, geosynthetic filter fabrics can provide adequate protection from the migration of fines. Aggregate filter blankets, with proper gradations, provide a larger surface area for protecting under-drains and are preferred.

Suggested specifications for filter materials include:

1. For use with heavy walled slotted pipe (see under-drain specification above):
   - Type 26 mineral aggregate (gravel backfill for drains, city of Seattle)

Sieve size	Percent Passing
¾ inch	100
¼ inch	30-60
US No. 8	20-50
US No. 50	3-12
US No. 200	0-1

   - Place under-drain on a 3-foot wide bed of the Type 26 aggregate at a minimum thickness of 6 inches and cover with Type 26 aggregate to provide a 1-foot minimum depth around the top and sides of the slotted pipe.

2. If proper gradation and/or slotted pipe are not available and perforated PVC or flexible HDPE pipe is used:
   - The under-drain pipe should be placed on a 3-foot wide bed of ½ to 1½-inch drain rock (ASTM No. 57 aggregate or equivalent) at a minimum thickness of 3 inches, and covered with 6 inches of No. 57 aggregate.

Double-washed stone is preferred to reduce suspended solids and potential for clogging (Low Impact Development Center, 2004).

- If filter fabric is used, use a non-woven material placed over the drain rock and extending 2 feet on either side of the under-drain. Wrapping the gravel blanket in filter fabric can cause premature failure due to clogging and is not recommended (Prince George's County, 2002).
- A pea gravel diaphragm (with or without a filter fabric) reduces the likelihood of clogging when used with drain rock. Use ¼ to ½-inch diameter double-washed gravel (ASTM D 448 or equivalent) placed over the drain rock to a thickness of 3 to 8 inches (Prince George's County, 2002). If filter fabric is used, place between the drain rock and pea gravel extending 2 feet on either side of the under-drain. The strip of filter fabric placed above the under-drain acts as an impediment to direct gravitational flow and causes the water to move laterally and then down toward the under-drain (personal communication, Derek Winogradoff, August 2004).

Surface overflow

Surface overflow can be provided by surface drains installed at the designed maximum ponding elevations that are connected to under-drain systems, or by overflow channels connected to downstream surface conveyance, such as bioretention swales and open space areas. Safe discharge points are necessary to convey flows that exceed the capacity of the facility and to protect adjacent natural site features and property.

Hydraulic restriction layers

Adjacent roads, foundations or other infrastructure may require that infiltration pathways are restricted to prevent excessive hydrologic loading. Three types of restricting layers can be incorporated into bioretention designs:

- Filter fabric can be placed along vertical walls to reduce lateral flows.
- Clay (bentonite) liners are low permeability liners. Where clay liners are used under-drain systems are necessary. See 2005 SMMWW Volume IV section 4.4.3 for guidelines.
- Geomembrane liners completely block flow and are used for groundwater protection when bioretention facilities are used for filtering stormflows from pollutant hotspots. Where geomembrane liners are used under-drain systems are necessary. The liner should have a minimum thickness of 30 mils and be ultraviolet (UV) resistant.

Plant materials

Plant roots aid in the physical and chemical bonding of soil particles that is necessary to form stable aggregates, improve soil structure, and increase infiltration capacity. During the wet months in the Pacific Northwest (November through March) interception and evaporation are the predominant above-ground mechanisms for attenuating precipitation in the native forest setting. Transpiration during the non-growing wet months is minimal (see Introduction for details). In a typical bioretention cell, transpiration is negligible unless the cell has a dense planting of trees, the stand is relatively mature (10 to 20 years), and the canopy structure is closing and varied. The relatively mature and dense canopy structure is necessary for adequate interception and advective evaporation in winter months. The primary and significant benefits of small trees, shrubs, and ground cover in bioretention areas during the wet season are the presence of root activity and contribution of organic matter that aids in the development of soil structure and infiltration capacity. See Appendix 3 for a bioretention plant table describing plant characteristics and optimum location within the bioretention area.

The primary design considerations for plant selection include:

- *Soil moisture conditions:* Plants should be tolerant of summer drought, ponding fluctuations, and saturated soil conditions for the lengths of time anticipated by the facility design.
- *Expected pollutant loadings:* Plants should tolerate typical pollutants and loadings from the surrounding land uses.
- *Above and below ground infrastructure in and near the facility:* Plant size and wind firmness should be considered within the context of the surrounding infrastructure. Rooting depths should be selected to not damage underground utilities if present. Slotted or perforated pipe should be more than 5 feet from tree locations (if space allows).
- *Adjacent plant communities and potential invasive species control.*
- *Site distances and setbacks for roadway applications.*
- *Visual buffering:* Plants can be used to buffer structures from roads, enhance privacy among residences, and provide an aesthetic amenity for the site.
- *Aesthetics:* Visually pleasing plant designs add value to the property and encourage community and homeowner acceptance. Homeowner education and participation in plant selection and design for residential projects should be encouraged to promote greater involvement in long-term care.

In general, the predominant plant material utilized in bioretention areas are facultative species adapted to stresses associated with wet and dry conditions (Prince George's County, 2002). Soil moisture conditions will vary within the facility from saturated (bottom of cell) to relatively dry (rim of cell). Accordingly, wetland plants may be used in the lower areas, if saturated soil conditions exist for appropriate periods, and drought-tolerant species planted on the perimeter of the facility or on mounded areas (Figure 6.1.14). See Appendix 3 for recommended plant species.

Planting schemes will vary with the surrounding landscape and design objectives. For example, plant themes can reflect surrounding wooded or prairie areas. Monoculture planting designs are not recommended. As a general guideline, a minimum of three tree, three shrubs, and three herbaceous groundcover species should be incorporated to protect against facility failure due to disease and insect infestations of a single species (Prince George's County, 2002). See Figure 6.1.15 for a sample planting plan.

Native plant species, placed appropriately, tolerate local climate and biological stresses and usually require no nutrient or pesticide application in properly designed soil mixes. Natives can be used as the exclusive material in a rain garden or in combination with hardy cultivars that are not invasive and do not require chemical inputs. In native landscapes, plants are often found in associations that grow together well given specific moisture, sun, soil, and plant chemical interactions. Native plant associations can, in part, help guide planting placement. For example, in partial sun and well-drained soils, beaked hazelnut (*Corylus cornuta*) and common snowberry (*Symphoricarpos albus*) are a common association in western Washington (Leigh, 1999). To increase survival rates and ensure quality of plant material, the following guidelines are suggested:

Figure 6.1.14 Examples of plants appropriate for different soil moisture zones in a bioretention area.

See Appendix 3 for a bioretention plant list organized by soil moisture zones.

Graphic by AHBL Engineering

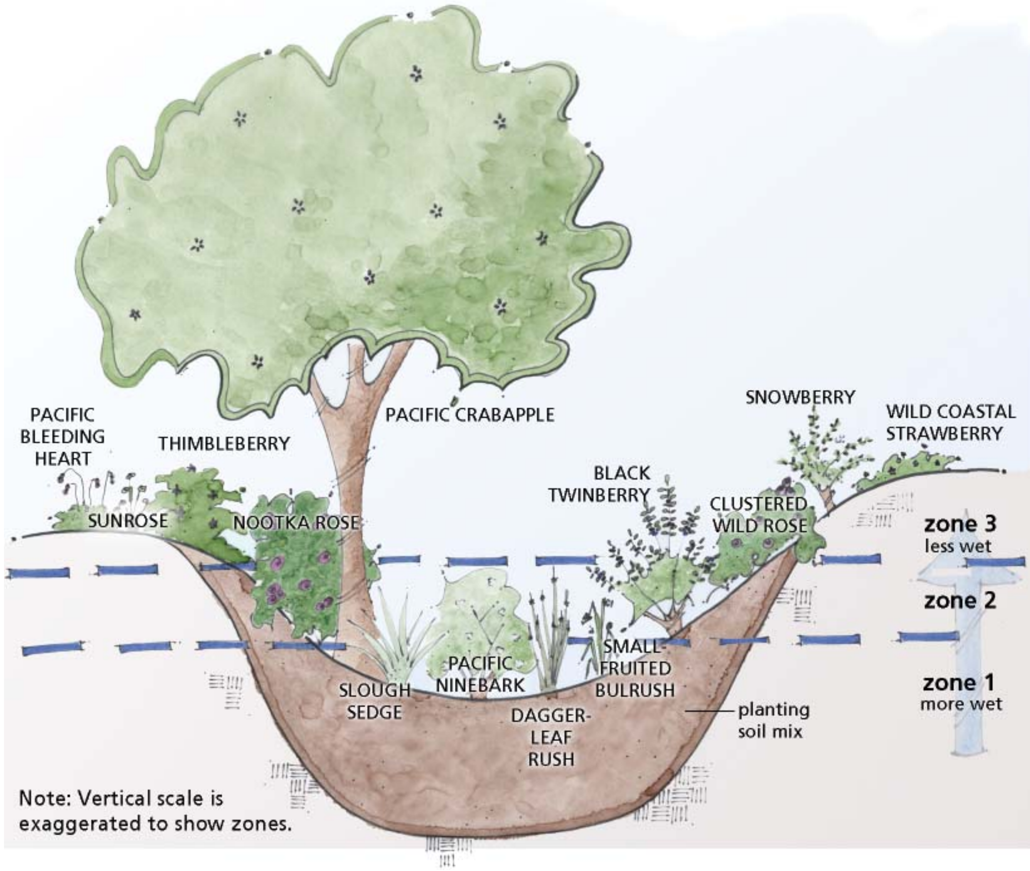
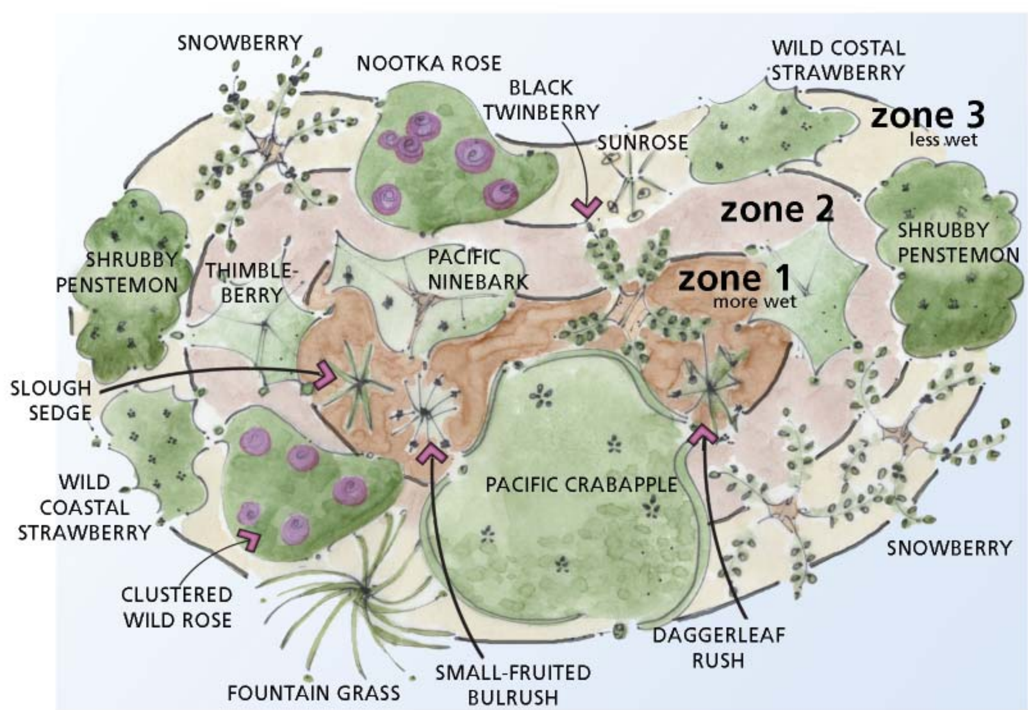


Figure 6.1.15 Sample planting plan for a bioretention area.

Graphic by AHBL Engineering



- Plants should conform to the standards of the current edition of *American Standard for Nursery Stock* as approved by the American Standards Institute, Inc. All plant grades shall be those established in the current edition of *American Standards for Nursery Stock* (current edition: ANSI Z60.1-2004) (Low Impact Development Center, 2004).
- All plant materials should have normal, well-developed branches and vigorous root systems, and be free from physical defects, plant diseases, and insect pests.
- Plant size: Bioretention areas provide excellent soil conditions and should have well defined maintenance agreements. In this type of environment small plant material provides several advantages and is recommended. Specifically, small plant material requires less careful handling, less initial irrigation, experiences less transplant shock, is less expensive, adapts more quickly to a site, and transplants more successfully than larger material (Sound Native Plants, 2000). Small trees and shrubs are generally supplied in pots of 3 gallons or less.
- All plants should be tagged for identification when delivered.
- Optimum planting time is fall (beginning early October). Winter planting is acceptable; however, extended freezing temperatures shortly after installation can increase plant mortality. Spring is also acceptable, but requires more summer watering than fall plantings. Summer planting is the least desirable and requires regular watering for the dry months immediately following installation.

Mulch layer

Bioretention areas can be designed with or without a mulch layer; however, there are advantages to providing a mulch application or a dense groundcover. Research indicates that most attenuation of heavy metals in bioretention cells occurs in the first 1 to 2 inches of the mulch layer. That layer can be easily removed or added to as part of a standard and periodic landscape maintenance procedure. No indications of special disposal needs are indicated at this time from older bioretention facilities in the eastern U.S. (personal communication, Larry Coffman). Properly selected mulch material also reduces weed establishment, regulates soil temperatures and moisture, and adds organic matter to soil. When used, mulch should be:

- Compost in the bottom of the facilities (compost is less likely to float and is a better source for organic materials) and shredded or chipped hardwood or softwood in surrounding areas.
- Free of weed seeds, soil, roots and other material that is not **bole** or branch wood and bark.
- A maximum of 2 to 3 inches thick (thicker applications can inhibit proper oxygen and carbon dioxide cycling between the soil and atmosphere) (Prince George's County, 2002).

Mulch should **not** be:

- Grass clippings (decomposing grass clippings are a source of nitrogen and are not recommended for mulch in bioretention areas).
- Pure bark (bark is essentially sterile and inhibits plant establishment).

Dense groundcover enhances soil structure from root activity, does not have the tendency to float during heavy rain events, inhibits weed establishment, provides additional aesthetic appeal, and is recommended when heavy metal loading is not anticipated (Prince George's County, 2002). Mulch is recommended in conjunction with the groundcover until groundcover is established.

Soil

Proper soil specification, preparation and installation are the most critical factors for bioretention performance. Soil specifications can vary according to the design objectives. Five different soil specifications are provided in Appendix 2 to illustrate various design approaches. In general, soil designed for bioretention areas should have the following characteristics:

- The texture for the soil component of the bioretention soil mix should be loamy sand (USDA Soil Textural Classification).
- The final soil mix (including compost and soil) should have a minimum long-term hydraulic conductivity of 1.0 inch/hour per ASTM Designation D 2434 (Standard Test Method for Permeability of Granular Soils) at 80 percent compaction per ASTM Designation D 1557 (Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort) (Tackett, 2004). Infiltration rate and hydraulic conductivity are assumed to be approximately the same in a uniform mix soil.
- The final soil mixture should have a minimum organic content of 10 percent by dry weight per ASTM Designation D 2974 (Standard Test Method for Moisture, Ash and Organic Matter of Peat and Other Organic Soils) (Tackett, 2004). Currently, gravelly sand bioretention soil mixtures for bioretention areas are being developed and installed to provide adequate infiltration rates at 85 to 95 percent compaction. While designers anticipate good performance from this specification, the mix may be slightly less than optimal for plant growth and has not been tested long-term for plant health performance (see Engineered Soil Mix and Bioretention Soil Mix 2 and 3 in Appendix 2).
- Achieving the above recommendations will depend on the specific soil and compost characteristics. In general, the recommendation can be achieved with 60 to 65 percent loamy sand mixed with 35 to 40 percent compost or 30 percent sandy loam, 30 percent course sand, and 40 percent compost.
- The final soil mixture should be tested by an independent laboratory prior to installation for fertility, micronutrient analysis, and organic material content. Soil amendments per laboratory recommendations (if any) should be uniformly incorporated for optimum plant establishment and early growth (Tackett, 2004).
- Clay content for the final soil mix should be less than 5 percent.
- The pH for the soil mix should be between 5.5 and 7.0 (Stenn, 2003). If the pH falls outside of the acceptable range, it may be modified with lime to increase the pH or iron sulfate plus sulfur to lower the pH. The lime or iron sulfate must be mixed uniformly into the soil prior to use in bioretention area (Low Impact Development Center, 2004).
- Soil depth should be a minimum of 18 inches to provide acceptable minimum pollutant attenuation and good growing conditions for selected plants. A minimum depth of 24 inches should be selected for improved phosphorus and nitrogen (TKN and ammonia) removal. Deeper soil profiles (> 24 inches) can enhance phosphorus, TKN and ammonia removal (Davis, Shokouhian, Sharma and Minami, 1998). Nitrate removal in bioretention cells can be poor and in some cases cells can generate nitrate due to nitrification (Kim et al., 2003). See under-drain section for design recommendations to enhance nitrate removal. Deeper or shallower profiles may be desirable for specific plant, soil, and storm flow management objectives.
- The soil mix should be uniform and free of stones, stumps, roots or other similar material > 2 inches.

Organic matter content of soil mixes

A quick way to determine the approximate organic matter content of a soil mix:

- Compost is typically 40-50% organic matter (use 50% as an average).
- Compost weighs approximately 50% as much as loam.
- A mix that is 40% compost measured by volume is roughly 20% organic matter by volume.
- Compost is only 50% as dense as the soil, so the mix is approximately 10% organic matter by weight (the organic matter content in soil is determined by weighing the organic material before combustion and then weighing the ash post-combustion).

- To reduce transportation and disposal needs, on-site excavated soil, rather than imported soil, can be used. However, using on-site excavated soil for the amended soil mix may reduce control over gradation, organic content, and final product performance, can increase project costs, and can complicate construction logistics when attempting to blend soil mix components in restricted space or during winter months (personal communication, Tracy Tackett). If on-site excavated soil is used, representative samples should be tested for gradation and adjusted, if necessary, to attain adequate infiltration capability.
- The above guidelines should provide a soil texture, organic content, and infiltration rate suitable to meet Ecology's SSC-6 "Soil Physical and Chemical Suitability for Treatment" recommendations for designing infiltration systems. A soils report evaluating these parameters should be provided to verify the treatment capability of the soil mix.

Compost

See Section 6.2.2 for compost specifications.

6.1.2.4 Installation

Excavation

Soil compaction can lead to facility failure; accordingly, minimizing compaction of the base and sidewalls of the bioretention area is critical (Prince George's County, 2002). Excavation should not be allowed during wet or saturated conditions. Excavation should be performed by machinery operating adjacent to the bioretention facility and no heavy equipment with narrow tracks, narrow tires, or large lugged, high pressure tires should be allowed on the bottom of the bioretention facility (Tackett, 2004). If machinery must operate in the bioretention cell for excavation, use light weight, low ground-contact pressure equipment and rip the base at completion to refracture soil to a minimum of 12 inches (Prince George's County, 2002).

Sidewalls of the facility, to the height of the grade established by the designed soil mix, can be vertical if soil stability is adequate. Exposed sidewalls should be no steeper than 3H:1V. The sidewalls and bottom should be roughened where scraped and sealed by excavation equipment (Prince George's County, 2002). The bottom of the facility should be flat.

Vegetation protection areas with intact native soil and vegetation should not be cleared and excavated for bioretention facilities.

Soil installation

On-site soil mixing or placement should not be performed if soil is saturated. The bioretention soil mixture should be placed and graded by excavators and/or backhoes operating adjacent to the bioretention facility. If machinery must operate in the bioretention cell for soil placement or soil grading, use light weight, low ground-contact pressure equipment. The soil mixture should be placed in horizontal layers not to exceed 12 inches per lift for the entire area of the bioretention facility.

The soil mixture will settle and proper compaction can be achieved by allowing time for natural compaction and settlement. To speed settling, each lift can be watered until just saturated. Water for saturation should be applied by spraying or sprinkling.

An appropriate sediment control device should be used to treat any sediment-laden water discharged from an under-drain (Low Impact Development Center, 2004).

Sediment Control

Erosion and sediment problems are most difficult during clearing, grading, and construction; accordingly, minimizing site disturbance to the greatest extent practicable is the most effective sediment control. Bioretention facilities should not be used as sediment control facilities and all drainage should be directed away from bioretention facilities after initial rough grading. Flow can be directed away from the facility with temporary diversion swales or other approved protection (Prince George's County, 2002). Bioretention facilities should not be constructed until all contributing drainage areas are stabilized according to erosion and sediment control BMPs and to the satisfaction of the engineer. Erosion and sediment control practices must be inspected and maintained on a regular basis. If deposition of fines occurs in the bioretention area, material should be removed and the surface scarified to the satisfaction of the project engineer (Prince George's County, 2002).

6.1.3 Maintenance

Bioretention areas require annual plant, soil, and mulch layer maintenance to ensure optimum infiltration, storage, and pollutant removal capabilities. In general, bioretention maintenance requirements are typical landscape care procedures and include:

- *Watering:* Plants should be selected to be drought tolerant and not require watering after establishment (2 to 3 years). Watering may be required during prolonged dry periods after plants are established.
- *Erosion control:* Inspect flow entrances, ponding area, and surface overflow areas periodically, and replace soil, plant material, and/or mulch layer in areas if erosion has occurred. Properly designed facilities with appropriate flow velocities should not have erosion problems except perhaps in extreme events. If erosion problems occur the following should be reassessed: (1) flow volumes from contributing areas and bioretention cell sizing; (2) flow velocities and gradients within the cell; and (3) flow dissipation and erosion protection strategies in the pretreatment area and flow entrance. If sediment is deposited in the bioretention area, immediately determine the source within the contributing area, stabilize, and remove excess surface deposits.
- *Plant material:* Depending on aesthetic requirements, occasional pruning and removing dead plant material may be necessary. Replace all dead plants and if specific plants have a high mortality rate, assess the cause and replace with appropriate species. Periodic weeding is necessary until plants are established. The weeding schedule should become less frequent if the appropriate plant species and planting density have been used and, as a result, undesirable plants excluded.
- *Nutrient and pesticides:* The soil mix and plants are selected for optimum fertility, plant establishment, and growth. Nutrient and pesticide inputs should not be required and may degrade the pollutant processing capability of the bioretention area, as well as contribute pollutant loads to receiving waters. By design, bioretention facilities are located in areas where phosphorous and nitrogen levels are often elevated and these should not be limiting nutrients. If in question, have soil analyzed for fertility.

- *Mulch:* Replace mulch annually in bioretention facilities where heavy metal deposition is likely (e.g., contributing areas that include parking lots and roads). In residential lots or other areas where metal deposition is not a concern, replace or add mulch as needed to maintain a 2 to 3 inch depth at least once every two years.
- *Soil:* Soil mixes for bioretention facilities are designed to maintain long-term fertility and pollutant processing capability. Estimates from metal attenuation research suggest that metal accumulation should not present an environmental concern for at least 20 years in bioretention systems (see Performance section below). Replacing mulch in bioretention facilities where heavy metal deposition is likely provides an additional level of protection for prolonged performance. If in question, have soil analyzed for fertility and pollutant levels.

6.1.4 Performance

Pollutant removal processes in bioretention

All primary pathways for removing pollutants from storm flows are active in bioretention systems. Schueler and Clayton (1996) list the following as the primary pathways:

- *Sedimentation* is the settling of particulates (not effective for removing soluble components). Sedimentation occurs in the pretreatment (if provided) and ponding area of the facility.
- *Filtration* is the physical straining of particulates (not an effective mechanism for removing soluble components). Some filtration occurs in the ponding area as stormwater moves through plants, but the soil is the primary filtering media. Pitt et al., (1995) report that 90 percent of small particles commonly found in urban storm flows (6 to 41 microns) can be trapped by an 18-inch layer of sand. This level of performance can be anticipated for bioretention soils typically high in sand content.
- *Adsorption* is the binding of ions and molecules to electrostatic receptor sites on the filter media particles. This is the primary mechanism for removing soluble nutrients, metals, and organics that occur in the soil of bioretention areas as storm flows infiltrate. Adsorption increases with increased organic matter, clay, and a neutral to slightly alkaline pH.
- *Infiltration* is the downward movement of surface water to interstitial soil water. This process initiates adsorption, microbial action, etc., for pollutant removal.
- *Phytoremediation* processes include degradation, extraction by the plant, containment within the plant (assimilation) or a combination of these mechanisms (USEPA, 2000). Studies have shown that vegetated soils are capable of more effective degradation, removal, and mineralization of total petroleum hydrocarbons (TPHs), polycyclic aromatic hydrocarbons (PAHs), pesticides, chlorinated solvents, and surfactants than are non-vegetated soils (USEPA, 2000). Certain plant roots can absorb or immobilize metal pollutants, including cadmium, copper, nickel, zinc, lead, and chromium, while other species are capable of metabolizing or accumulating organic and nutrient contaminants. A University of Maryland study found significant metal accumulation in creeping juniper plants in pilot-scale bioretention cells. Copper increased by a factor of 6.3, lead by a factor of 77, and zinc by a factor of 8.1 in the tissue of junipers after receiving synthetic stormwater applications compared to pre-application tissue samples (Davis, Shokouhian, Sharma,

Minami and Winogradoff, 2003). An intricate and complex set of relationships and interactions between plants, microbes, soils, and contaminants make these various phytoremediation processes possible (see Appendix 5 for a more detailed discussion of phytoremediation and stormwater).

- *Plant resistance* occurs as plant materials reduce flow velocities and increase other pollutant removal pathways such as sedimentation, filtering, and plant uptake of pollutants during growth periods.
- *Volatilization* occurs when a substance is converted to a more volatile vapor form. Transforming complex hydrocarbons to carbon dioxide is an example of volatilization active in bioretention cells (Prince George's County, 2002).
- *Thermal attenuation* reduces water temperatures as storm flows move through subsurface soil layers. A field study in Maryland found that the temperature of the input water was reduced by approximately 12 degrees C after infiltrating through a bioretention cell located in a parking lot (USEPA, 2000a).

Pollutant removal efficiency in bioretention areas

Metals

Laboratory and field research indicates that bioretention areas have excellent removal capabilities for heavy metals. Duration and flow rate can influence removal at shallow depths (10 inches), but not deeper in the soil profile (36 inches). Metal adsorption in soil is typically influenced by pH; however, the buffering capacity in the bioretention soil mix effectively negates the influence of pH variations in synthetic pollutant mixtures applied to pilot-scale systems (Davis et al., 2003). The most significant metal uptake occurs in the mulch layer that can retain a large portion of the total metals loads (Davis et al., 2001).

Table 6.1.1 summarizes percentages of pollutants removed from pilot-scale laboratory studies performed at University of Maryland. Also see Appendix 4 for summaries of bioretention swale and bioretention cell research. Table 6.1.2 provides data summarizing research on other typical stormwater BMPs for comparison.

Table 6.1.1 Percent pollutant removal by depth in bioretention facilities.

Depth (inches)	Cu (μg/L)	Pb (μg/L)	Zn (μg/L)	P (mg/L)	TKN (mg/L)	NH4 (mg/L)	NO3 (mg/L)	TN (mg/L)
10	90	93	87	0	37	54	-97	-29
22	93	>97	>96	73	60	86	-194	0
36	93	>97	>96	81	68	79	23	43

Adapted from Davis et al., 1998 (removal percentages are for total metals)

Table 6.1.2 Comparative pollutant removal capability of stormwater treatment practices (in percentages).

Pollutant	Dry Extended Detention Pond	Wetlands	Water Quality Swales	Ditches
TN (mg/L)	31	30	84	-9
NO3 (mg/L)	ND	ND	ND	ND
P (mg/L)	20	49	34	-16
Cu (µg/L)	26	40	51	14
Pb (µg/L)	54	68	67	17
Zn (µg/L)	26	44	71	0

Adapted from CWP, 2000b (removal percentages are for total metals)

Nutrients

Phosphorus removal in bioretention soils increases with depth of facility. Sorption of phosphorus onto aluminum, iron, and clay minerals in the soil is the likely mechanism of removal (Davis et al., 2001). Phosphorus can **desorb** if low pH or low oxygen conditions are present; accordingly, bioretention planting soil dewatering rate and drying should be maintained and pH monitored annually. Nitrate removal is highly variable, but generally poor and at times nitrate production and export has been observed (Kim et al., 2003). Production or export of nitrate is a result of organic and ammonia nitrogen that is converted to nitrate between storms (presumably through the **ammonification** and **nitrification** process). Nitrate is then washed from the facility during subsequent storm events (Kim et al., 2003).

Where nitrate is a concern, an under-drain can be elevated from the bottom of the bioretention facility and within the gravel blanket to create a fluctuating anaerobic/aerobic zone below the drain pipe. With a suitable carbon source (e.g., wood chips mixed in the gravel) acting as an electron donor, the anaerobic zone can enhance the denitrification process (see Figure 6.1.13 in the Under-drain section) (Kim et al., 2003).

Hydrocarbons and bacteria

Hong, Seagren and Davis (2002) examined the capacity of a mulch layer to capture oil and grease via sorption and filtration. Simulated stormwater runoff carrying naphthalene was applied to a bench-scale "reactor" with a 3-cm thick leaf compost layer. During the simulated storm event approximately 90 percent of dissolved naphthalene was removed from aqueous phase via sorption. After the simulated storm event (37 and 40 hours) approximately 32 percent of the naphthalene was removed from the solid phase via biodegradation in the mulch layer where the microbial population had been inhibited. Approximately 72 percent of the naphthalene was removed from the solid phase via biodegradation in the mulch layer at 37 and 40 hours and 95 percent after 74 hours where the microbial population was not inhibited. Losses due to volatilization were negligible. See bioretention research in Appendix 4 for more detail. No research for bacteria removal in bioretention areas has currently been located.

Stormwater pollutants can disrupt normal soil function by lowering cation exchange capacity. The oldest bioretention facilities operating in the U.S. (approximately 10 years) appear to develop soil structure and maintain soil functions that actually enhance pollutant processing capability (Prince George's County, 2002). Estimates from research suggest that metal accumulation would not present an environmental concern for at least 20 years in bioretention systems (Davis et al., 2003).

Flow control processes in bioretention

- *Evaporation* can occur as precipitation is intercepted by vegetation, from surface water in the ponding area, and from exposed soil or mulch layers in bioretention areas. Evaporation from vegetation is relatively minor unless the cell has a well developed, closed, and varied canopy.
- *Infiltration* is the downward migration of runoff through the planting soil and into the surrounding soils. Infiltration is the primary mechanism for attenuating storm flows in bioretention areas. In general, long-term infiltration rates degrade over time in typical infiltration facilities due to large hydrologic loads, biofilm, and sedimentation. Anecdotal information suggests that properly designed bioretention area soil infiltration rates do not degrade as rapidly and may improve over time due to biological, chemical, and physical processes that build soil structure. Focused studies have not confirmed this. The surrounding soil will be the limiting infiltration rate in till, compacted silt or clay or other tight soils; however, there are no studies quantifying vertical and lateral subsurface flows from bioretention areas in the Puget Sound region.

Flow control performance

In the city of Seattle, Seattle Public Utilities narrowed 660 feet of conventional residential road and installed bioretention swales within the right-of-way as part of the Street Edge Alternatives (SEA) Street project. A v-notch weir installed at the ultimate outfall of the project measured surface flow volumes and timing. The contributing area with swales is approximately 2.3 acres. Soils underlying the bioretention swales are heterogeneous till-like material with lens of silt, sand, and gravel of varying permeability. Some of the swales are lined with bentonite to restrict infiltration and reduce concerns of wet basements in homes near the swales. Flows for the conventional pre-construction street were compared to the retrofit design. During the pre-construction period (March-July 2000), 7.96 inches of rainfall produced 4979 cubic feet of runoff. During the post-construction period (March-July 2001), 9.00 inches of precipitation produced 132 cubic feet of runoff. Post-construction runoff volumes were reduced by approximately 97 percent compared to pre-construction volumes. An October 2003 record storm event (4.22 inches with a 32.5 hour storm duration) produced no runoff (Horner et al., 2002).

6.1.5 Costs

The city of Seattle is implementing a new Natural Drainage System Program (NDS) for retrofitting residential streets that replaces conventional curb and gutter or roadside ditches with bioretention swales. Two designs are used depending on the gradient. The SEA Street swales are designed for the lower gradient north-south streets, and the Cascade type (which incorporate catch basins or check dams between longer gravel bottom swales) are used on the higher gradient east-west streets. Both types use compost-amended soil and small trees, shrubs, and groundcover within the swale to provide enhanced storage, infiltration, and pollutant removal. (See Figure 6.1.16 for SEA Street design example.) Table 6.1.3 compares the estimated costs of a traditional curb and gutter street retrofit to a bioretention swale design with no curb and gutter and enhanced landscaping. Costs shown include comparable water quality treatment and detention volume.

Table 6.1.3 Cost comparisons for the NDS and conventional drainage designs

Street Type	**Local Street SEA Street**	**Local Street conventional**	**Collector Street Cascade**	**Collector Street Conventional**	**Broadview Green Grid**
Transportation & aesthetics	• 1 sidewalk per block • New street paving • Traffic calming • Enhanced landscaping	• 2 sidewalks per block • New street paving • No traffic calming • Convention-al landscap-ing	• No street improvement • Enhanced landscaping	• No street improvement • Conventional landscaping	• Incorporates SEA Street and Cascade type designs • 1 sidewalk per block • New paving • Enhanced landscaping
Stormwater management	• Higher protection for aquatic biota • More close-ly mimics natural hydrology • Bio-remediate pollutants	• Flood protection focus • Water quality treatment	• Improved water quality treatment • Some flood protection	• Flood protection focus • Water quality treatment	• Higher water quality and aquatic biota protection • Some flood protection
% impervious area	35%	35%	35%	35%	35%
Cost per block (330 linear ft)	$325,000	$425,000	$285,000	$520,400	Average/block $280,000

Adapted from *Cost Analysis of Natural vs. Traditional Drainage Systems Meeting NDS Stormwater Goals*, 2004

Figure 6.1.16 SEA Street bioretention swale, Seattle. *Photo by Colleen Owen*

6.2 Amending Construction Site Soils

Native soils are highly complex systems that provide essential environmental benefits including biofiltration of pollutants, nutrients for plant growth, and the storage and slow release of storm flows. The ability of soil to effectively store and slowly release water is dependent on soil texture, structure, depth, organic matter content, and biota (Washington Organic Recycling Council [WORC], 2003). Plant roots, macro fauna, and microbes tunnel, excavate, penetrate and physically and chemically bond soil particles to form stable aggregates that enhance soil structure and porosity. Micro-and macro-pores provide a balance of environments that improve water-holding capability, increase infiltration capacity, increase oxygen levels, and provide a variety of habitats necessary to support thousands of different organisms within the soil (Allen, 1994 and CH2M HILL, 2000).

Organic matter is a critical component of a functioning soil system. Mixed into the soil, organic matter absorbs water, physically separates clay and silt particles, and reduces erosion (Balousek, 2003 and WORC, 2003). Microbial populations and vegetation depend on the replenishment of organic matter to retain and slowly release nutrients for growth (Chollak, n.d.). Typically, native Puget Sound forest soils have an organic matter content of 4 to 6 percent and the sub-soils less than 1 percent (Chollak, n.d.). Construction activity removes the upper layers of soil, compacts exposed sub-soils low in organic matter, and alters the site's hydrologic characteristics by converting the predominantly subsurface flow regime of the pre-disturbance site to primarily overland flow.

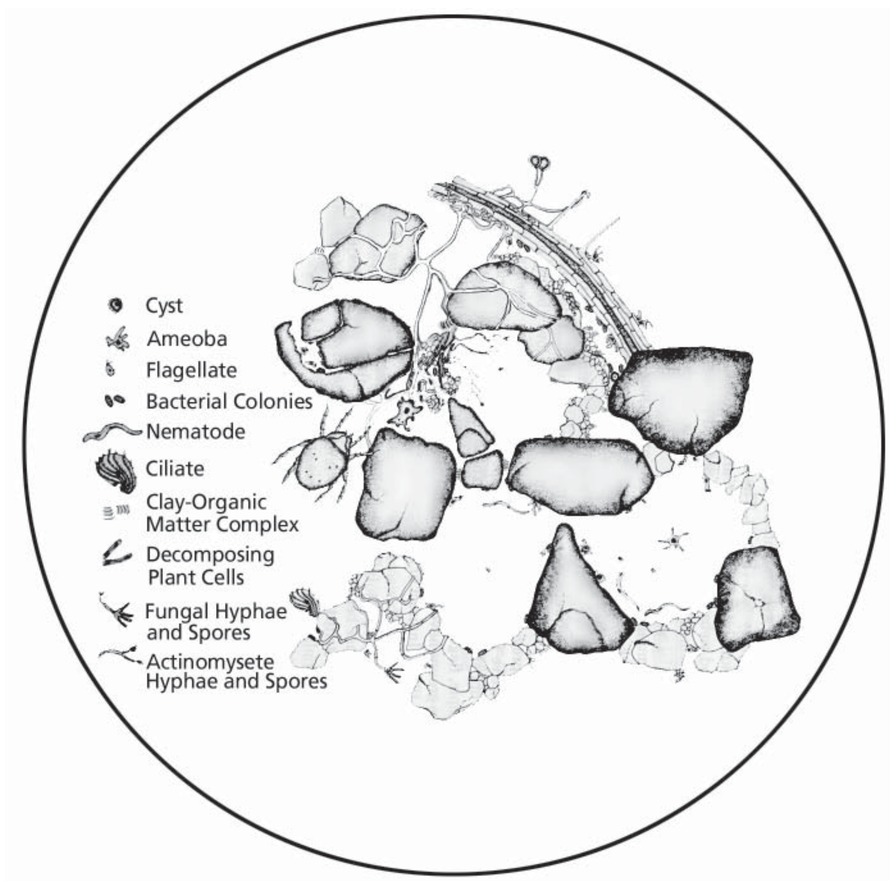


Figure 6.2.1 Close up of healthy soil structure.

Graphic courtesy of S. Rose and E.T. Elliott

Current landscape practices often do not encourage adequate preparation of turf and planting bed areas in order to regain any of the hydrologic benefits of native soils. As a result, compacted, unamended soil in landscape areas can behave similarly to impervious surfaces by generating considerable overland or shallow subsurface flows that rapidly reach receiving waters. A three-year study of a 17-hectare developed catchment near Seattle (approximately 71 percent coverage in lawn, gardens, and common areas) found that 60 percent of the total overland and rapid subsurface flow came from landscaped areas during large storms (Wigmosta, Burges and Meena, 1994). Without proper treatment and maintenance, compacted soil in lawn areas can take several years to decades to recover any beneficial infiltration and water storage characteristics of the pre-development condition (Leg, Bannerman and Panuska, 1996).

Compacted, unamended soil in landscaped areas can have similar characteristics of impervious surfaces and generate considerable overland or shallow subsurface flows that rapidly reach receiving waters.

The following section focuses on soil amendment guidelines for general landscape and vegetation protection areas. For specific application of soils in bioretention facilities see Section 6.1: Bioretention Areas.

6.2.1 Applications

The hydrologic characteristics of disturbed construction site soils for commercial, residential, and industrial projects, whether new or retrofit, can be enhanced with the addition of organic matter (CH2M HILL, 2000). In a low impact development, the landscape component of the project enhances water storage, attenuates storm flows, and is integral to the stormwater management design. When properly implemented and maintained, incorporating compost into the disturbed soils provides hydrologic, as well as other important environmental, functions including:

In a low impact development, the landscape component of the project enhances water storage, attenuates storm flows, and is integral to the stormwater management design.

- Reduced erosion.
- Increased sediment filtration.
- Pollutant adsorption and biofiltration.
- Improved plant growth, disease resistance, and overall aesthetics of the landscaping.
- Reduced (or elimination of) pesticide and fertilizer inputs for plant maintenance.
- Reduced peak summer irrigation needs (Chollak, n.d.).

Organic matter derived from compost, stockpiled on-site soil, or imported topsoil can be beneficial in all areas subject to clearing and grading. Engineered structural fill or LID drainage facilities will have specific design requirements for soil (see Section 6.1 for soil specifications in bioretention facilities). Application rates and techniques for incorporating amendments will vary with the use and plant requirements of the area. For example, application depths will be less in tree root protection zones than in turf and planting beds, and turf requiring maintenance or supporting foot traffic during the wet months will require different application rates than general landscaping areas (see Section 6.2.2: Design for details).

6.2.2 Design

Much of the information supplied here is a summary of *Guidelines and Resources for Implementing Soil Depth and Quality BMP T.5.13 in WDOE Western Washington Stormwater Manual* (Stenn, 2003). An update of this guidance is available at: http://www.soilsforsalmon.org. For details on specifications, verification, and inspection procedures, and additional resources consult the above cited manual.

To enhance the hydrologic and other environmental benefits of disturbed soils in a low impact development, the topsoil should have the following characteristics:

- A minimum organic matter content of 10 percent by dry weight for all planting beds and other landscaped areas (except turf requiring access during wet months).
- Organic matter content in turf areas that requires maintenance or supports foot traffic during the wet months should be 5 percent by dry weight.
- pH between 5.5 and 7.0 or a pH appropriate for installed plants.
- A minimum depth of 8 inches (except in tree root protection areas—see next page).
- Planting beds should be mulched with 2 to 3 inches (maximum) of organic material.
- Subsoils below topsoil applications should be scarified to a depth of at least 4 inches and some topsoil material incorporated to prevent stratification. See tilling recommendations below for specific application methods.

The minimum organic matter content may be achieved by using the pre-approved amendment methods as outlined below, or by calculating a custom amendment rate for the existing site soil conditions. The pre-approved method simplifies planning and implementation; however, the organic matter content of the disturbed on-site soils may be relatively good and not require as extensive an application of amendment material. In many cases, calculating a site-specific rate may result in significant savings in amendment material and application costs. Calculating a custom rate requires collecting soil samples from the area to be amended and samples from the compost material. The soil is then tested for bulk density and percent organic matter. The compost is tested for bulk density, percent organic matter, moisture content, carbon-to-nitrogen ratio, and heavy metals. Compost and topsoil producers can often supply the required information for the amendment material; however, on-site analysis would be necessary if vendor-supplied analysis is not available. See *Guidelines and Resources for Implementing Soil Depth and Quality BMP T.5.13 in WDOE Western Washington Stormwater Manual* (Stenn, 2003) for additional information on testing procedures.

Determining the site-specific compost application rate is calculated with the following equation:

$$CR = D\,(X)\;\frac{SBD\,(SOM\% - FOM\%)}{SBD\,(SOM\% - FOM\%) - CBD\,(COM\% - FOM\%)}$$

Where:

CR = compost application rate (inches)
D = depth of incorporation (inches)
SBD = soil bulk density *(lb/cubic yard dry weight)*
SOM% = initial soil organic matter (%)
FOM% = final target soil organic matter (%) *(target will be 5% or 10% depending on landscape area)*
CBD = compost bulk density *(lb/cubic yard dry weight)*
COM% = compost organic matter (%)

Recommended soil characteristics can be achieved by the following methods: (1) Set aside and protect native soil and vegetation areas; (2) Amend existing disturbed topsoil or subsoil; (3) Stockpile on-site topsoil from cleared and graded areas and replace prior to planting; or (4) Import topsoil with required organic matter content standards.

1. **Set aside and protect native soil and vegetation areas.**
   The most effective and cost efficient method for providing the hydrologic benefits of healthy soil is to designate and protect native soil and vegetation areas. See Chapter 4: Vegetation Protection, Reforestation and Maintenance and Chapter 5: Clearing and Grading for conservation techniques.

The most effective and cost efficient method for providing the hydrologic benefits of healthy soil is to designate and protect native soil and vegetation areas.

2. **Amend existing disturbed topsoil or subsoil.**
   Scarify or till soil to an 8-inch depth (or to depth needed to achieve a total depth of 12 inches of uncompacted soil after the calculated amount of amendment is added). The entire surface should be disturbed by scarification and amendment applied on soil surface. Do not scarify soil within the drip-line of existing trees to be retained. Within 3 feet of the tree drip-line, amendment should be incorporated no deeper than 3 to 4 inches to reduce damage to roots.

   Landscaped Areas (10 percent organic content): Place and till 3 inches (or custom calculated amount) of composted material into 5 inches of soil (a total depth of about 9.5 inches, for a settled depth of 8 inches). Rake beds smooth, remove rocks larger than 2 inches diameter and mulch areas with 2 inches of organic mulch.

   Turf Areas (5 percent organic content): Place and till 1.75 inches (or custom calculated amount) of composted material into 6.25 inches of soil (a total amended depth of about 9.5 inches, for a settled depth of 8 inches). Water or roll to compact soil to 85 percent of maximum. Rake to level, and remove surface woody debris and rocks larger than 1-inch diameter.

3. **Stockpile on-site topsoil from cleared and graded areas and replace prior to planting.**
   Stockpile and cover soil with weed barrier or other breathable material that sheds moisture yet allows air transmission, in approved location, prior to grading. Test the stockpiled material and amend with organic matter or topsoil if required to achieve organic content to 8-inch depth. Replace stockpiled topsoil prior to planting.

   If replaced topsoil plus compost or other organic material will amount to less than 12 inches, scarify or till subgrade to a depth needed to achieve 12 inches of loosened soil after topsoil and amendment are placed. The entire surface should be disturbed by scarification and amendment applied on soil surface. Do not scarify soil within drip-line of existing trees to be retained. Within 3 feet of tree drip-line, amendment should be incorporated no deeper than 3 to 4 inches to reduce damage to roots.

   Landscaped Areas (10 percent organic content): Place and till 3 inches of composted material into 5 inches of replaced soil (a total depth of about 9.5 inches, for a settled depth of 8 inches). Rake beds to smooth, remove rocks larger than 2 inches diameter, and mulch areas with 2 inches of organic mulch or stockpiled duff.

Turf Areas (5 percent organic content): Place and till 1.75 inches of composted material into 6.25 inches of replaced soil (a total amended depth of about 9.5 inches, for a settled depth of 8 inches). Water or roll compact soil to 85 percent of maximum. Rake to level, and remove surface woody debris and rocks larger than 1-inch diameter.

4. **Import topsoil with required organic matter content standards.**
   Scarify or till subgrade in two directions to a 6-inch depth. The entire surface should be disturbed by scarification and amendment applied on soil surface. Do not scarify soil within drip-line of existing trees to be retained. Within 3 feet of tree drip-line, amendment should be incorporated no deeper than 3 to 4 inches to reduce damage to roots.

   Landscaped Areas (10 percent organic content): Use imported topsoil mix containing 10 percent organic matter (typically around 40 percent compost). The soil portion must be sand or sandy loam as defined by the USDA soil classification system. Place 3 inches of imported topsoil mix on surface and till into 2 inches of soil. Place 3 inches of topsoil mix on the surface. Rake smooth, remove surface rocks over 2 inches in diameter, and mulch planting beds with 2 inches of organic mulch.

   Turf Areas (5 percent organic content): Use imported topsoil mix containing 5 percent organic matter (typically around 25 percent compost). Soil portion must be sand or sandy loam as defined by the USDA soil classification system. Place 3 inches of topsoil mix on surface. Water or roll to compact soil to 85 percent maximum. Rake to level and remove surface rocks larger than 1-inch diameter.

   The soil portion of the topsoil must be sand or sandy loam as defined by the USDA soil classification system. The soil and compost mix should have less than 25 percent pass through a #200 sieve and 100 percent should pass through a ¾-inch screen (WORC, 2003).

Compost

Organic soil amendment, suitable for landscaping and stormwater management, should be a stable, **mature compost** derived from organic waste materials including yard debris, manures, bio-solids, wood wastes or other organic materials that meet the intent of the organic soil amendment specification. **Compost stability** indicates the level of microbial activity in the compost and is measured by the amount of CO_2 produced over a given period of time by a sample in a closed container. Unstable compost can render nutrients temporarily unavailable and create objectionable odors.

Compost quality can be determined by examining the material and qualitative tests. A simple way to judge compost quality is to smell and examine the finished product, which should have the following characteristics (WORC, 2003):

- Earthy smell that is not sour, sweet or ammonia like.
- Brown to black in color.
- Mixed particle sizes.
- Stable temperature and does not get hot when re-wetted.
- Crumbly texture.

Qualitative tests and producer documentation should have the following specifications:

- Material must meet the definition for "composted materials" in WAC 173-350 section 220. This code is available online at http://www.ecy.wa.gov/programs/swfa/facilities/350.html.
- Organic matter content between 35 and 65 percent as determined by loss of ignition test method (ASTM D 2974).
- pH between 5.5 and 7.0.
- Carbon:nitrogen ratio between 20:1 and 35:1 (a CN ratio of 35:1 is preferred for native plantings).
- Maximum electrical conductivity of 3 ohms/cm.
- Moisture content range between 35 and 50 percent.
- No viable weed seeds.
- Manufactured inert material (plastic, concrete, ceramics, etc.) should be less than 1 percent on a dry weight or volume basis.
- Metals should not be in excess of limits in the following table:

Metal	Limit (mg/kg dry weight)
Arsenic	≤ 20 ppm
Cadmium	≤ 10 ppm
Copper	≤ 750 ppm
Lead	≤ 150 ppm
Mercury	≤ 8 ppm
Molybdenum	≤ 9 ppm
Nickel	≤ 210 ppm
Selenium1	≤ 18 ppm

(Stenn, 2003)

Determining final grade with amended soils

To achieve the appropriate grade, changes in soil depth from tilling and incorporating soil amendments need to be estimated.

The difference in volume of the dense versus the loose soil condition is determined by the "fluff factor" of the soil. The fluff factor of compacted subsoils in the Puget Sound area tends to be between 1.3 and 1.4. Tilling typically penetrates the upper 6 to 8 inches of the existing soil. Assuming a 6-inch depth is achieved, the depth adjusted by the fluff factor will correspond to a 7.8 to 8.4-inch depth of loose soil. This loose volume is then amended at a 2:1 ratio of loose soil to compost, corresponding to an imported amendment depth of approximately 4 inches for this example. In the loose state, both the soil and compost have a high percentage of pore space (volume of total soil not occupied by solids), and the final amended soil elevation must account for compost settling into void spaces of the loose soil and compaction (this example assumes that 15 percent of the soil's void spaces become occupied by compost particles). For a fluff factor of 1.3, use a compression factor of 1.15 and for soils with a fluff factor of 1.4 use a compression factor of 1.2 (i.e., 15 to 20 percent of the soils' void spaces will become occupied by compost particles). The resulting increase in elevation for soils amended to a 6-inch depth will be approximately 3 inches. See Table 6.2.1 for an example calculation.

Table 6.2.1 Example for estimating soil depth and height changes.

Procedure	Calculation	Relative Elevation Inches
Beginning Elevation		0
Rototill soil to a depth of 6 inches and assuming 1.4-inch fluff factor	Depth achieved by machinery x fluff factor of soil: (6 x 1.4) = 8.4 8.4 – 6 = 2.4	+2.4
Add compost, 2 units soil to 1 unit compost, by loose volume	Depth of soil ÷ 2: 8.4 ÷ 2 = 4.2	+4.2
Filling of pore spaces	Depth of loose soil x percentage of pore space filled by compost addition: 8.4 x (-.15) = -1.3	-1.3
Rototill compost into soil and roll site to compact soil, assuming compression factor of 1.2	(Amended soil depth ÷ compression factor) – amended soil depth:	-2.1
Resulting Elevation Change	Sum	+3.2

Turf areas

If the site is well drained and acceptable for traditional lawn installation, then a compost-amended soil lawn will drain equally well while providing superior storm flow storage, pollutant processing, and growth medium (see Section 6.2.4: Performance for details).

If the site being considered for turf establishment does not drain well, an alternative to planting a lawn should be considered. If the site is not freely draining, turf is still being attempted, and maintenance or other activity is required during the wet months, compost amendment will still provide stormwater benefits. However, the ratio of organic matter to soil should be reduced to a maximum of 30 percent by volume. This upper limit is suggested for the Puget Sound region to reduce the spongy feel of soils with high organic matter content and potential compaction during the wet months (Chollak, n.d.). A drainage route or subsurface collection system may be necessary for composted or non-composted turf applications in poorly draining soils.

Steep slopes

WSDOT has been applying compost to condition soils on slopes ranging up to 33 percent since 1992. No stability problems have been observed as a result of the increased water holding capacity of the compost (Chollak, n.d.). Steep slope areas, which have native soils with healthy native landscapes, should be protected from disturbance. On steep slopes where native soils and vegetation are disturbed or removed, soils should be amended and re-vegetated with deep rooting plants to improve slope stability. Compost can be applied to the ground surface without incorporation to improve plant growth and prevent erosion on steep slopes that cannot be accessed by equipment.

WSDOT has been applying compost to condition soils on slopes ranging up to 33 percent since 1992. No stability problems have been observed as a result of the increased water holding capacity of the compost.

6.2.3 Maintenance

- Incorporate soil amendments at the end of the site development process.
- Protect amended areas from excessive foot traffic and equipment to prevent compaction and erosion.
- Plant and mulch areas immediately after amending soil to stabilize site as soon as possible.
- Minimize or eliminate use of pesticides and fertilizers. Landscape management personnel should be trained to adjust chemical inputs accordingly and manage the landscape areas to minimize erosion, recognize soil and plant health problems, and optimize water storage and soil permeability.

6.2.4 Performance

The surface bulk density of construction site soils generally range from 1.5 to 2.0 gm/cc (CWP, 2000a). At 1.6 to 1.7 gm/cc plant roots cannot penetrate soil and oxygen content, biological activity, nutrient uptake, porosity, and water holding capacity are severely degraded (CWP, 2000a and Balousek, 2003). Tilling alone has limited effect for reducing the bulk density and enhancing compacted soil. A survey of research examining techniques to reverse soil compaction by Schueler found that tilling reduced bulk density by 0.00 to 0.15 gm/cc. In contrast, tilling with the addition of compost amendment decreased bulk density by 0.25 to 0.35 gm/cc (CWP, 2000a).

Balousek (2003) prepared combinations of deep tillage, chisel plow, and compost amended plots on an area with silt loam soil that was cleared and graded to simulate construction site conditions. The deep-tilled plots increased runoff volume compared to the control, and the combined chisel plow and deep-tilled treatment reduced runoff volume by 36 to 53 percent. With compost added to the combined plow and till treatment, runoff volume was reduced by 74 to 91 percent.

Research plots at University of Washington, prepared with various amounts and types of compost mixed with till soil and planted with turf, generated 53 to 70 percent of the runoff volume observed from the unamended control plots. The greatest attenuation was observed in treatments with a ratio of 2 parts soil to 1 part fine, well-aged compost. The study indicates that using compost to amend lawn on till soils can "significantly enhance the ability of the lawn to infiltrate, store and release water as baseflow" (Kolsti, Burges, and Jensen, 1995).

6.3 Permeable Paving

Permeable paving surfaces are designed to accommodate pedestrian, bicycle, and vehicle traffic while allowing infiltration, treatment, and storage of stormwater. The general categories of permeable paving systems include:

- *Open-graded concrete or hot-mix asphalt pavement,* which is similar to standard pavement, but with reduced or eliminated fine material (sand and finer) and special admixtures incorporated (optional). As a result, channels form between the aggregate in the pavement surface and allow water to infiltrate.
- *Aggregate or plastic pavers* that include cast-in-place or modular pre-cast blocks. The cast-in-place systems are reinforced concrete made with reusable forms. Pre-cast systems are either high-strength Portland cement concrete or plastic blocks. Both systems have wide joints or openings that can be filled with soil and grass or gravel.

Permeable paving surfaces accommodate pedestrian, bicycle, and vehicle traffic while allowing infiltration, treatment and storage of stormwater.

- *Plastic grid systems* that come in rolls and are covered with soil and grass or gravel. The grid sections interlock and are pinned in place.

6.3.1 Applications

Typical applications for permeable paving include industrial and commercial parking lots, sidewalks, pedestrian and bike trails, driveways, residential access roads, and emergency and facility maintenance roads. Highways and other high traffic load roads have not been considered appropriate for permeable paving systems. However, porous asphalt has proven structurally sound and remained permeable in a highway application on State Route 87 near Phoenix, Arizona and permeable concrete and pavers have been successfully used in industrial settings with high vehicle loads (Hossain, Scofield and Meier, 1992).

Figure 6.3.1 The residential access road at Jordan Cove Urban Monitoring Project in Connecticut is paved entirely with permeable pavers.
Photo by Tom Wagner

Benefits of permeable pavement
Initial research indicates that properly designed and maintained permeable pavements can virtually eliminate surface flows for low intensity storms common in the Pacific Northwest; store or significantly attenuate subsurface flows (dependent on underlying soil and aggregate storage design); and provide water quality treatment for nutrients, metals, and hydrocarbons (see Section 6.3.4: Performance for additional information).

Permeable paving systems have been designed with aggregate storage to function as infiltration facilities with relatively low subgrade infiltration rates (as low as 0.1 inch/hour). When water is not introduced from adjacent areas, these systems have a lower contribution to infiltration area ratio than conventional infiltration facilities (i.e., 1 to 1) and are less likely to have excessive hydraulic loading. Directing surface flows to permeable paving surfaces from adjacent areas is not recommended. If design constraints require that surface flow be introduced from adjacent areas, particular caution should be taken to ensure that excessive sediment is not directed to the system or that additional flows will not exceed the hydraulic loading capability.

The permeable paving systems examined in this section provide acceptable surfaces for disabled persons. WAC 51-40-1103 Section 1103 (Building Accessibility) states that abrupt changes in height greater than ¼ inch in accessible routes of travel shall be beveled to 1 vertical in 2 horizontal. Changes in level greater than ½ inch shall be accomplished with an approved ramp. Permeable asphalt and concrete, while rougher than conventional paving, do not have abrupt changes in level when properly installed. The concrete pavers have small cells filled with aggregate to a level just under the top of the paver, as well as beveled edges. Gravel pave systems use a specific aggregate with a reinforcing grid that creates a firm and relatively smooth surface (see Section 6.3.2: Design).

Two qualifications for use of permeable paving and disabled access should be noted. Sidewalk designs incorporate scoring, or more recently, truncated domes, near the curb ramp to indicate an approaching traffic area for the blind. The rougher surfaces of permeable paving may obscure this transition; accordingly, standard concrete with scoring or concrete pavers with truncated domes should be used for curb ramps (Florida Concrete and Products Association [FCPA], n.d.). Also, the aggregate within the cells of permeable pavers (such as Eco-Stone) can settle or be displaced from vehicle use. As a result, paver installations for disabled parking spaces and walkways may need to include solid pavers. Individual project designs should be tailored to site characteristics and local regulatory requirements.

Many individual products with specific design requirements are available and cannot all be examined in this manual. To present a representative sample of widely applied products, this section will examine the design, installation, maintenance, and performance of permeable hot-mix asphalt, Portland cement concrete, a concrete paver system, and a flexible plastic grid system.

6.3.2 Design

Handling and installation procedures for permeable paving systems are different from conventional pavement. For the successful application of any permeable paving system three general guidelines must be followed.

> *For successful application of any permeable paving system follow these three general guidelines:*
> - *Use correct design specifications.*
> - *Use qualified contractors.*
> - *Strictly control erosion and sediment.*

1. **Correct design specifications**
   Proper site preparation, correct aggregate base and wearing course gradations, separation layer, and under-drain design (if included) are essential for adequate infiltration, storage, and release of storm flows, as well as structural integrity. For example, over compaction of the underlying soil and excessive fines present in the base or top course will significantly degrade or effectively eliminate the infiltration capability of the system.

2. **Qualified contractors**
   Contractors must be trained and have experience with the product, and suppliers must adhere to material specifications. Installation contractors should provide data showing successful application of product specifications for past projects. If the installation contractor does not have adequate experience the contractor should retain a qualified consultant to monitor production, handling, and placement operations (U.S. Army Corps of Engineers, 2003). Substituting inappropriate materials or installation techniques will likely result in structural or hydrologic performance problems. For example, using vibrating plate compactors (typical concrete installation procedure) with excessive pressures and frequencies will seal the void spaces in permeable cast-in-place concrete.

3. **Sediment and erosion control**
   Erosion and introduction of sediment from surrounding land uses should be strictly controlled during and after construction to reduce clogging of the void spaces in the base material and permeable surface. Filter fabric between the underlying soil and base material is required to prevent soil fines from migrating up and into the aggregate base. Muddy construction equipment should not be allowed on the base material or pavement, sediment laden runoff

should be directed to pre-treatment areas (e.g., settling ponds and swales), and exposed soil should be mulched, planted, and otherwise stabilized as soon as possible.

The preceding guidelines are not optional for the installation of permeable paving systems. Past design failures are most often attributed to not adhering to the above general guidelines, and failure is likely without qualified contractors and strict adherence to correct installation specifications.

Properly designed permeable paving installations have performed well in the Midwestern and Northeastern U.S. where freeze-thaw cycles are severe (Adams, 2003 and Wei, 1986). Risk of freeze damage can be minimized by extending the base of the permeable paving system to a minimum of half the freeze depth. For example, a total minimum depth for the wearing course and aggregate base material would be 6 inches in the Seattle area, where the freeze-thaw depth is 12 inches (Diniz, 1980).

Determining infiltration rates

Depending on the design, permeable paving installations can be modeled as landscaped area over the underlying soil type or as an infiltration basin. If the installation is modeled as an infiltration basin, determining the infiltration rate of the underlying soil is necessary to equate flow reduction benefits when using the WWHM or MGS Flood. For details on flow modeling guidance see Chapter 7. See Figure 6.3.2 for a graphic representation of the process to determine infiltration rates. The following tests are recommended for soils below the aggregate base material:

- Small permeable paving installations (patios, walkways, and driveways on individual lots): The flow control credits on private property do not include subsurface storage; accordingly, no infiltration field tests are necessary. Soil texture, grain size analysis, or soil pit excavation and infiltration tests may still be prudent if highly variable soil conditions or seasonal high water tables are suspected.
- Large permeable paving installations (sidewalks, alleys, parking lots, roads) that include storage volume using base material below the grade of the surrounding land and the installations are modeled as an infiltration basin:
  - Method 1: Use USDA Soil Textural Classification (Rawls survey) every 200 feet of road or every 5,000 square feet.
  - Method 2: Use ASTM D422 Gradation Testing at Full Scale Infiltration Facilities every 200 feet of road or every 5,000 square feet. See the 2005 SMMWW Volume III for details on methods 1 and 2. This method uses the *2004 WSDOT Highway Runoff Manual* protocol.
  - Method 3: Use small-scale infiltrometer tests every 200 feet of road or every 5,000 square feet. Small-scale infiltrometer tests such as the USEPA Falling Head or double ring infiltrometer tests (ASTM 3385-88) may not adequately measure variability of conditions in test areas. If used, measurements should be taken at several locations within the area of interest.
  - Method 4: Pilot Infiltration Test (PIT) or small-scale test infiltration pits (septic test pits) at a rate of 1 pit/500 feet of road or 10,000 ft^2. This infiltration test better represents soil variability and is recommended for highly variable soil conditions or where seasonal high water tables are suspected. See the 2005 SMMWW Appendix III-D (formerly V-B) for PIT method description.

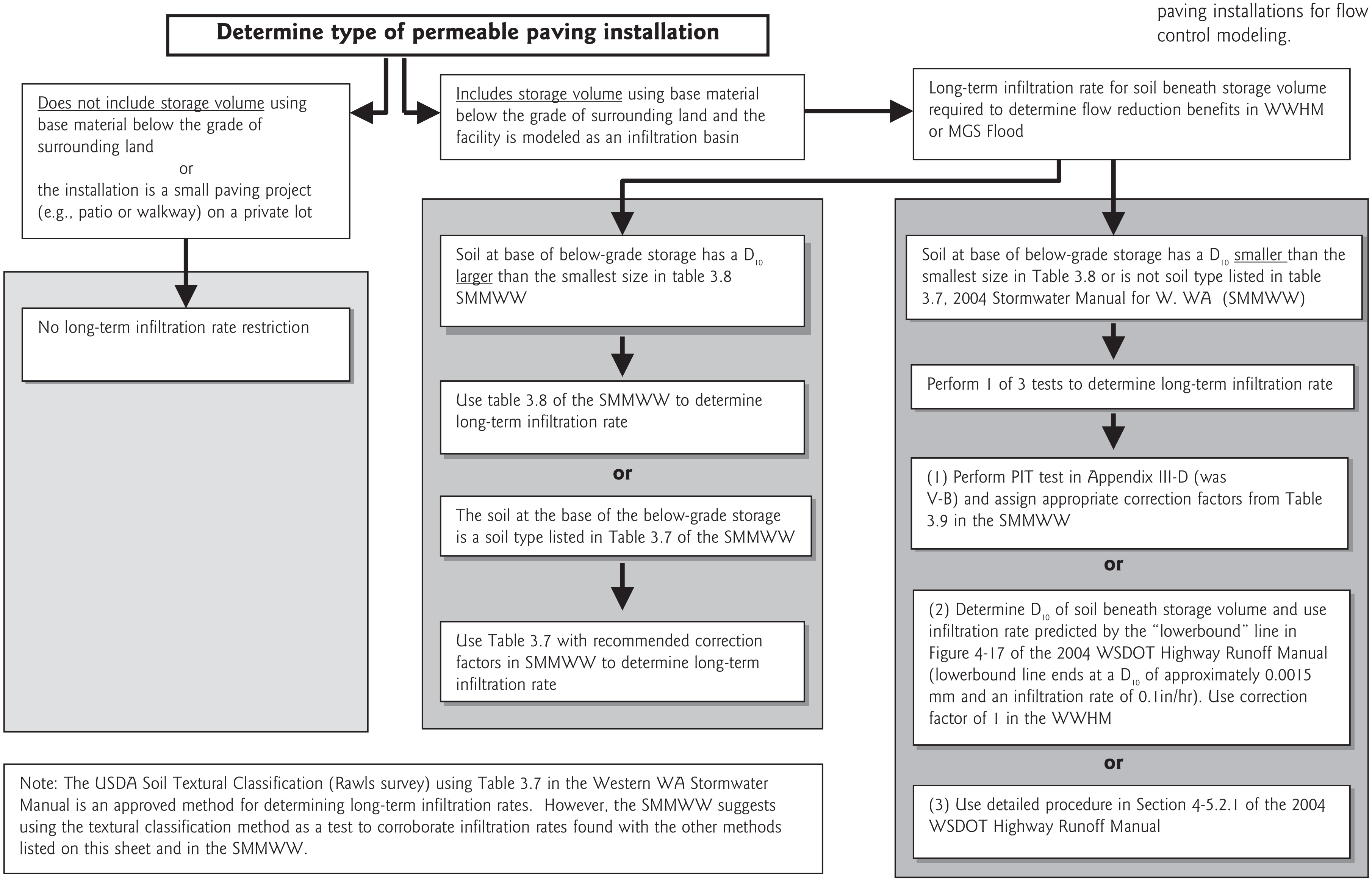


Figure 6.3.2 Determining long-term infiltration rates in soils under permeable paving installations for flow control modeling.

Utility excavations under or beside the road section can provide pits for soil classification, textural analysis, stratigraphy analysis, and/or infiltration tests and minimize time and expense for permeable paving infiltration tests.

Components of permeable paving systems

The following provides a general description and function for the components of permeable paving systems. Design details for specific permeable paving system components are included in the section describing specific types of permeable paving.

Wearing course or surface layer

The wearing course provides compressive and flexural strength for the designed traffic loads while maintaining adequate porosity for storm flow infiltration. Wearing courses include cast-in-place concrete, asphalt, concrete and plastic pavers, and plastic grid systems. In general, permeable top courses have very high initial infiltration rates with various asphalt and concrete research reporting 28 to 1750 inches per hour when new (see Appendix 7: Porous Paving Research for details). Various rates of clogging have been observed in wearing courses and should be anticipated and planned for in the system design (see Section 6.3.5: Performance for research on infiltration rates over time). Permeable paving systems allow infiltration of storm flows; however, the wearing course should not be allowed to become saturated from excessive water volume stored in the aggregate base layer.

Aggregate base

The aggregate base provides: (1) a stable base for the pavement; (2) a highly permeable layer to disperse water downward and laterally to the underlying soil; and (3) a temporary reservoir that stores water prior to infiltration in the underlying soil or collection in under-drains for conveyance (Washington State Department of Transportation [WSDOT], 2003). Base material is often composed of larger aggregate (1.5 to 2.5 inches) with smaller stone (leveling or choker course) between the larger stone and the wearing course. Typical void space in base layers ranges from 20 to 40 percent (WSDOT, 2003 and Cahill, Adams and Marm, 2003). Depending on the target flow control standard and physical setting, retention or detention requirements can be partially or entirely met in the aggregate base. Aggregate base depths of 18 to 36 inches are common depending on storage needs and provide the additional benefit of increasing the strength of the wearing course by isolating underlying soil movement and imperfections that may be transmitted to the wearing course (Cahill et al., 2003).

Separation and water quality treatment layer

The separation layer is a non-woven geotextile fabric that provides a barrier to prevent fine soil particles from migrating up and into the base aggregate. If required, the water quality treatment layer filters pollutants from surface water and protects groundwater quality (generally, a treatment layer will be necessary in critical aquifer recharge areas). The treatment media can consist of a sand layer or an engineered amended soil. Engineered amended soil layers should be a minimum of 18 inches and incorporate compost, sphagnum peat moss or other organic material to provide a **cation exchange capacity** of ≥ 5 milliequivalents/100 grams dry soil (Ecology, 2001). Soil gradation and final mix should provide a minimum infiltration rate of 0.5 inch/hour at final compaction.

Flow modeling guidance

See Chapter 7 for guidance and flow reduction credits for permeable paving systems when using the WWHM.

A treatment layer is not required where the subgrade soil has a long-term infiltration rate of < 2.4 inches/hour and a cation exchange capacity of ≥ 5 milliequivalents/100 grams dry soil.

Figure 6.3.3 Permeable pavers were installed at this Marysville parking lot for infiltration. Organic material was mixed with sand as part of the sub-base to enhance treatment.

Photo by Colleen Owen

Types of permeable paving

The following section provides general design specifications for permeable hot-mix asphalt, Portland cement concrete, a flexible plastic grid system, a cement paver, and a rigid plastic block product. Each product has specific design requirements. Most notably the permeable Portland cement concrete and hot-mix asphalt differ from the paver systems in subgrade preparation. Concrete and asphalt systems are designed and constructed to minimize subgrade compaction and maintain the infiltration capacity of the underlying soils. Paver systems require subgrade compaction to maintain structural support. Some soils with high sand and gravel content can retain useful infiltration rates when compacted; however, many soils in the Puget Sound region become essentially impermeable when compacted to 95 percent modified proctor or proctor rates.

The specifications below are provided to give designers general guidance. Each site has unique characteristics and development requirements; accordingly, qualified engineers and other design disciplines should be consulted for developing specific permeable paving systems.

1. Permeable hot-mix asphalt

Permeable asphalt is similar to standard hot-mix asphalt; however, the aggregate fines (particles smaller than No. 30 sieve) are reduced, leaving a matrix of pores that conduct water to the underlying aggregate base and soil (Cahill et al., 2003). Porous asphalt can be used for light to medium duty applications including residential access roads, driveways, utility access, parking lots, and walkways; however, porous asphalt has been used for heavy applications such as airport runways (with the appropriate polymer additive to increase bonding strength) and highways (Hossain, Scofield and Meier, 1992). While freeze-thaw cycles are not a large concern in

Properly installed and maintained permeable asphalt should have a service life that is comparable or longer than conventional asphalt.

the Puget Sound lowland, permeable asphalt can and has been successfully installed in wet, freezing conditions in the Midwestern U.S. and Massachusetts with proper section depths (Cahill et al., 2003 and Wei, 1986). Properly installed and maintained permeable asphalt should have a service life that is comparable or longer than conventional asphalt (personal communication, Tom Cahill, 2003).

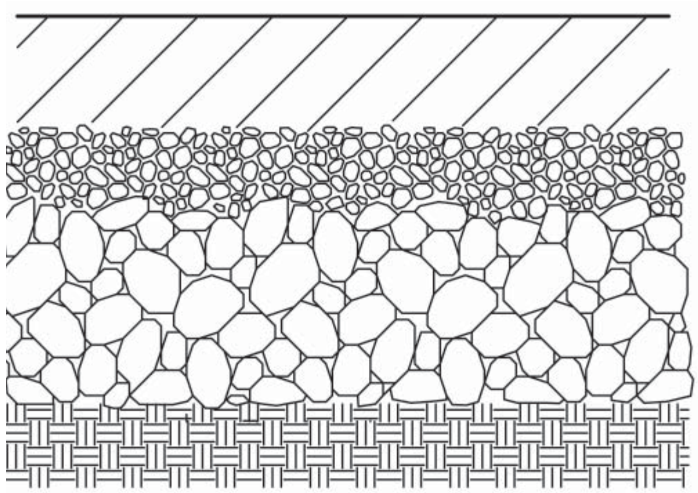


Figure 6.3.4 Permeable asphalt section.

Graphic by AHBL Engineering

Design

Several permeable bituminous asphalt mixes and design specifications have been developed for friction courses (permeable asphalt layer over conventional asphalt) and as wearing courses that are composed entirely of a porous asphalt mix. The friction courses are designed primarily to reduce noise and glare off standing water at night and hydroplaning; however, this design approach provides minimal attenuation of stormwater during the wet season in the Puget Sound region. The following provides specifications and installation procedures for permeable asphalt applications where the wearing top course is entirely porous, the base course accepts water infiltrated through the top course, and the primary design objective is to significantly or entirely attenuate storm flows.

Application: parking lots, driveways, and residential and utility access roads.

Soil infiltration rate

- As long as runoff is not directed to the permeable asphalt from adjacent surfaces, the estimated long-term infiltration rate may be as low as 0.1 inch/hour. Soils with lower infiltration rates should have under-drains to prevent prolonged saturated soil conditions at or near the ground surface within the pavement section.
- Directing surface flows to permeable paving surfaces from adjacent areas is not recommended. Surface flows from adjacent areas can introduce excess sediment, increase clogging, and result in excessive hydrologic loading. However, it may be acceptable to direct flows after treatment to the subgrade if storage volume and infiltration rates allow.

Subgrade

- Soil conditions should be analyzed by a qualified engineer for load bearing given anticipated soil moisture conditions.

- After grading, the existing subgrade should not be compacted or subjected to excessive construction equipment traffic.
- If using the base course for retention in parking areas, excavate the storage bed level to allow even distribution of water and maximize infiltration across entire parking area.
- Immediately before base aggregate and asphalt placement, remove any accumulation of fine material from erosion with light equipment and scarify soil to a minimum depth of 6 inches.

Aggregate base/storage bed

- Minimum base depth for structural support should be 6 inches (Washington State Department of Transportation, 2003).
- Maximum depth is determined by the extent to which the designer intends to achieve a flow control standard with the use of a below-grade storage bed. Aggregate base depths of 18 to 36 inches are common depending on storage needs.
- Coarse aggregate layer should be a 2.5- to 0.5-inch uniformly graded crushed (angular) thoroughly washed stone (AASHTO No. 3).
- Choker course should be 1 to 2 inches in depth and consist of 1.5-inch to U.S. sieve size number 8 uniformly graded crushed washed stone for final grading of base reservoir. The upper course is needed to reduce rutting from construction vehicles delivering and installing asphalt and to more evenly distribute loads to the base material (Diniz, 1980).

Installation of Aggregate base/storage bed

- Stabilize area and install erosion control to prevent runoff and sediment from entering storage bed.
- Install approved non-woven filter fabric on subsoil according to manufacturer's specifications. Where installation is adjacent to conventional paving surfaces, filter fabric should be wrapped up sides to top of base aggregate to prevent migration of fines from densely graded material to the open graded base, maintain proper compaction, and avoid differential settling.
- Overlap adjacent strips of fabric at least 24 inches. Secure fabric 4 feet outside of storage bed to reduce sediment input to bottom of area storage reservoir.
- Install coarse (1.5 to 2.5 inch) aggregate in maximum of 8-inch lifts and lightly compact each lift.
- Install a 1 to 2-inch choker course evenly over surface of course aggregate base.
- Following placement of base aggregate and again after placement of the asphalt, the filter fabric should be folded over placements to protect installation from sediment inputs. Excess filter fabric should not be trimmed until site is fully stabilized (U.S. Army Corps of Engineers, 2003).

Top course

- Parking lots: 2 to 4 inches typical.
- Residential access roads: 2 to 4 inches typical.
- Permeable asphalt has similar strength and flow properties as conventional asphalt; accordingly, the wearing course thickness is similar for either surface given equivalent load requirements (Diniz, 1980).

Aggregate grading:	U.S. Standard Sieve	Percent Passing
	1/2	100
	3/8	92-98
	4	32-38
	8	12-18
	16	7-13
	30	0-5
	200	0-3

- A small percentage of fine aggregate is necessary to stabilize the larger porous aggregate fraction. The finer fraction also increases the viscosity of the asphalt cement and controls asphalt drainage characteristics.
- Total void space should be approximately 16 percent (conventional asphalt is 2 to 3 percent) (Diniz, 1980).

Bituminous asphalt cement

- Content: 5.5 to 6.0 percent by weight dry aggregate. The minimum content assures adequate asphalt cement film thickness around the aggregate to reduce photo-oxidation degradation and increase cohesion between aggregate. The upper limit is to prevent the mixture from draining during transport.
- Grade: 85 to 100 penetration recommended for northern states (Diniz, 1980).
- An elastomeric polymer can be added to the bituminous asphalt to reduce drain-down.
- Hydrated lime can be added at a rate of 1.0 percent by weight of the total dry aggregate to mixes with granite stone to prevent separation of the asphalt from the aggregate and improve tensile strength.

General installation

- Install permeable asphalt system toward the end of construction activities to minimize sediment problems. The subgrade can be excavated to within 6 inches of final grade and grading completed in later stages of the project (Cahill et al., 2003).
- Erosion and introduction of sediment from surrounding land uses should be strictly controlled during and after construction. Erosion and sediment controls should remain in place until area is completely stabilized with soil amendments and landscaping.
- Adapting aggregate specifications can influence bituminous asphalt cement properties and permeability of the asphalt wearing course. Before final installation, test panels are recommended to determine asphalt cement grade and content compatibility with the aggregate (Diniz, 1980).
- Insulated covers over loads during hauling can reduce heat loss during transport and increase working time (Diniz, 1980). Temperatures at delivery that are too low can result in shorter working times, increased labor for hand work, and increased cleanup from asphalt adhering to machinery (personal communication Leonard Spodoni, April 2004).

Backup systems for protecting permeable asphalt systems

- For backup infiltration capacity (in case the asphalt top course becomes clogged) an unpaved stone edge can be installed that is hydrologically connected to the storage bed (see Figure 6.3.5).

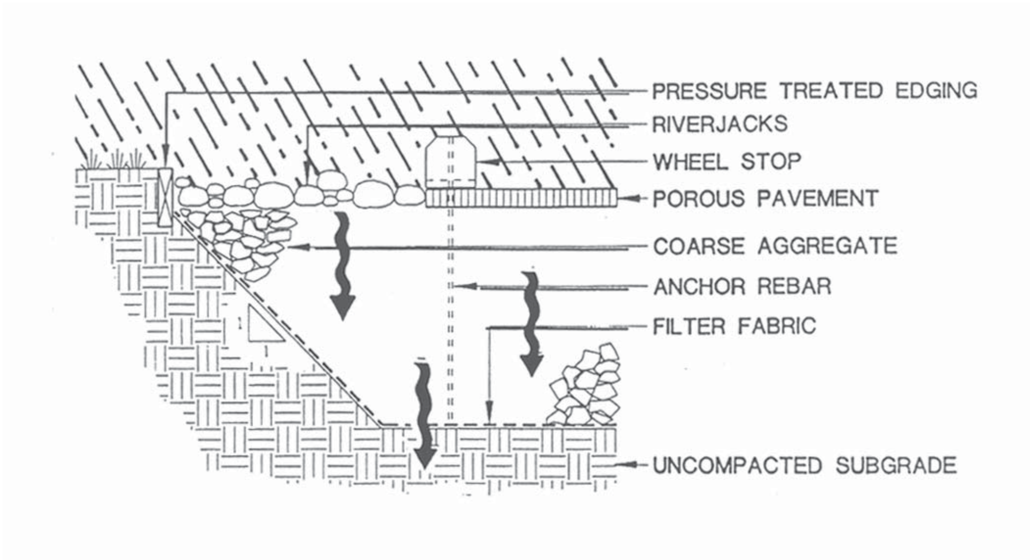


Figure 6.3.5 Unpaved section (river jacks) provides backup infiltration.

Graphic courtesy of Cahill Associates

- As with any paving system, rising water in the underlying aggregate base should not be allowed to saturate the pavement (Cahill et al., 2003). To ensure that the asphalt top course is not saturated from excessively high water levels in the aggregate base (as a result of subgrade soil clogging), a positive overflow can be installed.

For a sample specification for permeable asphalt paving see Appendix 8.

Cost

Materials and mixing costs for permeable asphalt are similar to conventional asphalt. In general, local contractors are currently not familiar with permeable asphalt installation, and additional costs for handling and installation should be anticipated. Estimates for porous pavement material and installation are approximately $.60 to .70/square foot and will likely be comparable to standard pavement as contractors become more familiar with the product. Due to the lack of experience regionally, this is a rough estimate. The cost for base aggregate will vary significantly depending on base depth for stormwater storage and is not included in the cost estimate.

2. Portland cement permeable concrete

Florida and Georgia use permeable concrete extensively for stormwater management. The material and installation specifications in Washington are derived primarily from the field experience and testing through the Florida Concrete and Products Association. In the Puget Sound region, the cities of Seattle and Olympia and Stoneway Concrete have tested materials and installed several projects including parking lots, sidewalks, and driveways.

Permeable Portland cement concrete is similar to conventional concrete without the fine aggregate (sand) component. The mixture is a washed coarse aggregate (3/8 or 5/8 inch), hydraulic cement, admixtures (optional) and water, yielding a surface with a matrix of pores that conducts water to the underlying aggregate base and soil. Permeable concrete can be used for light to medium duty applications including residential access roads, driveways, utility access, parking lots, and walkways. Permeable concrete can also be used in heavy load applications. For example, test sections in a city of Renton aggregate recycling yard have performed well structurally after being subjected to regular 50,000- to 100,000-pound vehicle loads for the past three years (personal communication, Greg McKinnon, March 2004). Properly installed and maintained concrete should have a service life comparable to conventional concrete.

Designing the aggregate base to accommodate retention or detention storage will depend on several factors, some of which include project specific stormwater flow control objectives, costs, and regulatory restrictions. However, deeper subgrade to base courses (e.g., 12 to 36 inches) can provide important benefits including significant reduction of above ground stormwater retention or detention needs and uniform subgrade support (FCPA, n.d.). Base courses that are placed above the surrounding grade cannot be used, or given credit for, reducing retention or detention pond sizes. (See Chapter 7 for flow modeling guidance and flow reduction credits.)

Figure 6.3.6 Permeable concrete adjacent to stamped concrete in Des Moines.
Photo by Curtis Hinman

Design and installation

Three general classes of permeable concrete are prevalent: (1) the standard mix using washed course aggregate (3/8 or 5/8 inch), hydraulic cement, admixtures (optional) and water; (2) a Stoneycrete mixture which is similar to the standard mix, but incorporates a strengthening additive; and (3) Percocrete which uses a higher percentage of sand, incorporates an additive to enhance strength and the pore structure, and produces a smoother surface texture. The following design section examines the standard concrete mix. Additional information for Stoneycrete is available at Stoney Creek Materials L.L.C. Austin, Texas and for Percocrete at Michiels International Inc., Kenmore, Washington.

Application: parking lots, driveways, sidewalks, utility access, and residential roads.

Soil infiltration rate

- If runoff is not directed to the permeable concrete from adjacent surfaces, the estimated long-term infiltration rate may be as low as 0.1 inch/hour. Soils with lower infiltration rates should have under-drains to prevent prolonged saturated soil conditions at or near the ground surface within the pavement section.
- Directing surface flows to permeable paving surfaces from adjacent areas is not recommended. Surface flows from adjacent areas can introduce excess sediment, increase clogging, and result in excessive hydrologic loading.

However, it may be acceptable to direct flows after treatment to the subgrade if storage volume and infiltration rates allow.

Subgrade

- Soil conditions should be analyzed for load bearing given anticipated soil moisture conditions by a qualified engineer.
- After grading, the existing subgrade should not be compacted or subject to excessive construction equipment traffic (U.S. Army Corps of Engineers, 2003).
- Immediately before base aggregate and concrete placement, remove any accumulation of fine material from erosion with light equipment and scarify soils to a minimum depth of 6 inches if compacted (U.S. Army Corps of Engineers, 2003).

Aggregate base/storage bed

- Minimum base depth for structural support should be 6 inches (FCPA, n.d.).
- Maximum depth is determined by the extent to which the designer intends to achieve a flow control standard with the use of a below-grade storage bed. Aggregate base depths of 18 to 36 inches are common when designing for retention or detention.
- The coarse aggregate layer varies depending on structural and stormwater management needs. Typical placements include round or crushed washed drain rock (1 to 1.5 inches) or 1.5 to 2.5-inch crushed washed base rock aggregate (e.g., AASTHO No. 3).
- The concrete can be placed directly over the coarse aggregate or a choker course (e.g., 1.5 inch to US sieve size number 8, AASHTO No 57 crushed washed stone) can be placed over the larger stone for final grading.

Installation of aggregate base/storage bed

- Stabilize area and install erosion control to prevent runoff and sediment from entering storage bed.
- If using the aggregate base for retention in parking areas, excavate storage bed level to allow even distribution of water and maximize infiltration across entire parking area.
- Install approved non-woven filter fabric on subsoil according to manufacturer's specifications. Where concrete installations are adjacent to conventional paving surfaces the filter fabric should be wrapped up the sides and to the top of base aggregate to prevent migration of fines from the densely graded base to the open graded base material, maintain proper compaction, and avoid differential settling.
- Overlap adjacent strips of fabric at least 24 inches. Secure fabric 4 feet outside of storage bed to reduce sediment input to bottom of storage reservoir.
- Install coarse aggregate in maximum of 8-inch lifts and lightly compact each lift (U.S. Army Corps of Engineers, 2003).
- If utilized, install a 1-inch choker course evenly over surface of coarse aggregate base (typically No. 57 AASHTO) and lightly compact.
- Following placement of base aggregate and again after placement of concrete, the filter fabric should be folded over placements to protect installation from sediment inputs. Excess filter fabric should not be trimmed until site is fully stabilized (U.S. Army Corps of Engineers, 2003).

Top course

- Parking lots: 4 inches typical.
- Roads: 6 to 12 inches typical.
- Unit weight: 120 to 130 pounds per cubic foot (permeable concrete is approximately 70 to 80 percent of the unit weight of conventional concrete) (FCPA, n.d.).
- Void space: 15 to 21 percent according to ASTM C 138.
- Water cement ratio: 0.27 to 0.35.
- Aggregate to cement ratio: 4:1 to 4.5:1.
- Aggregate: several aggregate specifications are used including:
  - o 3/8-inch to No. 16 washed crushed or round per ASTM C 33.
  - o 3/8-inch to No. 50 washed crushed or round per ASTM D 448.
  - o 5/8-inch washed crushed or round.
  - o In general the 3/8-inch crushed or round produces a slightly smoother surface and is preferred for sidewalks, and the 5/8-inch crushed or round produces a slightly stronger surface.
- Portland cement: Type I or II conforming to ASTM C 150 or Type IP or IS conforming to ASTM C 595.
- Admixtures: Can be used to increase working time and include: Water Reducing/Retarding Admixture in conformance with ASTM C 494 Type D and Hydration stabilizer in conformance with ASTM C 494 Type B.
- Water: Use potable water.
- Fiber mesh can be incorporated into the cement mix for added strength.

Installation of top course

- See testing section below for confirming correct mixture and proper installation.
- If mixture contains excess water the cement paste can flow from the aggregate, resulting in a weak surface layer and reduced void space in the lower portion of surface. With the correct water content, the delivered mix should have a wet metallic sheen, and when hand squeezed the mix should not crumble or become a highly plastic mass (FCPA, n.d.).
- Cement mix should be used within 1 hour after water is introduced to mix, and within 90 minutes if an admixture is used and concrete mix temperature does not exceed 90 degrees Fahrenheit (U.S. Army Corps of Engineers, 2003).
- Base aggregate should be wetted to improve working time of cement.
- Concrete should be deposited as close to its final position as possible and directly from the truck or using a conveyor belt placement.
- A manual or mechanical screed can be used to level concrete at 1/2 inch above form.
- Cover surface with 6-mil plastic and use a static drum roller for final compaction (roller should provide approximately 10 pounds per square inch vertical force).
- Edges that are higher than adjacent materials should be finished or rounded off to prevent chipping (standard edging tool is applicable for pervious concrete).
- Cement should be covered with plastic within 20 minutes and remain covered for curing time.
- Curing: 7 days minimum for Portland cement Type I and II. No truck traffic should be allowed for 10 days (U.S. Army Corps of Engineers, 2003).

- Placement widths should not exceed 15 feet unless contractor can demonstrate competence to install greater widths.
- High frequency vibrators can seal the surface of the concrete and should not be used.
- Jointing: Shrinkage associated with drying is significantly less for permeable than conventional concrete. Florida installations with no control joints have shown no visible shrink cracking. A conservative design can include control joints at 60 foot spacing cut to 1/4 the thickness of the pavement (FCPA, n.d. and U.S. Army Corps of Engineers, 2003). Expansion joints can also facilitate a cleaner break point if sections become damaged or are removed for utility work.

Testing

Differences in local materials, handling, and placement can affect permeable concrete performance. The following tests should be conducted even if the contractor or consultant has experience with the material to ensure proper performance.

- The contractor should place and cure two test panels, each covering a minimum of 225 square feet at the required project thickness, to demonstrate that specified unit weights and permeability can be achieved on-site (Georgia Concrete and Products Association [GCPA], 1997).
- Test panels should have two cores taken from each panel in accordance with ASTM C 42 at least 7 days after placement (GCPA, 1997).
- Untrimmed cores should be measured for thickness according to ASTM C 42.
- After determining thickness, cores should be trimmed and measured for unit weight per ASTM C 140.
- Void structure should be tested per ASTM C 138.
- If the measured thickness is greater than 1/4 inch less than the specified thickness, or the unit weight is not within ± 5 pounds per cubic foot, or the void structure is below specifications, the panel should be removed and new panels with adjusted specifications installed (U.S. Army Corps of Engineers, 2003). If test panel meets requirements, panel can be left in place as part of the completed installation.
- Collect and sample delivered material once per day to measure unit weight per ASTM C 172 and C 29 (FCPA, n.d.).

Backup systems for protecting permeable concrete systems

- For backup infiltration capacity (in case the concrete top course becomes clogged) an unpaved stone edge can be installed that is connected to the base aggregate storage reservoir (see Figure 6.3.5).
- As with any paving system, rising water in the underlying aggregate base should not be allowed to saturate the pavement (Cahill et al., 2003). To ensure that the top course is not saturated from excessively high water levels (as a result of subgrade soil clogging), a positive overflow can be installed in the base.

Cost

Permeable concrete material and installation is approximately $3.00 to $5.00 per square foot depending on surface thickness and site conditions. Cost for base aggregate will vary significantly depending on base depth for stormwater storage and is not included in the cost estimate.

3. Eco-Stone permeable interlocking concrete pavers

Eco-Stone is a high-density concrete paver that allows infiltration through a built-in pattern of openings filled with aggregate. When compacted, the pavers interlock and transfer vertical loads to surrounding pavers by shear forces through fine aggregate in the joints (Pentec Environmental, 2000). Eco-Stone interlocking pavers are placed on open graded sub-base aggregate topped with a finer aggregate layer that provides a level and uniform bedding material. Properly installed and maintained, high-density pavers have high load bearing strength and are capable of carrying heavy vehicle weight at low speeds. Properly installed and maintained pavers should have a service life of 20 to 25 years (Smith, 2000).

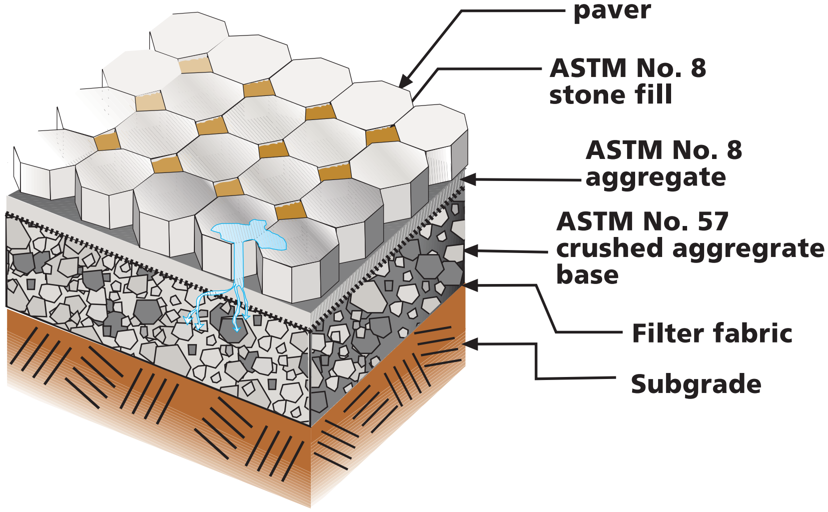


Figure 6.3.7 Permeable interlocking concrete paver section.
Graphic by Gary Anderson

Figure 6.3.8 Close-up view of permeable pavers.
Photo by Curtis Hinman

Design

Application: Industrial and commercial parking lots, utility access, residential access roads, driveways, and walkways. Experienced contractors with a current certificate in the ICPI Contractor Certification Program should perform installations.

Soil infiltration rate

- If runoff is not directed to the permeable pavers from adjacent surfaces, the estimated long-term infiltration rate may be as low as 0.5 inch/hour. Soils with lower infiltration rates should have under-drains at the bottom of the base course to prevent prolonged saturated soil conditions at or near the ground surface within the pavement section. Drain-down time for the base should not exceed 24 hours.
- Directing surface flows to permeable paving surfaces from adjacent areas is not recommended. Surface flows from adjacent areas can introduce excess sediment, increase clogging, and result in excessive hydrologic loading. However, it may be acceptable to direct flows after treatment to the subgrade if storage volume and infiltration rates allow.

Subgrade

- Soils should be analyzed by a qualified engineer for infiltration rates and load bearing, given anticipated soil moisture conditions. **California Bearing Ratio** values should be at least 5 percent.
- For vehicle traffic areas, grade and compact to 95 percent modified proctor density (per ASTM D 1557) and compact to 95 percent standard proctor density for pedestrian areas (per ASTM D698) (Smith, 2000). Soils with high sand and gravel content can retain useful infiltration rates when compacted; however, many soils in the Puget Sound region become essentially impermeable at this compaction rate. For detention designs on compacted soils that will provide very low permeability, adequate base aggregate depths and under-drain systems should be incorporated to reduce risk of continued saturation that can weaken subgrades subject to vehicle traffic (Smith, 2000).

Aggregate base/storage bed

- Minimum base thickness depends on vehicle loads, soil type, stormwater storage requirements, and freeze thaw conditions. Typical depths range from 6 to 22 inches; however, increased depths can be applied for increased storage capacity (Smith, 2000). Interlocking Concrete Paver Institute guidelines for base thickness should be followed.
- Minimum base depth for pedestrian and bike applications should be 6 inches (Smith, 2000).
- ASTM No. 57 crushed aggregate or similar gradation is recommended for the sub-base (Smith, 2000).
- ASTM No. 8 is recommended for the leveling or choker course.

Installation of aggregate base/storage bed

- Stabilize area and install erosion control to prevent runoff and sediment from entering storage bed.
- If using the base course for retention in parking areas, excavate storage bed level to allow even distribution of water and maximize infiltration across entire parking area.

- Install approved non-woven filter fabric to bottom and sides of excavation according to manufacturer's specifications. Where paver installation is adjacent to conventional paving surfaces, filter fabric should be wrapped up sides to top of base aggregate to prevent migration of fines from densely graded base to the open graded base material, maintain proper compaction, and avoid differential settling. A concrete curb the depth of the base can also be used to separate the open graded and dense graded bases.
- Overlap adjacent strips of fabric at least 24 inches. Secure fabric 4 feet outside of storage bed to reduce sediment input to bottom of area storage reservoir (Smith, 2000).
- Install No. 57 aggregate in 4 to 6-inch lifts.
- Compact the moist No. 57 aggregate with at least 4 passes of a 10-ton (minimum) steel drum roller. Initial passes can be with vibration and the final two passes should be static (Smith, 2000). Testing for appropriate density per ASTM D 698 or D 1557 will likely not provide accurate results. The Interlocking Concrete Pavement Institute specification recommends that adequate density and stability are developed when no visible movement is observed in the open-graded base after compaction (personal communication, Dave Smith ICPI).
- Install three inches of No. 8 aggregate for the leveling or choker course and compact with at least 4 passes of a 10-ton roller. Surface variation should be within ± 1/2 inch over 10 feet. The No. 8 aggregate should be moist to facilitate compaction into the sub-base (Smith, 2000).
- Asphalt stabilizer can be used with the No. 57 stone if additional bearing support is needed, but should not be applied to the No. 8 aggregate. To maintain adequate void space, use a minimum of asphalt for stabilization (approximately 2 to 2.5 percent by weight of aggregate). An asphalt grade of AC20 or higher is recommended. The addition of stabilizer will reduce storage capacity of base aggregate and should be considered in the design (Smith, 2000).
- Following placement of base aggregate and again after placement of pavers, the filter fabric should be folded over placements to protect installation from sediment inputs. Excess filter fabric should not be trimmed until site is fully stabilized.
- Designs for full infiltration of stormwater to the subgrade should have a positive overflow to prevent water from entering the surface layer during extreme events. Designs with partial or no **exfiltration** require under-drains. All installations should have an observation well (typically 6-inch perforated pipe) installed at the furthest downslope area (Smith, 2000).

Top course installation

- Pavers should be installed immediately after base preparation to minimize introduction of sediment and to reduce the displacement of base material from ongoing activity (Smith, 2000).
- Loosen and evenly smooth 3/4 to 1 inch of the compacted No. 8 stone.
- Place pavers by hand or with mechanical installers and compact with a 5000 lbf, 75 to 90 Hz plate compactor. Fill openings with No. 8 stone and compact again. Sweep to remove excess stone from surface. The small amount of finer aggregate in the No. 8 stone will likely be adequate to fill narrow joints between pavers in pedestrian and light vehicle applications. If the installation is subject

to heavy vehicle loads, additional material may be required for joints. Sweep in additional material (ASTM No. 89 stone is recommended) and use vibratory compaction to place joint material (Smith, 2000).

Figure 6.3.9 Mechanical installation of Eco-Stone pavers.

Photo by Curtis Hinman

- Do not compact within 3 feet of unrestrained edges (Pentec Environmental, 2000).
- Sand placed in paver openings or used as a leveling course will clog and should not be applied for those purposes.
- Cast-in-place or pre-cast concrete (approximately 6 inches wide by 12 inches high) are the preferred material for edge constraints. Plastic edge confinement secured with spikes is not recommended (Smith, 2000).

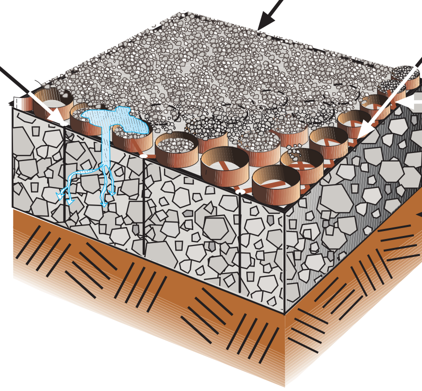
Cost

Eco-Stone material and installation costs range from $2.50 to $4.50 per square foot for the pavers, aggregate leveling layer, aggregate for the paver openings and joints, and installation. Costs for base aggregate will vary significantly depending on stormwater storage needs. Base material and installation, geotextile, excavation, and sediment controls are not included in this price estimate. Large jobs (e.g., 150,000 square feet) utilizing mechanical placement of pavers would qualify for the lower end of the cost range and smaller jobs (e.g., 40,000 square feet) with mechanical installation would likely be at the higher end of the cost range (personal communication, Brian Crooks and Dave Parisi, July 2004).

4. Gravelpave2 flexible plastic grid system

Gravelpave2 is a lightweight grid of plastic rings in 20” wide x 20” long x 1” high units with a geotextile fabric heat fused to the bottom of the grid. The grid and fabric is provided in pre-assembled rolls of various dimensions (Invisible Structures, 2003). This and other similar plastic grid systems have a large amount of open cell available for infiltration in relation to the solid support structure. Flexible grid systems conform to the grade of the aggregate base, and when backfilled with appropriate aggregate top course, provide high load bearing capability (Gravelpave2 load capacity is approximately 5700 psi) (Invisible Structures, 2003). Gravelpave2 is not impacted by the degree of freeze-thaw conditions found in the Puget Sound region. Properly installed and maintained, Gravelpave2 has an expected service life of approximately 20 years (Bohnhoff, 2001).

Figure 6.3.10 Gravelpave2 system.
Graphic by Gary Anderson



Design

Application: Typical uses include alleys, driveways, utility access, loading areas, trails, and parking lots with relatively low traffic speeds (15 to 20 mph maximum). Higher speeds may require use of a binder at 10 percent cement by weight with fill stone (Bohnhoff, 2001).

Soil infiltration rate

- If runoff is not directed to the Gravelpave system from adjacent surfaces, the estimated long-term infiltration rate may be as low as 0.5 inch/hour. Soils with lower infiltration rates should have under-drains in the base course to prevent prolonged saturated soil conditions within the top course section.
- Directing surface flows to permeable paving surfaces from adjacent areas is not recommended. Surface flows from adjacent areas can introduce excess sediment, increase clogging, and result in excessive hydrologic loading. However, it may be acceptable to direct flows after treatment to the subgrade if storage volume and infiltration rates allow.

Subgrade

- Soil conditions should be analyzed for load bearing given anticipated soil moisture conditions by a qualified engineer.
- After grading, the existing subgrade should not be compacted or subject to excessive construction equipment traffic.
- Immediately before base aggregate and top course, remove any accumulation of fine material from erosion with light equipment.

Aggregate base/storage bed

- Minimum base thickness depends on vehicle loads, soil type, and stormwater storage requirements. Typical minimum depth is 4 to 6 inches for driveways, alleys, and parking lots (less base course depth is required for trails) (personal communication, Andy Gersen, July 2004). Increased depths can be applied for increased storage capacity.

- Base aggregate is a sandy gravel material typical for road base construction (Invisible Structures, 2003).

Aggregate grading:	U.S. Standard Sieve	Percent Passing
	3/4	100
	3/8	85
	4	60
	8	15
	40	30
	200	<3

Base course installation

- Stabilize area and install erosion control to prevent runoff and sediment from entering storage bed.
- If using the base course for retention in parking areas, excavate storage bed level to allow even distribution of water and maximize infiltration across entire parking area.
- Install approved non-woven filter fabric to bottom and sides of excavation according to manufacturer's specifications. Where the installation is adjacent to conventional paving surfaces, the filter fabric should be wrapped up the sides and to the top of base aggregate to prevent migration of fines from the densely graded base to the open graded base aggregate, maintain proper compaction, and avoid differential settling.
- Overlap adjacent strips of fabric at least 24 inches. Secure fabric 4 feet outside of storage bed to reduce sediment input to bottom of area storage reservoir.
- Install aggregate in 6-inch lifts maximum.
- Compact each lift to 95 percent modified proctor.

Top course aggregate

Aggregate should be clean, washed angular stone with a granite hardness.

Aggregate grading:	U.S. Standard Sieve	Percent Passing
	4	100
	8	80
	16	50
	30	30
	50	15
	100	5

Top course installation

- Grid should be installed immediately after base preparation to minimize introduction of sediment and to reduce the displacement of base material from ongoing activity.
- Place grid with rings up and interlock male/female connectors along unit edges.
- Install anchors at an average rate of 6 pins per square meter. Higher speed and transition areas (for example where vehicles enter a parking lot with a plastic grid system from an asphalt road) or where heavy vehicles execute tight turns will require additional anchors (double application of pins).
- Aggregate should be back dumped to a minimum depth of 6 inches so that delivery vehicle exits over aggregate. Sharp turning on rings should be avoided.

- Spread gravel using power brooms, flat bottom shovels or wide asphalt rakes. A stiff bristle broom can be used for finishing.
- If necessary, aggregate can be compacted with a plate compactor to a level no less than the top of the rings or no more than 0.25 inch above the top of the rings (Invisible Structures, 2003).
- Provide edge constraints along edges that may have vehicle loads (particularly tight radius turning). Cast-in-place or pre-cast concrete edging is preferred.

6.3.3 Maintenance

The following provides maintenance recommendations applicable to all permeable paving surfaces.

- Erosion and introduction of sediment from surrounding land uses should be strictly controlled after construction by amending exposed soil with compost and mulch, planting exposed areas as soon as possible, and armoring outfall areas.
- Surrounding landscaped areas should be inspected regularly and possible sediment sources controlled immediately.
- Clean permeable paving surfaces to maintain infiltration capacity once or twice annually following maintenance recommendations under each paving type.
- Utility cuts should be backfilled with the same aggregate base used under the permeable paving to allow continued conveyance of stormwater through the base, and to prevent migration of fines from the standard base aggregate to the more open graded permeable base material (Diniz, 1980).

The following provides maintenance recommendations for specific permeable paving surfaces.

- Permeable asphalt and concrete
  - Clean surfaces using suction, sweeping with suction or high-pressure wash and suction (sweeping alone is minimally effective). Street cleaning equipment using high-pressure wash with suction provides the best results on asphalt and concrete for improving infiltration rates. However, there are currently no high-pressure wash and suction machines for cleaning pavement in the U.S. The city of Olympia will be importing the first machine of this type and expects delivery early 2005 (personal communication, Mark Blosser, July 2004). Hand held pressure washers are effective for cleaning void spaces and appropriate for smaller areas such as sidewalks.
  - Small utility cuts can be repaired with conventional asphalt or concrete if small batches of permeable material are not available or are too expensive.
- Eco-Stone permeable pavers
  - Washing should not be used to remove debris and sediment in the openings between the pavers. Sweeping with suction can be applied to paver openings when surface and debris are dry. Vacuum settings may have to be adjusted to prevent excess uptake of aggregate from paver openings or joints (Smith, 2000).
  - Pavers can be removed individually and replaced when utility work is complete.
  - Replace broken pavers as necessary to prevent structural instability in the surface.

- o The structure of the top edge of the paver blocks reduces chipping from snowplows. For additional protection, skids on the corner of plow blades are recommended.

- Gravelpave2
  - o Remove and replace top course aggregate if clogged with sediment or contaminated (vacuum trucks for stormwater collection basins can be used to remove aggregate).
  - o Remove and replace grid segments where three or more adjacent rings are broken or damaged.
  - o Replenish aggregate material in grid as needed.
  - o Snowplows should use skids to elevate blades slightly above the gravel surface to prevent loss of top course aggregate and damage to plastic grid.

6.3.4 Limitations

Permeable paving materials are not recommended where:

- Excessive sediment is deposited on the surface (e.g., construction and landscaping material yards).
- Steep erosion prone areas that are likely to deliver sediment and clog pavement are upslope of the permeable surface.
- Concentrated pollutant spills are possible such as gas stations, truck stops, and industrial chemical storage sites.
- Seasonally high groundwater creates prolonged saturated conditions at or near ground surface and within the pavement section.
- Fill soils can become unstable when saturated.
- Maintenance is unlikely to be performed at appropriate intervals.
- Sealing of surface from sealant application or other uncontrolled use is likely. Residential driveways can be particularly challenging and clear, enforceable guidelines, education, and backup systems should be part of the stormwater management plan for a residential area utilizing permeable paving for driveways.
- Regular, heavy application of sand is used for maintaining traction during winter.
- Permeable paving should not be placed over solid rock without an adequate layer of aggregate base.

Slope restrictions result primarily from flow control concerns and to a lesser degree structural limitations of the permeable paving. Excessive gradient increases surface and subsurface flow velocities and reduces storage and infiltration capacity of the pavement system. Baffle systems placed on the subgrade can be used to detain subsurface flow and increase infiltration (personal communication, Tracy Tackett). See Chapter 7 for the flow control credit associated with permeable paving and subgrade baffles.

- Permeable asphalt is not recommended for slopes exceeding 5 percent.
- Permeable concrete is not recommended on slopes exceeding 6 percent.
- Eco-Stone is not recommended for slopes exceeding 10 percent.
- Gravelpave2 is not recommended for slopes exceeding 6 percent (primarily a traction rather than infiltration or structural limitation).

6.3.5 Permeable Paving Performance

Infiltration

Initial research indicates that properly designed and maintained permeable pavements can virtually eliminate surface flows for low intensity storms common in the Pacific Northwest, store or significantly attenuate subsurface flows (dependent on underlying soil and aggregate storage design), and provide water quality treatment for nutrients, metals, and hydrocarbons. A six-year University of Washington permeable pavement demonstration project found that nearly all water infiltrated various test surfaces (included Eco-Stone, Gravelpave, and others) for all observed storms (Brattebo and Booth, 2003). Observed infiltration was high despite minimal maintenance conducted. See Figure 6.3.11 for infiltration plotted with precipitation for one of the permeable paving test surfaces (turfstone).

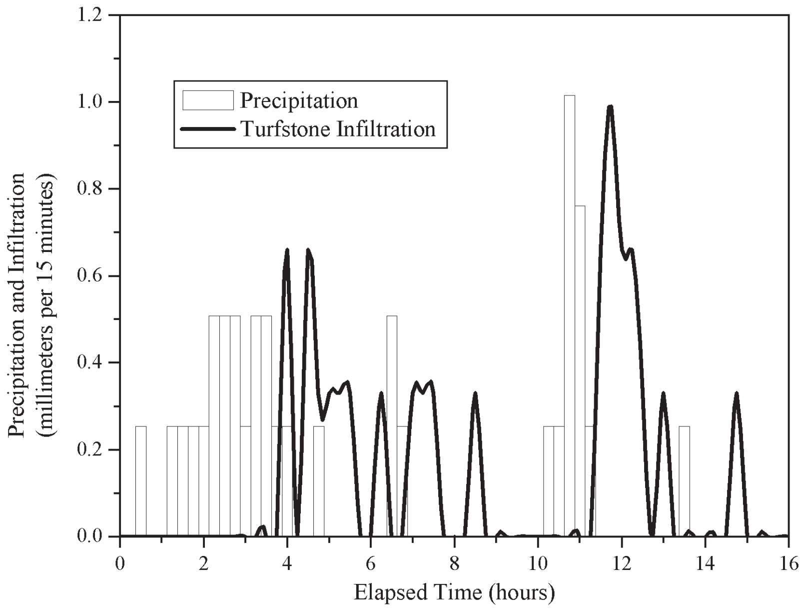


Figure 6.3.11 Infiltration plotted with precipitation at a test permeable pavement parking stall in the city of Renton. Note that essentially all precipitation infiltrates.

Source: Brattebo and Booth, 2003

Initial infiltration rates for properly installed permeable pavement systems are high. Infiltration rates for in-service surfaces decline to varying degrees depending on numerous factors, including initial design and installation, sediment loads, and maintenance. Ranges of new and in-service infiltration rates for research cited in the Appendix 7: Porous Paving Research are summarized below. To provide context for the infiltration rates below, typical rainfall rates are approximately 0.05 inch/hour in the Puget Sound region with brief downpours of 1 to 2 inches/hour.

Porous asphalt:	highest initial rate (new installation): 1750 in/hr lowest initial rate (new installation): 28 in/hr highest in-service rate: 1750 in/hr (1 year of service, no maintenance) lowest in-service rate: 13 in/hr (3 years of service no maintenance)
Pervious concrete:	highest initial rate: 1438.20 in/hr lowest in-service rate: 240 in/hr (6.5 years of service, no maintenance) Note: City of Olympia has observed (anecdotal) evidence of lower infiltration rates on a sidewalk application; however, no monitoring data have been collected to quantify observations (personal communication Mark Blosser, August 2004).

Pervious pavers:	highest initial infiltration rate (new installation): none reported lowest initial rate (new installation): none reported highest in-service rate: 2000 in/hr lowest in-service rate: 0.58 in/hr

Clogging from fine sediment is a primary mechanism that degrades infiltration rates. However, the design of the porous surface (i.e., percent fines, type of aggregate, compaction, asphalt density, etc.) is critical for determining infiltration rates and performance over time as well.

Various levels of clogging are inevitable depending on design, installation, and maintenance and should be accounted for in the long-term design objectives. Studies reviewed in the Porous Paving Research (see Appendix 7) and a review conducted by St. John (1997) indicate that a 50 percent infiltration rate reduction is typical for permeable pavements.

European research examining several permeable paver field sites estimates a long-term design rate at 4.25 inches per hour (Borgwardt, 1994). David Smith from Interlocking Concrete Pavement Institute, however, recommends using a conservative 1.1-inch per hour infiltration rate for the base course (surface intake can be higher) for the typical 20-year life span of permeable paver installations (Smith, 2000).

The lowest infiltration rate reported for an in-service permeable paving surface that was properly installed was approximately 0.58 inches/hour (Uni Eco-Stone parking installation).

Results from the three field studies evaluating cleaning strategies indicate that infiltration rates can be restored. Pervious paver research in Ontario, Canada indicates that infiltration rates can be maintained for Eco-Stone with suction equipment (see Appendix 7: Porous Paving Research). Standard street cleaning equipment with suction may need to be adjusted to prevent excessive uptake of aggregate in paver cells (Gerrits and James, 2001). Washing should not be used to remove debris and sediment in the openings between pavers. Suction should be applied to paver openings when surface and debris are dry.

Street cleaning equipment with sweeping and suction perform adequately on moderately degraded porous asphalt while high pressure washing with suction provides the best performance on highly degraded asphalt (Dierkes, Kuhlmann, Kandasamy and Angelis, 2002 and Balades, Legret and Madiec, 1995). Sweeping alone does not improve infiltration on porous asphalt.

Water Quality

Research indicates that the pollutant removal capability of permeable paving systems is very good for constituents examined. Laboratory evaluation of aggregate base material in Germany found removal capability of 89 to 98 percent for lead, 74 to 98 percent for cadmium, 89 to 96 percent for copper, and 72 to 98 percent for zinc (variability in removal rates depended on type of stone). The same study excavated a 15-year old permeable paver installation in a commercial parking lot and found no significant concentrations of heavy metals, no detection of PAHs, and elevated, but still low concentrations of mineral oil in the underlying soil (Dierkes et al., 2002).

Pratt, Newman and Bond recorded a 97.6 percent removal of automobile mineral oil in a 780 mm (approximately 31-inch) deep permeable paver section in England. Removal was attributed largely to biological breakdown by microbial activity within the pavement section, as well as adhesion to paving materials (Pratt, Newman and Bond, 1999).

A study in Connecticut compared driveways constructed from conventional asphalt and permeable pavers (UNI group Eco-Stone) for runoff depth (precipitation measured on-site), infiltration rates, and pollutant concentrations. The Eco-Stone driveways were two years old. During 2002 and 2003, mean weekly runoff depth recorded for asphalt was 1.8 mm compared to 0.5mm for the pavers. Table 6.3.1 summarizes pollutant concentrations from the study (Clausen and Gilbert, 2003).

Table 6.3.1 Mean weekly pollutant concentration in stormwater runoff, Jordan Cove, CT.

Variable	Asphalt	Paver
TSS	47.8 mg/L	15.8 mg/L
NO_3-N	0.6 mg/L	0.2 mg/L
NH_3-N	0.18 mg/L	0.05 mg/L
TP	0.244 mg/L	0.162 mg/L
Cu	18 ug/L	6 ug/L
Pb	6 ug/L	2 ug/L
Zn	87 ug/L	25 ug/L

(Adapted from Clausen and Gilbert, 2003)

In the Puget Sound region, a six-year permeable parking lot demonstration project conducted by the University of Washington found toxic concentrations of copper and zinc in 97 percent of the surface runoff samples from an asphalt control parking stall. In contrast, copper and zinc in 31 of 36 samples from the permeable parking stall—that produced primarily subsurface flow—fell below toxic levels and a majority of samples fell below detectable levels. Motor oil was detected in 89 percent of the samples from the surface flow off the asphalt stall. No motor oil was detected in any samples that infiltrated through the permeable paving sections. (Brattebo and Booth, 2003).

6.4 Vegetated Roofs

Vegetated roofs (also known as green roofs and eco-roofs) fall into two categories: intensive and extensive. Intensive roofs are designed with a relatively deep soil profile (6 inches and deeper) and are often planted with ground covers, shrubs, and trees. Intensive green roofs may be accessible to the public for walking or serve as a major landscaping element of the urban setting. Extensive vegetated roofs are designed with shallow, light-weight soil profiles (1 to 5 inches) and ground cover plants adapted to the harsh conditions of the roof top environment. This discussion focuses on the extensive design.

Vegetated roofs improve energy efficiency and air quality, reduce temperatures and noise in urban areas, improve aesthetics, extend the life of the roof, and reduce stormwater flows.

Extensive green roofs offer a number of benefits in the urban landscape including: increased energy efficiency, improved air quality, reduced temperatures in urban areas, noise reduction, improved aesthetics, extended life of the roof, and central to this discussion, improved stormwater management (Grant, Engleback and Nicholson, 2003).

Companies specializing in vegetated roof installations emerged in Germany and Switzerland in the late 1950s, and by the 1970s extensive green roof applications were common in those countries. In 2003, 13.5 million square meters of green roofs were installed in Germany (Grant et al., 2003; Peck, Callaghan, Kuhn and Bass, 1999; and Peck, Kuhn and Arch, n.d.). While roof gardens are not as prevalent in the U.S., designers in North America are discovering the value of the technology and green roofs are becoming more common with installations on large buildings and individual residences in Portland, Philadelphia, Chicago, Seattle, and other cities.

Figure 6.4.1 Vegetated roof on the Multnomah County building in Portland, Oregon.

Photo by Erica Guttman

6.4.1 Applications

Initial vegetated roof installations in the 1970s were prone to leaking. New technologies and installation techniques have improved and essentially eliminated past problems. Green roofs can be installed on almost any building with slopes up to 40 degrees and are effective strategies for managing stormwater in highly urbanized settings where rooftops comprise a large percentage of the total impervious surface (Scholtz-Barth, 2001).

6.4.2 Design

Native soils are heavy and would exert unnecessarily heavy loads for an extensive green roof installation, particularly when wet. Extensive roofs utilize light-weight soil mixes to reduce loads. Installations often range from 1 to 6 inches in depth and research from Germany indicates that, in general, a 3-inch soil depth offers the best environmental and aesthetic benefit to cost ratio (Miller, 2002).

While roof gardens can be installed on slopes up to 40 degrees, slopes between 5 and 20 degrees (1:12 and 5:12) are most suitable, and can provide natural drainage by gravity (depending on design, sloped roofs may also require a drainage layer). Flat roofs require a drainage layer to move water away from the root zone and the waterproof membrane. Roofs with slopes greater than 20 degrees require a lath grid to hold the soil substrate and drainage aggregate in place (Scholtz-Barth, 2001).

Vegetated roofs are comprised of four basic components: waterproofing membrane, drainage layer, growth medium, and vegetation. (See Figure 6.4.2 for a typical cross-section of a green roof.)

Waterproof membranes are made from PVC, Hypolan, rubber (EPDM) or polyolifins. Sixty to 80-mil reinforced PVC with heat sealed seams provides a highly durable and waterproof membrane. EPDM seams must be glued and may be more susceptible to leakage. Thermoplastic polyolifins are currently not well tested in the U.S., and U.S. manufacturers use bromides in the manufacturing process as a fire retardant which may interfere with long-term performance. Asphalt-based roofing material should be covered with high-density polyethylene membrane to prevent roots and other organisms from utilizing the organic asphalt as an energy source (Scholtz-Barth, 2001). Some membranes are not compatible with asphalt-based or other roofing materials. Follow manufacturer's recommendations for material compatibility.

The *drain layer* consists of either aggregate and/or a manufactured material that provides channels designed to transmit water at a specific rate. This layer can include a separation fabric, which with the drainage layer, reduces moisture contact with the waterproof membrane and provides additional protection from root penetration (Peck et al., n.d.).

The light-weight growth medium is designed to support plants and infiltrate and store water at a specific rate. The growth medium typically has a high mineral to organic material content and can be a mixture of various components including: gravel, sand, crushed brick, pumice, perlite, encapsulated Styrofoam, compost, and soil (Peck et al., n.d.). Saturated loads of 15 to 50 pounds/square foot are typical for extensive roofs with 1- to 5-inch soil depths (Scholtz-Barth, 2001). Currently, vegetated roofs weighing 15 pounds/square foot (comparable to typical gravel ballast roofs) have been installed and are functioning in the U.S. At 15 to 50 pounds, many roofs can be retrofitted with no or minimal reinforcement. Separating the growth medium from the building perimeter and roof penetrations with a non-combustible material (e.g., gravel) can provide increased protection against spread of fire, easier access to flashing and membrane connections, and additional protection from root penetration (Peck et al., n.d.).

Vegetation is typically succulents, grass, herbs, and/or wildflowers adapted to harsh conditions (minimal soils, seasonal drought, high winds, and strong sun exposure—i.e., alpine conditions) prevalent on rooftops. Plants should be adapted or native to the installation area. Some examples of species include: sempervivum, sedum, creeping thyme, allium, phloxes, and anntenaria. (Scholtz-Barth, 2001). Plants can be installed as vegetated mats, individual plugs, spread as cuttings, or by seeding. Vegetated mats and plugs provide the most rapid establishment for sedums. Cuttings spread over the substrate are slower to establish and will likely have a high mortality rate; however, this is a good method for increasing plant coverage on a roof that is in the process of establishing a plant community (Scholtz-Barth, 2001). During the plant establishment period soil erosion can be reduced by using a biodegradable mesh blanket.

A bonus for eco-roofs

The city of Portland encourages the application of eco-roofs in the central city to reduce stormwater runoff. Buildings using eco-roofs can earn bonus floor area (exceeding maximum floor area ratios) depending on the extent of coverage. For example, if the total area of the eco-roof is at least 60 percent of the building's footprint, each square foot of eco-roof earns three square feet of additional floor area.

Flow modeling guidance

See Chapter 7 for flow modeling guidelines for vegetated roofs when using WWHM.

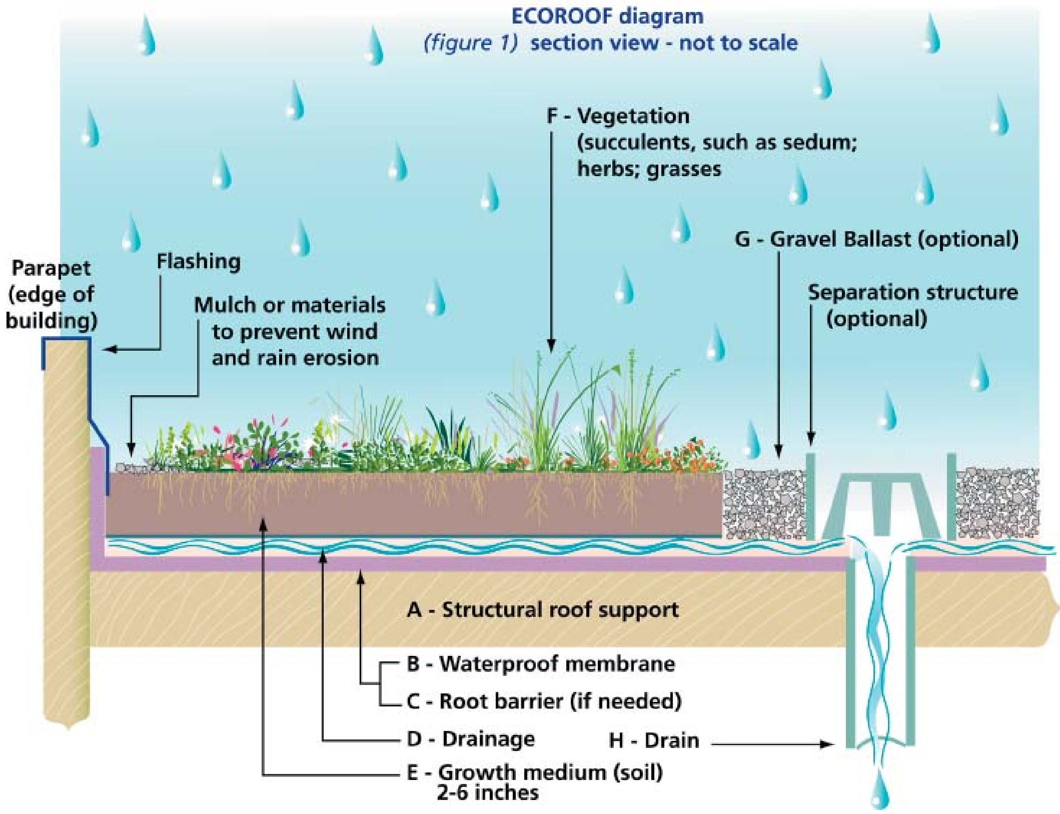


Figure 6.4.2 Cross section of vegetated roof garden. © *Environmental Services, Portland, Oregon*

For a sample vegetated roof specification, see Appendix 9.

6.4.3 Maintenance

Proper maintenance and operation are essential to ensure that designed performance and benefits continue over the full life cycle of the installation. Each roof garden installation will have specific design, operation, and maintenance guidelines provided by the manufacturer and installer. The following guidelines provide a general set of standards for prolonged roof garden performance. Note that some maintenance recommendations are different for extensive versus intensive roof gardens. The procedures outlined below are focused on extensive roof systems and different procedures for intensive roof recommendations are noted.

Schedule

- All facility components, including structural components, waterproofing, drainage layers, soil substrate, vegetation, and drains should be inspected for proper operation throughout the life of the roof garden.
- The property owner should provide the maintenance and operation plan, and inspection schedule.
- All elements should be inspected twice annually for extensive installations and four times annually for intensive installations.
- The facility owner should keep a maintenance log recording inspection dates, observations, and activities.
- Inspections should be scheduled to coincide with maintenance operations and with important horticultural cycles (e.g., prior to major weed varieties dispersing seeds).

Structural and drainage components

- Structural and drainage components should be maintained according to manufacturer's requirements and accepted engineering practices.
- Drain inlets should provide unrestricted stormwater flow from the drainage layer to the roof drain system unless the assembly is specifically designed to impound water as part of an irrigation or stormwater management program:
    - Clear the inlet pipe of soil substrate, vegetation or other debris that may obstruct free drainage of the pipe. Sources of sediment or debris should be identified and corrected.
    - Inspect drain pipe inlet for cracks, settling and proper alignment, and correct and re-compact soils or fill material surrounding pipe if necessary.
- If part of the roof design, inspect fire ventilation points for proper operation.

Vegetation Management

- The vegetation management program should establish and maintain a minimum of 90 percent plant coverage on the soil substrate.
- During regularly scheduled inspections and maintenance, bare areas should be filled in with manufacturer recommended plant species to maintain the required plant coverage.
- Normally, dead plant material will be recycled on the roof; however specific plants or aesthetic considerations may warrant removing and replacing dead material (see manufacturer's recommendations).
- Invasive or nuisance plants should be removed regularly and not allowed to accumulate and exclude planted species. At a minimum, schedule weeding with inspections to coincide with important horticultural cycles (e.g., prior to major weed varieties dispersing seeds).
- Weeding should be done manually and without herbicide applications.
- Extensive roof gardens should be designed to not require fertilization after plant establishment. If fertilization is necessary during plant establishment or for plant health and survivability after establishment, use an encapsulated, slow release fertilizer (excessive fertilization can contribute to increased nutrient loads in the stormwater system and receiving waters).
- Intensive green roofs installations require fertilization. Follow manufacturer and installer recommendations.
- Avoid application of mulch on extensive roof gardens. Mulch should be used only in unusual situations and according to the roof garden provider guidelines. In conventional landscaping mulch enhances moisture retention; however, moisture control on a vegetated roof should be through proper soil/growth media design. Mulch will also increase establishment of weeds.

Irrigation

- Surface irrigation systems on extensive roof gardens can promote weed establishment and root development near the drier surface layer of the soil substrate, and increase plant dependence on irrigation. Accordingly, subsurface irrigation methods are preferred. If surface irrigation is the only method available, use drip irrigation to deliver water to the base of the plant.
- Extensive roof gardens should be watered only when absolutely necessary for plant survival. When watering is necessary (i.e., during early plant

establishment and drought periods), saturate to the base of the soil substrate (typically 30 to 50 gallons per 100 square feet) and allow the soil to dry completely.

Operation and Maintenance Agreements

- Written guidance and/or training for operating and maintaining roof gardens should be provided along with the operation and maintenance agreement to all property owners and tenants.

Contaminants

- Measures should be taken to prevent the possible release of pollutants to the roof garden from mechanical systems or maintenance activities on mechanical systems.
- Any cause of pollutant release should be corrected as soon as identified and the pollutant removed.

Insects

- Roof garden design should provide drainage rates that do not allow pooling of water for periods that promote insect larvae development. If standing water is present for extended periods, correct drainage problem.
- Chemical sprays should not be used.

Access and Safety

- Egress and ingress routes should be clear of obstructions and maintained to design standards.

(City of Portland, 2002 and personal communication, Charlie Miller, February 2004)

6.4.4 Cost

Costs for vegetated roofs can vary significantly due to several factors including size of installation, complexity of system, growth media depth, and engineering requirements. Costs for new construction including structural support range from $10 to $15 per square foot. Retrofit costs range from $15 to $25 per square foot (Portland Bureau of Environmental Services, 2002). While initial installation costs are higher than for conventional roof systems, they are competitive on a full life cycle basis. Vegetated roofs increase the energy efficiency of a building and significantly reduce associated cooling and heating costs. European evidence indicates that a correctly installed green roof can last twice as long as a conventional roof, thereby deferring maintenance and replacement costs (Peck et al., n.d.). The above costs do not include savings on conventional stormwater management infrastructure as a result of reduced flows from a green roof or reduced stormwater utility fees.

6.4.5 Performance

Vegetated roof designs require careful attention to the interaction between the different components of the system. **Saturated hydraulic conductivity**, porosity and moisture retention of the growth media, and **transmissivity** of the drainage layer strongly influence hydrologic performance and reliability of the design (Miller and Pyke, 1999).

Research in Europe, in climates similar to the northeastern U.S., has consistently indicated that roof gardens can reduce up to 50 percent of the annual rooftop

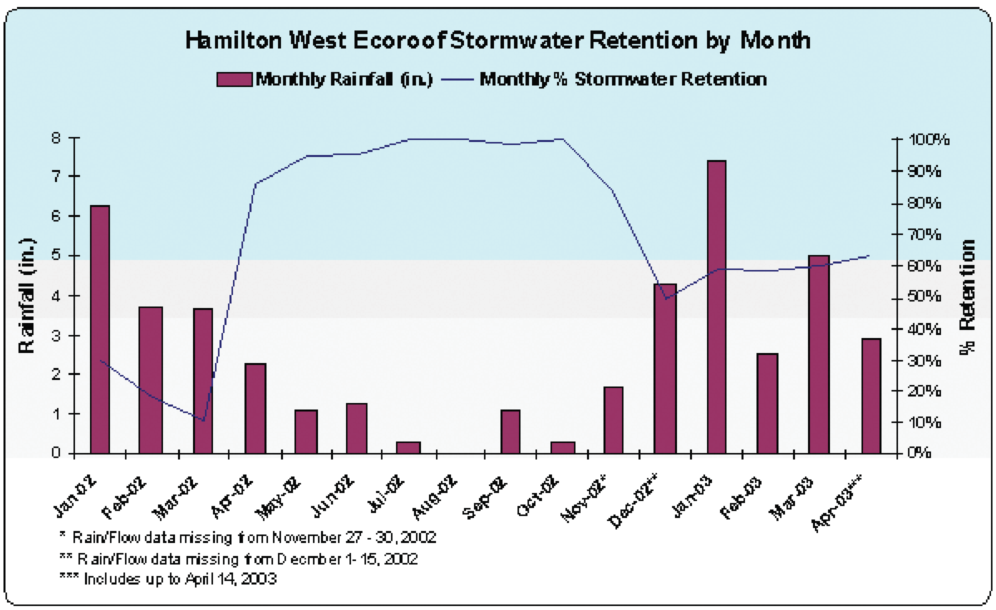
European research, in climates similar to the northeastern U.S., has consistently indicated that roof gardens can reduce up to 50 percent of the annual rooftop stormwater runoff.

stormwater runoff (Miller and Pyke, 1999). During a 9-month pilot test in eastern Pennsylvania, 14 and 28 square foot trays with test vegetated roof sections received a total of 44 inches of precipitation and generated 15.5 inches of runoff (runoff was negligible for storm events producing less than 0.6 inches of rainfall). The pilot section was 2.74 inches thick, including the drainage layer (USEPA, 2000b).

In Portland Oregon, a 4- to 4.5-inch eco-roof retained 69 percent of the total rainfall during a 15-month monitoring period. In the first January-to-March period (2002), rainfall retention was 20 percent and during the January-to-March (2003) period retention increased to 59 percent. The most important factors likely influencing the different retention rates are vegetation and substrate maturity, and rainfall distribution. The 2002 period was a more even rainfall distribution and the 2003 period more varied with longer dry periods between storms (Hutchison, Abrams, Retzlaff and Liptan, 2003). This supports observations by other researchers that vegetated roofs are likely more effective for controlling brief (including relatively intense) events compared to long-duration storms (Miller, 2002).

Figure 6.4.3 Precipitation and percent stormwater retained on a 4- to 4.5-inch eco-roof, Portland, OR.

Graphic from Hutchison et al,. 2003



6.5 Minimal Excavation Foundation Systems

Excavation and movement of heavy equipment during construction compacts and degrades the infiltration and storage capacity of soils. Minimal excavation foundation systems limit soil disturbance and allow storm flows to more closely approximate natural shallow subsurface flow paths. When properly dispersed into the soils adjacent to and in some cases under the foundation, roof runoff that would otherwise be directed to bioretention areas or other LID facilities can be significantly reduced.

Minimal excavation foundation systems can take many forms, but in essence are a combination of driven piles and a connection component at, or above, grade. The piles allow the foundation system to reach or engage deep load-bearing soils without having to dig out and disrupt upper soil layers, which infiltrate, store and filter stormwater flows. These piles are a more "surgical" approach to earth engineering, and may be vertical, screw-augured or angled pairs that can be made of corrosion protected steel, wood or concrete. The connection component handles the transfer of loads from the above structure to the piles and is most often made of concrete. Cement connection components may be pre-cast or poured on site, in continuous perimeter wall, or isolated pier configurations. For a given configuration the appropriate engineering (analyzing gravity, wind and earthquake loads) is applied for the intended structure. Several jurisdictions in the Puget Sound region have permitted minimal excavation foundations for the support of surface structures, including Pierce and King counties and the city of Olympia.

Minimal excavation foundation systems limit soil disturbance and allow storm flows to more closely approximate natural shallow subsurface flow paths under and around the foundation.

6.5.1 Applications

Minimal excavation foundations in both pier and perimeter wall configurations are suitable for residential or commercial structures up to three stories high. Secondary structures such as decks, porches, and walkways can also be supported, and the technology is particularly useful for elevated paths and foot-bridges in nature reserves and other environmentally sensitive areas. Wall configurations are typically used on flat to sloping sites up to 10 percent, and pier configurations flat to 30 percent. Some applications may be "custom" or "one-off" designs where a local engineer is employed to design a combination of conventional piling and concrete components for a specific application. Other applications may employ pre-engineered, manufactured systems that are provided by companies specifically producing low-impact foundation systems for various markets.

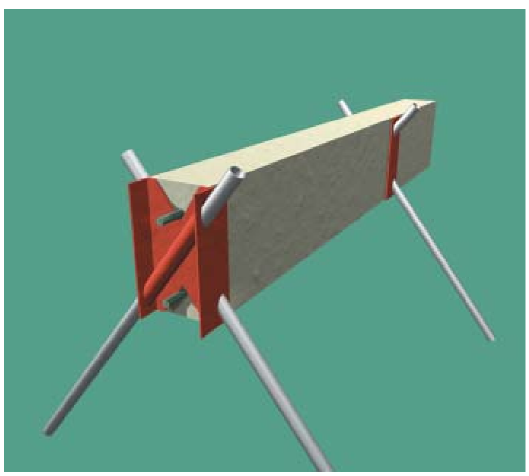


Figure 6.5.1 Typical minimal excavation foundation wall.

Graphic courtesy of Pin Foundations, Inc.

Figure 6.5.2 Building a house on Bainbridge Island using minimal excavation pier system.

Photo courtesy of R. Gagliano

The minimal excavation foundation approach can be installed on A/B and C/D soils (USDA Soil Classification) provided that the material is penetrable and will support the intended type of piles. Typical soils in the Puget Sound region, including silt loams, sandy loams, fine gravels, tight soils with clay content, and partially cemented tills are applicable. Soils typically considered problematic due to high organic content (top soils or peats) or overall bearing characteristics may often remain in place provided their depth is limited and the pins have adequate bearing in suitable underlying soils. These systems may be used on fill soils if the depth of the fill does not exceed the **reaction range** of the intended piles. Fill compaction requirements for support of such foundations may be below those of conventional development practice in some applications. In all cases, both for custom and pre-engineered systems, a qualified engineer should determine the appropriate pile and connection components, and define criteria for specific soil conditions and construction requirements.

Flow modeling guidance

See Chapter 7 for flow modeling guidelines for minimal excavation foundation systems when using the WWHM.

6.5.2 Design

Grading

In general, wall configurations require some site blading or surface terracing to accommodate the wall component itself. The lightest possible tracked equipment should be used for preparing or grading the site. Permeability of some soil types can be significantly reduced even with minimal equipment activity. Consult a qualified hydrological engineer for soil recommendations.

On relatively flat sites, blading should be limited to knocking down the highs and lows to provide a better working surface. Removing the top organic "duff" layer is not typically necessary. A free draining, compressible buffer material (pea gravel, corrugated vinyl or foam product) should be placed on surface soils to prepare the site for the placement of pre-cast or site poured wall components. This buffer material separates the base of the grade beam from surface of the soil to prevent impact from expansion or frost heave, and in some cases is employed to allow the movement of saturated flows under the wall.

Figure 6.5.3 Minimal excavation foundation pins driven with machine-mounted automatic hammer.

Photo courtesy of R. Gagliano

On sloped sites, the soils may be bladed smooth at their existing pitch to receive pier systems, pre-cast walls with sloped bases, or slope cut forms for pouring continuous walls. Grading should be limited to knocking down the superficial highs and lows on the site to provide a better working surface only. This technique will result in the least disturbance to the upper permeable soil layers on sloped sites.

While creating more soil disturbance, the site may be terraced to receive conventional square cut forms or pre-cast walls. The height difference between terraces will be a result of the slope percentage and the width of the terrace itself. The least soil impacts will be achieved by limiting the width of each terrace to the width of the equipment blade and cutting as many terraces as possible. Some footprint designs will be more conducive to limiting these cuts, and should be considered by the architect. The terracing technique removes more of the upper permeable soil layer, and this loss should be figured into any analysis of storm flows through the site. Buffer material as described above should be used on sloping sites regardless of the grading style employed.

Additional soil may remain from foundation construction depending on grading strategy and site conditions. The material may be used to backfill the perimeter of the structure if the impacts of the additional material and equipment used to place the backfill are considered for runoff conditions.

Construction

Minimal excavation systems may be installed "pile first" or "post pile." The pile first approach involves driving or installing all the required piles in specified locations to support the structure, and then installing a connecting component (such as a formed and poured concrete grade beam) to engage the piles. Post pile methods require the setting of pre-cast or site poured components first, through which the piles are then driven. Pile first methods are typically used for deep or problematic soils where final pile depth and embedded obstructions are unpredictable. Post pile methods are typically shallower—using shorter, smaller diameter piles—and used where the soils and bearing capacities are definitive. In either case, the piles are placed at specified intervals correlated with their capacity in the soil, the size and location of the loads to be supported, and the carrying capacity of the connection component. Soil conditions are determined by geotechnical analysis. Depending on the pile system type, the size or scale of the supported structure, and the nature of the site and soils, a complete soils report including slope stability and **liquifaction** analysis may be required. For other systems a simple statement of soil properties to a limited depth, such as dry unit weight, angle of internal friction, and/or cohesive strength, may be sufficient.

The piles are driven with a machine mounted, frame mounted, or hand-held automatic hammer. The choice of driving equipment should be considered based on the size of pile and intended driving depth, the potential for equipment site impacts, and the limits of movement around the structure. Corrosion rates for buried galvanized or coated steel piling, or degradation rates for buried concrete piling, are typically low to non-existent, and piling for these types of foundations are usually considered to last the life of the structure. Special conditions such as exposure to salt air or highly caustic soils in unique built environments such as industrial zones should be considered. Wood piling typically has a more limited lifetime. Some foundation systems allow for the removal and replacement of pilings, which can extend the life of the support indefinitely.

Figure 6.5.4 Using an automatic hand-held hammer to drive pins.
Photo courtesy of R. Gagliano

Stormwater Dispersion

Where the top or upper levels of soils have been sufficiently retained without significant loss of their permeability and storage characteristics, roof runoff and surrounding storm flows may be allowed to infiltrate without the intervention of man-made conveyance.

Where possible, roof runoff should be infiltrated uphill of the structure and across the broadest possible area. Infiltrating upslope more closely mimics natural (pre-construction) conditions by directing subsurface flows through minimally impacted soils surrounding, and in some cases, under the structure. This provides infiltration and subsurface storage area that would otherwise be lost in the construction and placement of a conventional "dug-in" foundation system. Passive gravity systems for dispersing roof water are preferred; however, active systems can be used if back-up power sources are incorporated and a consistent and manageable maintenance program is ensured.

Garage slabs, monolithic poured patios or driveways can block dispersed flows from the minimal excavation foundation perimeter, and dispersing roof runoff uphill of these areas is not recommended or must be handled with conventional means. Some soils and site conditions may not warrant intentionally directing subsurface flows directly beneath the structure, and in these cases, only the preserved soils surrounding the structure and across the site may be relied on to mimic natural flow pathways.

6.5.3 Performance

From 2000 to 2001 a minimal excavation foundation system was monitored on the Gig Harbor Peninsula. The study site was a two-story, 2300-square foot single-family residence located on a slightly sloped south facing lot with grass surrounding the house and second growth forest on the perimeter. Preparation for the foundation installation involved applying a thin layer of pea gravel directly on the existing lawn to separate the grade beam from the soil, pouring the grade beam from a pump truck, and driving steel pin piling with a hand held pneumatic hammer. The surface organic material was not removed from the construction area. Roof drains fed perforated weep hoses buried 2 to 3 inches in shallow perimeter landscape beds upslope of the house to infiltrate roof runoff and direct it along its natural pre-existing downslope path below the structure.

Soil pits were excavated around and within the foundation perimeter and gravimetric sampling was conducted to measure soil moisture content on a transect from high slope to low slope within the foundation perimeter. Relative humidity in the crawl space below the house was assessed by comparing the minimum excavation foundation system with two conventional foundation crawl spaces in the same area. The soil analysis found 2 to 6 inches of topsoil overlying a medium dense to very dense silty, fine to coarse sand with small amounts of rounded gravel. Bulk density analysis of the upper 6 inches of the soil profile found no indication of compaction after construction (0.89 to 1.46g/cc or below average to average) and the original lawn vegetation had degraded to a fine brown loam under the plastic vapor barrier in the crawl space. Soil moisture readings indicated that roof runoff was infiltrating into the soils under the house and moving downslope through the subsurface soils. At no time was water ponded above the surface, either outside or under the house. The humidity readings in the crawl space under the minimal excavation foundation system were slightly drier than the conventional crawl space, but statistically equivalent, given the variance of the monitoring equipment (Palazzi, 2002).

Additional structures installed on similar systems over the last three years, though not monitored for subsurface flows, have shown similar reductions in soil compaction impacts to the site and foundation perimeter soils.

6.6 Roof Rainwater Collection Systems

Collecting or harvesting rainwater from rooftops has been used for centuries to satisfy household, agricultural, and landscape water needs. Many systems are operating in the Puget Sound region in a variety of settings. On Marrowstone and San Juan islands, where overuse, saltwater intrusion or natural conditions limit groundwater availability, individual homes use rainwater collection for landscaping and potable supplies. In Seattle, the King Street Center building harvests approximately 1.2 million gallons of rainwater annually to supply 60 to 80 percent of the water required for flushing the building's toilets (CH2M HILL, 2001).

6.6.1 Application

Typically, rainwater collection is used where rainfall or other environmental conditions limit the availability of domestic water supply. In a low impact development, rainwater harvesting serves two purposes: water conservation and, most importantly, elimination or the large reduction of the stormwater contribution from rooftops. This practice is particularly applicable in medium to high-density development where the roof is likely to be equal to or greater than the road, driveway, and sidewalk impervious surface contribution. In the medium to high density residential setting with detached single family homes and till soil conditions, the primary LID objective of approximating pre-development hydrology is likely not feasible without reducing or eliminating the stormwater contribution from rooftops through rainwater harvesting applications.

Roof rainwater harvesting systems can be used in residential, commercial or industrial development for new or retrofit projects. The focus of this section is on residential applications. Rainwater harvesting technology is well developed and components readily available; however, system design and construction is relatively complex and should be provided by a qualified engineer or experienced designer.

In a low impact development, rainwater harvesting serves two purposes: water conservation and, most importantly, elimination or a large reduction of the stormwater contribution from rooftops.

6.6.2 Design

Collection systems should be sized according to precipitation inputs, indoor and/or outdoor water needs, and the flow reduction required to approximate pre-development hydrology. Rainwater harvesting should work in concert with other LID practices and therefore reduce the flow reduction requirements from the roof contribution and additional costs of the system.

In the Pacific Northwest the highest precipitation (supply) and lowest demand months are November to May. June through October is relatively dry and demand, driven primarily by landscape needs, is greatest during this period. To collect and remove adequate storm flows during the higher precipitation months and provide a reliable water source, large storage reservoirs or cisterns are required. Where stormwater is a primary incentive for installation and municipal or groundwater supplies are available, the rainwater collection system is installed with, and augmented by, a conventional water source.

Components of a rainwater collection system

Catchment or roof area

The roof material should not contribute contaminants (such as zinc, copper or lead) to the collection system. The National Sanitation Foundation (NSF) certifies products for rainwater collection systems. Products meeting NSF protocol P151 are certified for drinking water system use and do not contribute contaminants at levels greater than specified in the USEPA Drinking Water Regulations and Health Advisories (Stuart, 2001).

Roof materials

- Rainfall present in the Pacific Northwest is surprisingly acidic and will tend to leach materials from roofing material.
- Currently, few roof materials have been tested and the only recommendation for common roof coverings is to not use treated wood shingles or shakes.
- Metal, ceramic tile or slate are durable and smooth, presumed to not contribute significant contaminants, and are the preferred materials for potable supply. Composition or 3-tab roofing should only be used for irrigation catchment systems. Composition roofing is not recommended for irrigation supply if zinc has been applied for moss treatment.
- Lead solder should not be used for roof or gutter construction and existing roofs should be examined for lead content.
- Galvanized surfaces may deliver elevated particulate zinc during initial flushing and elevated dissolved zinc throughout a storm event (Stuart, 2001).
- Copper should never be considered for roofing or gutters. When used for roofing material, copper can act as an herbicide if rooftop runoff is used for irrigation. Copper can also be present in toxic amounts if used for a potable source.

The following general guidelines are used for calculating water production for a rainwater collection system:

- The catchment area is equal to the length times width of the guttered area (slope is not considered).

- One inch of rain falling on one square foot of rooftop will produce 0.6233 gallons of water or approximately 600 gallons per 1,000 square feet of roof without inefficiencies.
- Assume that the system will lose approximately 25 percent of the total rainfall due to evaporation, initial wetting of the collection material, and inefficiencies in the collection process (Texas Water Development Board, 1997). Precipitation loss is the least with metal, more with composition, and greatest with wood shake or shingle.

Roof washers

Roof washers collect and route the first flush away from the collection system. The first flush can contain higher levels of contaminants from particulates settling on the roof, bird droppings, etc. A simple roof washer consists of a downspout (located upstream of the downspout to the cistern) and a pipe that is fitted and sealed so that water does not back flow into the gutter. Once the pipe is filled, water flows to the cistern downspout. The pipe often extends to the ground and has a clean out and valve.

The Texas Rainwater Guide recommends that 10 gallons be diverted for every 1000 square feet of roof (applicable for areas with higher storm intensities) (Texas Water Development Board, 1997). However, local factors such as rainfall frequency, intensity, and pollutants will influence the amount of water diverted. In areas with low precipitation and lower storm intensities such as the San Juan Islands, roof washing may divert flows necessary to support system demands. Additionally, the gentle rainfall prevalent in western Washington may not be adequate to wash contaminants from the roof in the first flush. In this scenario, pre-filtration for coarse material before the storage reservoir and fine filtration (e.g., 5 microns) before disinfection is likely more effective (personal communication Tim Pope, August 2004).

Storage tank or cistern

The cistern is the most expensive component of the collection system. If the system will be used for a potable water source, the tank and any sealants and paints used in the tank should be approved by the Food and Drug Administration (FDA), USEPA or NSF. Tanks can be installed above ground (either adjacent to or remote from a structure), under a deck, or in the basement or crawl space. Above ground installations are less expensive than below ground applications. Aesthetic preferences or space limitations may require that the tank be located below ground, or away from the structure. Additional labor expenditures for excavation and structural requirements for the tank will increase costs of subsurface installations compared to above ground storage (Stuart, 2001). Multiple tank systems are generally less expensive than single tank and the multi-reservoir configurations can continue to operate if one of the tanks needs to be shut down for maintenance.

Cisterns are commonly constructed of fiberglass, polyethylene, concrete, metal, or wood. Larger tanks for potable use are available in either fiberglass for burial or corrugated, galvanized steel with PVC or Poly liners for above ground installations. Tanks should have tight fitting covers to exclude contaminants and animals, and above ground tanks should not allow penetration of sunlight to limit algae growth (Texas Water Development Board, 1997).

Figure 6.6.1 Buried tanks on San Juan Island.
Photo courtesy of Tim Pope

Figure 6.6.2 Collection tanks being installed under deck of a home on San Juan Island.
Photo courtesy of Tim Pope

Figure 6.6.3 Collection tanks hidden under the deck of a home on San Juan Island.
Photo courtesy of Tim Pope

Figure 6.6.4 Storage tank on Lopez Island.
Photo courtesy of Tim Pope

Conveyance

Gutters are commonly made from aluminum, galvanized steel, and plastic. Rainwater is slightly acidic; accordingly, collected water entering the cistern should be evaluated for metals or other contaminants associated with the roof and gutters, and appropriate filters and disinfection techniques installed. Screens should be installed in the top of each downspout. Screens installed along the entire length of the gutter do not prevent most debris from entering the gutter; however, they can complicate cleaning. Leaf guard type gutters will exclude leaves and needles, but do not prevent pollen and dust (the most important contaminant to remove) from entering the gutter.

Unless the tank is elevated sufficiently above the point of delivery, pumps are required to provide acceptable pressure. Municipal water supply pressures are typically between 40 to 60 psi. Pressure tanks are often installed in addition to the pump to prolong the life of the pump and provide a more constant delivery pressure (Stuart, 2001).

Water treatment

Water treatment falls into three broad categories: filtration, disinfection, and buffering.

Filtration

Filters remove leaves, sediment, and other suspended particles and are placed between the catchment and the tank or in the tank. Filtering begins with screening gutter downspouts to exclude leaves and other debris and routing the first flush through roof washers, if compatible with precipitation and water needs (filtration can be incorporated with the roof washer). Types of filters for removing the smaller remaining particles include single cartridges (similar to swimming pool filters) and multi-cartridge filters (Texas Water Development Board, 1997). For potable systems, water must be filtered and disinfected after the water exits the storage reservoir and immediately before point of use.

Disinfection technologies include:

- *Ultra-violet (UV) radiation* uses short wave UV light to destroy bacteria, viruses, and other microorganisms. UV disinfection requires pre-filtering of fine particles where bacteria and viruses can lodge and elude the UV light. This disinfection strategy should be equipped with a light sensor and a readily visible alert to detect adequate levels of UV light (Texas Water Development Board, 1997).

- *Ozone* is a form of oxygen produced by passing air through a strong electrical field. Ozone kills microorganisms and oxidizes organic material to CO_2 and water. The remaining ozone reverts back to dissolved O_2 (Texas Water Development Board, 1997). Care must be exercised in the choice of materials used in the system using this disinfection technique due to ozone's aggressive properties.
- *Activated carbon* removes chlorine and heavy metals, objectionable tastes, and most odors.
- *Membrane technologies* include reverse osmosis and nano-filtration and are used primarily to filter dissolved materials such as salts or metals.
- *Chlorine* (commonly in the form of sodium hypochlorite) is a readily available and dependable disinfection technique. Household bleach can be applied in the cistern or feed pumps that release small amounts of solution while the water is pumped (Texas Water Development Board, 1997). There are two significant limitations of this technique: chlorine leaves an objectionable taste (which can be removed with activated charcoal); and prolonged presence of chlorine with organic matter can produce chlorinated organic compounds (e.g., trihalomethanes) that can present health risks (Texas Water Development Board, 1997).

Buffering

As stated previously, rainwater is usually slightly acidic (a pH of approximately 5.6 is typical). Total dissolved salts and minerals are low in precipitation and buffering with small amounts of a common buffer, such as baking soda, can adjust collected rainwater to near neutral (Texas Water Development Board, 1997). Buffering should be done each fall after tanks have first filled.

6.6.3 Barriers to Implementation

Two factors present the largest barriers to implementing rainwater harvesting:

1. **Regulatory**

   Authorizing agencies for rainwater collection include the Washington Department of Health, Ecology, and the local jurisdiction. The Department of Health does not recommend rainwater harvesting for potable supplies; however, there are no laws restricting the practice other than appropriate pollutant level criteria for human consumption. The USEPA classifies roof water collection as a surface water system and requires that the water be filtered to federal standards if for potable use. Ecology technically requires that all systems collecting surface water for consumption apply for a water right. Currently, Ecology is not enforcing its authority over roof collection for small systems (e.g., individual homes) (Stuart, 2001). Many local jurisdictions are not familiar with or restrict rainwater harvesting from roofs. In most locations, installing these systems will require special permit considerations.

2. **Cost**

   Roof water harvesting systems can add significant costs to residential construction. Systems that provide adequate storage for reliable indoor use and detain sufficient precipitation require large storage tanks, filtration and disinfection. In the example provided in Section 6.6.5: Perfomance, the system (10,000 gallon storage capacity for supplying toilets and clothes washing) added approximately $8,000/home to the construction costs. Roof water harvesting systems can, on the other hand, provide cost savings. New stormwater management requirements will increase infrastructure costs on challenging sites with medium to high density zoning and soils with low infiltration rates. Much, if not all, of the additional costs associated with a rainwater collection system may be offset by reducing conventional conveyance and pond infrastructure and expenditures. Building owners who use a rainwater harvest system will also reduce monthly expenses by significantly reducing their water bills.

6.6.4 Maintenance

Maintenance requirements for rainwater collection systems include typical household and system specific procedures. All controls, overflows and cleanouts should be readily accessible and alerts for system problems should be easily visible and audible. The following procedures are operation and maintenance requirements recorded with the deed of homes using roof water harvesting systems in San Juan County (personal communication, Tim Pope, August 2004).

- Debris should be removed from the roof as it accumulates.
- Gutters should be cleaned as necessary (for example in September, November, January, and April. The most critical cleaning is in mid to late-spring to flush the pollen deposits from surrounding trees.
- Screens at the top of the downspout should be maintained in good condition.
- Pre-filters should be cleaned monthly.
- Filters should be changed every six months or as pressure drop is noticed.
- UV units should be cleaned every six months and the bulb should be replaced every 12 months (or according to manufacturer's recommendation).
- Storage tanks should be chlorinated quarterly to 0.2ppm to 0.5ppm at a rate of 1/4 cup of household bleach (5.25 percent solution) to 1,000 gallons of stored water.
- Storage tanks should be inspected and debris removed periodically as needed.
- When storage tanks are cleaned, the inside surface should be rinsed with a chlorine solution of 1 cup bleach to 10 gallons water.
- When storage tanks are cleaned, the carbon filter should be removed and all household taps flushed until chlorine odor is noticed. Chlorinated water should be left standing in the piping for 30 minutes. Replace the carbon filter and resume use of the system.

6.6.5 Performance

In 2001, CH2M HILL performed an LID study on a 24-acre subdivision with 103 lots in Pierce County (CH2M HILL, 2001). The site was selected for its challenging conditions–medium density development (4 to 6 dwelling units/acre) located on a topographically closed depressional area and type C soils (USDA soils classification) with low infiltration rates. The study utilized LID principles and practices to redesign the project (on paper only) with the goal of approximating pre-development (forested) hydrologic conditions. LID practices used in the design included reducing the development envelope, minimizing impervious surfaces, increasing native soil and vegetation areas, amending disturbed soils with compost, and bioretention. Hydrologic analysis using continuous simulation (HSPF) was performed to assess the effectiveness of the selected LID practices for achieving the project goal.

The hydrologic simulations of the proposed low impact development design indicated that the goals of the project could not be achieved by site planning and reducing impervious surfaces alone while maintaining four or more dwelling units per acre. The challenging site conditions required that additional LID tools be utilized to approximate forested hydrology. Accordingly, the potential to collect and use rooftop stormwater was considered to reduce surface flows.

A 1,300-sq. ft. impervious footprint was used to reflect the compact, two-story design for the detached single-family homes. At this density the rooftop contributing to the total impervious surface in the development was almost 60 percent. Only non-potable uses such as laundry, toilet, and irrigation were investigated to reduce design costs and regulatory barriers. To estimate the storage volume required for non-potable uses, the amount of water used inside the house was first estimated. The average inside water use for homes that conserve water is approximately 49.2 gallons per person per day (Maddaus, William O., 1987, Water Conservation, American Water Works Association). Table 6.6.1 contains a breakdown of average daily water use per person/day.

Table 6.6.1 Household water use.

Type of Use	Gallons per person per day	**Percent of Total***
Showers	8.2	17
Toilets	6.4	13
Toilet leakage	4.1	8
Baths	7.0	14
Faucets	8.5	17
Dishwashers	2.4	5
Washing machines	12.6	26

* The average inside water use for homes that conserve water is approximately 49.2 gallons per person per day

The project considered using captured rainwater in toilets and washing machines. Stormwater collected from roof runoff may also be used for irrigation but because of the small lot sizes, this use was not factored into the calculation for storage requirements. However, the calculations assume that the storage system will be empty at the beginning of the wet season, so any excess stored water during the summer months should be used for irrigation.

To estimate the amount of storage required, the volume of rainfall from a 1300-sq. ft. surface was plotted over time against curves showing water usage based on a 5-gallon toilet, a 3.3-gallon toilet, a low-flow toilet (1.6 gallon), and a low-flow toilet combined with a washing machine. Monthly average rainfall for Pierce County was used (41.5 inches annually). Although the 5-gallon toilet resulted in the smallest required storage volume, new construction requires the use of low flow toilets, so the storage required for a combination low flow toilet and washing machine was used. This resulted in a required storage volume of approximately 10,000 gallons, or 1,333 cu. ft. Accounting for evaporation and other inefficiencies in the collection process, the 103 houses on the LID site would capture and use approximately 8 acre-ft of water annually.

From a hydrologic standpoint, collecting and using rooftop runoff reduces or removes the roof contribution from the surface water system. Collecting the appropriate percentage of total precipitation can simulate the amount of water that is naturally transpired and evaporated in a forested environment. As a result, the surface water system in the low impact development responds more like a forested system.

7 Washington Department of Ecology Low Impact Development Design and Flow Modeling Guidance

In this chapter...

Flow control "credits" for:

- *Permeable pavements*
- *Dispersion*
- *Vegetated roofs*
- *Rainwater harvesting*
- *Reverse slope sidewalks*
- *Minimal excavation foundations*
- *Bioretention*

The Washington Department of Ecology (Ecology) encourages the use of the Western Washington Hydrology Model (WWHM) and other approved runoff models to estimate surface runoff and size stormwater control and treatment facilities. Other currently approved models are the King County Runoff Time Series and MGS Flood. This guidance suggests how to represent various LID techniques within those models so that their benefit in reducing surface runoff can be estimated. The lower runoff estimates should translate into smaller stormwater treatment and flow control facilities. In certain cases, the use of various techniques can result in the elimination of those facilities.

An LID credit committee comprised of stormwater managers from various local jurisdictions, Washington State University Extension, and Ecology developed the flow control credits presented in this chapter. The guidance is also available through Ecology's web site as an addendum to the 2005 *Stormwater Management Manual for Western Washington* (SMMWW).

This section identifies seven categories of LID techniques. For each category, the guidance includes basic design criteria that Ecology considers necessary in order to justify use of the suggested runoff "credit" or "runoff model representation." More detailed design guidance is available in Chapter 6: Integrated Management Practices.

As the Puget Sound community gains more experience with and knowledge of LID techniques, the design criteria will evolve. Also, our ability to model their performance will change as modeling techniques improve. Therefore, we anticipate this guidance will be updated periodically to reflect new knowledge and modeling approaches. Meanwhile, we encourage all to use the guidance, and to give us feedback on its usefulness and accuracy. Comments can be sent to Ed O'Brien of Ecology at eobr461@ecy.wa.gov.

Note that the terminology for grass has changed in the WWHM. The term "grass" has been replaced with "landscaped area."

7.1 Permeable Pavements

7.1.1 Credits

7.1.1.1 Porous Asphalt or Concrete

Description of public road or public parking lot	Model Surface as
(1) Base material laid above surrounding grade:	
(a) Without underlying perforated drain pipes to collect stormwater	Landscaped area over underlying soil type (till or outwash)
(b) With underlying perforated drain pipes for stormwater collection:	
at or below bottom of base layer	Impervious surface
elevated within the base course	Impervious surface
(2) Base material laid partially or completely below surrounding grade:	
(a) Without underlying perforated drain pipes	Option 1: Landscaped area over underlying soil type Option 2: Impervious surface routed to an infiltration basin[1]
(b) With underlying perforated drain pipes:	
at or below bottom of base layer	Impervious surface
elevated within the base course[2]	Model as impervious surface routed to an infiltration basin[1]

Description of private facilities (driveways, parking lots, walks, patios)	
1. Base material below grade without underlying perforated drain pipes	50% landscaped area on underlying soil; 50% impervious
2. Base material below grade with underlying perforated drain pipes	Impervious surface

7.1.1.2 Grid/lattice Systems (Non-concrete) and Paving Blocks

Description of public road or public parking lot	Model Surface as
(1) Base material laid above surrounding grade	
(a) Without underlying perforated drain pipes	*Grid/lattice systems:* landscaped area on underlying soil (till or outwash). *Paving Blocks:* 50% landscaped area on underlying soil; 50% impervious.
(b) With underlying perforated drain pipes	Impervious surface

[1] See Section 7.8 for detailed instructions concerning how to represent the base material below grade as an infiltration basin in the Western Washington Hydrology Model.

[2] If the perforated pipes function is to distribute runoff directly below the wearing surface, and the pipes are above the surrounding grade, follow the directions for 2a above.

(2) Base material laid partially or completely below surrounding grade	
(a) Without underlying perforated drain pipes	Option 1: *Grid/lattice systems:* landscaped area on underlying soil. *Paving blocks:* 50% landscaped area; 50% impervious. Option 2: Impervious surface routed to an infiltration basin.[1]
(b) With underlying perforated drain pipes	
at or below bottom of base layer	Impervious surface
elevated within the base course[2]	Model as impervious surface routed to an infiltration basin.[1]

Description of private facilities (driveways, parking lots, walks, patios)

Base material laid partially or completely below surrounding grade	
(a) Without underlying perforated drain pipes	50% landscaped area; 50% impervious
(b) With underlying drain pipes	Impervious surface

7.1.2 Design Criteria for Permeable Pavements

Subgrade

- Compact the subgrade to the minimum necessary for structural stability. Use small static dual wheel mechanical rollers or plate vibration machines for compaction. Do not allow heavy compaction due to heavy equipment operation. The subgrade should not be subject to truck traffic.
- Use on soil types A through C.

Geotextile

- Use geotextile between the subgrade and base material/separation layer to keep soil out of base materials.
- The geotextile should pass water at a greater rate than the subgrade soils.

Separation or bottom filter layer (recommended but optional)

- A layer of sand or crushed stone (0.5 inch or smaller) graded flat is recommended to promote infiltration across the surface, stabilize the base layer, protect underlying soil from compaction, and serve as a transition between the base course and the underlying geotextile material.

Base material

- Many design combinations are possible. The material must be free draining. For more detailed specifications for different types of permeable pavement, see Section 6.3: Permeable Paving.
  - o Driveways (recommendation):
    - ✓ > 4-inch layer of free-draining crushed rock, screened gravel, or washed sand.

    - ✓ < 5 percent fines (material passing through #200 sieve) based on fraction passing #4 sieve.
  - o Roads: The standard materials and quantities used for asphalt roads should be followed. For example:
    - ✓ Pierce County cites larger rock on bottom, smaller on top (e.g., 2" down to 5/8"); compacted; minimal fines; 8 inches total of asphaltic concrete and base material.
    - ✓ Washington State Department of Transportation (WSDOT) lists coarse crushed stone aggregate (AASHTO Grading No. 57: 1.5 inch and lower); stabilized or unstabilized with modest compaction; meets fracture requirements.
    - ✓ The Federal Highway Administration suggests three layers between the porous pavement and geotextile. Typical layers would be:

      Filter course: 13 mm diameter gravel, 25 to 50 mm thick.

      Stone reservoir: 40 to 75 mm diameter stone.

      Filter course: 13 mm diameter gravel, 50 mm thick.

Wearing layer

- For all surface types, a minimum initial infiltration rate of 10 inches per hour is necessary. To improve the probability of long-term performance, significantly higher infiltration rates are desirable.
- *Porous Asphalt:* Products must have adequate void spaces through which water can infiltrate. A void space within the range of 12 to 20 percent is common.
- *Porous Concrete:* Products must have adequate void spaces through which water can infiltrate. A void space within the range of 15 to 21 percent is common.
- *Grid/lattice systems filled with gravel, sand, or a soil of finer particles with or without grass*: The fill material must be at least a minimum of 2 inches of sand, gravel, or soil. It should be underlain with 6 inches or more of sand or gravel to provide an adequate base. The fill material should be at or slightly below the top elevation of the grid/lattice structure. Modular-grid openings must be at least 40 percent of the total surface area of the modular grid pavement. Provisions for removal of oil and grease contaminated soils should be included in the maintenance plan.
- *Paving blocks:* 6 inches of sand or aggregate materials should fill spaces between blocks and must be free draining. Do not use sand for the leveling layer or filling spaces with Eco-Stone.
- The block system should provide a minimum of 12 percent free draining surface area.
- Provisions for removal of oil and grease contaminated soils should be included in the maintenance plan.

Drainage conveyance

Roads should still be designed with adequate drainage conveyance facilities as if the road surface was impermeable. Roads with base courses that extend below the surrounding grade should have a designed drainage flow path to safely move water away from the road prism and into the roadside drainage facilities. Use of perforated storm drains to collect and transport infiltrated water from under the road surface will result in less effective designs and less flow reduction credit.

Acceptance test

- Driveways can be tested by simply emptying a bucket of water on the surface. If anything other than a scant amount puddles or runs off the surface, additional testing is necessary prior to accepting the construction.
- Roads may be initially tested with the bucket test. In addition, test the initial infiltration with a 6-inch ring, sealed at the base to the road surface, or with a sprinkler infiltrometer. Wet the road surface continuously for 10 minutes. Begin test to determine compliance with 10 inches per hour minimum rate.

Limitations

- No run-on from pervious surfaces is preferred. If runoff comes from minor or incidental pervious areas, those areas must be fully stabilized.
- Slope impervious runoff away from the permeable pavement to the maximum extent practicable. Sheet flow from up-gradient impervious areas is not recommended, but permissible if porous surface flow path ≥ impervious surface flow path. Impervious surface that drains to a permeable pavement can also be modeled as noted in Section 7.1.1 as long as the flow path restriction is met.
- Do not use on "high use sites" (as defined in the 2005 SMMWW, Volume V, Section 3.2), auto commercial services (gas stations, mini-marts, commercial fueling stations, auto body and auto repair shops, auto wash), commercial truck parking areas, areas with heavy industrial activity (as defined by U.S. EPA regulations), or areas with high pesticide use.
- Soils must not be tracked onto the wear layer or the base course during construction.
- Slopes:
  - Asphalt: Works best on level slopes and up to 2 percent. Do not use on slopes ≥ 5 percent.
  - Concrete: Maximum recommended slope of 6 percent.
  - Interlocking pavers: Maximum recommended slope of 10 percent.
  - Grid/lattice systems: Maximum generally in 5 to 6 percent range.
- Do not use in areas subject to heavy, routine sanding for traction during snow and ice accumulation.
- Comply with local building codes for separation distances from buildings and wells. Inquire with the local jurisdiction concerning applicable setbacks.

Maintenance

- Inspect project upon completion to correct accumulation of fine material. Conduct periodic visual inspections to determine if surfaces are clogged with vegetation or fine soils. Clogged surfaces should be corrected immediately.
- Surfaces should be swept with a high-efficiency or vacuum sweeper twice per year; preferably once in the autumn after leaf fall and again in early spring. For porous asphalt and concrete surfaces, high-pressure hosing should follow sweeping once per year.

7.2 Dispersion

7.2.1 Full Dispersion for the Entire Development Site (fulfills treatment and flow control requirements)

Developments that preserve 65 percent of a site (or a **threshold discharge area** of a site) in a forested or native condition can disperse runoff from the developed portion of the site into the native vegetation area as long as the developed areas draining to the native vegetation do not have impervious areas that exceed 10 percent of the entire site. Runoff must be dispersed into the native area in accordance with the BMPs cited in BMP T5.30 of the 2005 SMMWW. Additional impervious areas are allowed, but should not drain to the native vegetation area and are subject to the thresholds, and treatment and flow control requirements of the stormwater manual.

7.2.2 Full Dispersion for all or Part of the Development Site

Developments that cannot preserve 65 percent or more of the site in a forested or native condition may disperse runoff into a forested or native area in accordance with the BMPs cited in BMP T5.30 of the 2005 SMMWW if:

- The effective impervious surface of the area draining into the native vegetation area is ≤ 10 percent; and
- The development maintains ratios proportional to the 65 percent forested or native condition and 10 percent effective impervious area. Examples of such ratios are:

% Native Vegetation Preserved (min. allowed)	% Effective Impervious (max. allowed)	% Lawn/Landscape (max. allowed)
65	10	35
60	9	40
55	8.5	45
50	8	50*
45	7	55*
40	6	60*
35	5.5	65*

* Where lawn/landscape areas are established on till soils, and exceed 50 percent of the total site, they should be developed using guidelines in Section 6.2: Amending Construction Site Soils or a locally approved alternative specification for soil quality and depth.

Within the context of this dispersion option, the only impervious surfaces that are ineffective are those that are routed into an appropriately sized dry well or into an infiltration basin that meets the flow control standard and does not overflow into the forested or native vegetation area.

Note: For options in 7.2.1 and 7.2.2, native vegetation areas must be protected from future development. Protection must be provided through legal documents on record with the local government. Examples of adequate documentation include a conservation easement, conservation parcel, and deed restriction.

7.2.3 Partial Dispersion on Residential Lots and Commercial Buildings

If roof runoff is dispersed on single-family lots greater than 22,000 square feet according to the design criteria and guidelines in BMP T5.10 of the 2005 SMMWW, and the vegetative flow path is 50 feet or longer through undisturbed native landscape or lawn/landscape area that meets the guidelines in Section 6.2: Amending Construction Site Soils, the roof area may be modeled as landscaped area. This is done by clicking on the "Credits" button in the WWHM and entering the percent of roof area that is being dispersed.

The vegetated flow path is measured from the downspout or dispersion system discharge point to the downstream property line, stream, wetland, or other impervious surface.

Where BMP T5.11 (concentrated flow dispersion) or BMP T5.12 (sheet flow dispersion) of the 2005 SMMWW is used to disperse runoff into a native vegetation area or an area that meets the guidelines in Section 6.2: Amending Construction Site Soils, the impervious area may be modeled as landscaped area. This can be done by entering the impervious area as landscaped area rather than entering it as impervious area.

7.2.4 Road Projects

(1) Uncollected or natural dispersion into adjacent vegetated areas (i.e., sheet flow into the dispersion area)

Full dispersion credit (i.e., no other treatment or flow control required) is given to projects that meet the following criteria:

(a) *Outwash soils* (Type A – sands and sandy gravels, possibly some Type B – loamy sands) that have an initial saturated infiltration rate of 4 inches per hour or greater. The infiltration rate must be based on one of the following: (1) A D_{10} size (10 percent passing the size listed) greater than 0.06 mm (based on the estimated infiltration rate indicated by the upper-bound line in Figure 4-17 of the WSDOT Highway Runoff Manual) for the finest soil within a three foot depth; (2) field results using procedures (Pilot Infiltration Test) identified in Appendix III-D (formerly V-B) of the 2005 SMMWW.

- 20 feet of impervious flow path needs 10 feet of dispersion area width.
- Each additional foot of impervious flow path needs 0.25 feet of dispersion area width.

(b) *Other soils:* (Types C and D and some Type B not meeting the criterion in 1(a) above)

- Dispersion area must have 6.5 feet of width for every 1-foot width of impervious area draining to it. A minimum distance of 100 feet is necessary.

(c) *Criteria applicable to all soil types:*

- Depth to the average annual maximum groundwater elevation should be at least 3 feet.
- Impervious surface flow path must be $\leq$ 75 ft. Pervious flow path must be $\leq$ 150 feet. Pervious flow paths are up-gradient road side slopes that run onto the road and down-gradient road side slopes that precede the dispersion area.

- Lateral slope of impervious drainage area should be ≤ 8 percent. Road side slopes must be ≤ 25 percent. Road side slopes do not count as part of the dispersion area unless native vegetation is re-established and slopes are less than 15 percent. Road shoulders that are paved or graveled to withstand occasional vehicle loading count as impervious surface.
- Longitudinal slope of road should be ≤ 5 percent.
- Length of dispersion area should be equivalent to length of road.
- Average longitudinal (parallel to road) slope of dispersion area should be ≤ 15 percent.
- Average lateral slope of dispersion area should be ≤ 15 percent.

(2) Channelized (collected and re-dispersed) stormwater into areas with (a) native vegetation or (b) cleared land in areas outside of urban growth areas that do not have a natural or man-made drainage system

Full dispersion credit (i.e., no other treatment or flow control required) is given to projects that meet the following criteria:

(a) *Outwash soils* (Type A – sands and sandy gravels, possibly some Type B – loamy sands) that have an initial saturated infiltration rate of 4 inches per hour or greater. The infiltration rate must be based on one of the following: (1) A D_{10} size (10% passing the size listed) greater than 0.06 mm (based on the estimated infiltration rate indicated by the upper-bound line in Figure 4-17 of the WSDOT Highway Runoff Manual) for the finest soil within a 3-foot depth; 2 field results using procedures (Pilot Infiltration Test) identified in Appendix III-D (previously V-B) of the 2005 SMMWW.

- Dispersion area should be at least ½ of the impervious drainage area.

(b) *Other soils:* (Types C and D and some Type B not meeting the criterion in 2a above)

- Dispersion area must have 6.5 feet of width for every 1-foot width of impervious area draining to it. A minimum distance of 100 feet is necessary.

(c) *Other criteria applicable to all soil types*:

- Depth to the average annual maximum groundwater elevation should be at least 3 feet.
- Channelized flow must be re-dispersed to produce the longest possible flow path.
- Flows must be evenly dispersed across the dispersion area.
- Flows must be dispersed using rock pads and dispersion techniques as specified in BMP T5.30 of the 2005 SMMWW.
- Approved energy dissipation techniques may be used.
- Limited to on-site (associated with the road) flows.
- Length of dispersion area should be equivalent to length of the road.
- Average longitudinal and lateral slopes of the dispersion area should be ≤ 8 percent.

(3) Engineered dispersion of stormwater runoff into an area with engineered soils

Full dispersion credit (i.e., no other treatment or flow control required) is given to projects that meet the following criteria:

- Stormwater can be dispersed via sheet flow or via collection and re-dispersion in accordance with the techniques specified in BMP T5.30 of the 2005 SMMWW.

- Depth to the average annual maximum groundwater elevation should be at least 3 feet.
- Type C and D soils must be compost-amended following guidelines in Section 6.2: Amending Construction Site Soils. The guidance document *Guidelines and Resources for Implementing Soil Depth & Quality BMP T5.13 in WDOE Western Washington Stormwater Manual*, 2003 (revised 2005) can be used, or an approved equivalent soil quality and depth specification approved by Ecology.
  - o Dispersion area must meet the 6.5 to 1 ratio for full dispersion credit.
- Type A and B soils that meet the 4 inches per hour initial saturated infiltration rate minimum (See Section 7.2.4 a above) must be compost-amended in accordance with guidelines in Section 6.2: Amending Construction Site Soils. Compost may be incorporated into the soil in accordance with the guidance document cited above, or can be placed on top the native soil.
  - o 20 feet of impervious flow path needs 10 feet of dispersion area width.
  - o Each additional foot of impervious flow path needs 0.25 feet of dispersion area width.
- Average longitudinal (parallel to road) slope of dispersion area should be ≤ 15 percent.
- Average lateral slope of dispersion area should be ≤ 15 percent.
- The dispersion area should be planted with native trees and shrubs.

(4) Other characteristics for dispersal areas

- Dispersal areas inside the urban growth area must be protected through legal agreements (easements, conservation tracts, public parks).
- If outside urban growth areas, legal agreements should be reached with property owners of dispersal areas subject to stormwater that has been collected and is being re-dispersed.
- An agreement with the property owner is advised for uncollected, natural dispersion via sheet flow that is a continuation of past practice. If not a continuation of past practice, an agreement should be reached with the property owner.

7.3 Vegetated Roofs

7.3.1 Option 1 Design Criteria

- 3 to 8 inches of soil/growing media

Runoff Model Representation

- till landscaped area

7.3.2 Option 2 Design Criteria

- > 8 inches of soil/media

Runoff Model Representation

- till pasture

7.3.3 Other Necessary Design Criteria

- Soil or growth media that has a high field capacity, and a saturated hydraulic conductivity that is $\geq$ 1 inch/hour (i.e., equivalent to a sandy loam or soil with a higher hydraulic conductivity).
- Drainage layer that allows free drainage under the soil/media.
- Vegetative cover that is both drought and wet tolerant.
- Waterproof membrane between the drain layer and the structural roof support.
- Maximum slope of 20 percent.

7.4 Rainwater Harvesting

7.4.1 Design Criteria

- 100 percent reuse of the annual average runoff volume (use continuous runoff model to get annual average for drainage area).
- System designs involving interior uses must have a monthly water balance that demonstrates adequate capacity for each month and reuse of all stored water annually.

Runoff Model Representation:

- Do not enter drainage area into the runoff model.

7.4.2 Other Criteria

- Restrict use to 4 homes/acre housing and lower densities when the captured water is solely for outdoor use.

7.5 Reverse Slope Sidewalks

Reverse slope sidewalks are sloped to drain away from the road and onto adjacent vegetated areas.

7.5.1 Design Criteria:

- $\geq$ 10 feet of vegetated surface downslope that is not directly connected into the storm drainage system.
- Vegetated area receiving flow from sidewalk must be undisturbed native soil or meet guidelines in Section 6.2: Amending Construction Site Soils.

7.5.2 Runoff Model Representation:

- Enter sidewalk area as landscaped area.

7.6 Minimal Excavation Foundations

Low impact foundations are defined as those techniques that do not disturb, or minimally disturb, the natural soil profile within the footprint of the structure. This preserves most of the hydrologic properties of the native soil. Pin foundations are an example of a minimal excavation foundation.

7.6.1 Runoff Model Representation

- Where residential roof runoff is dispersed on the up gradient side of a structure in accordance with the design criteria and guidelines in BMP T5.10 of the 2005 SMMWW, the tributary roof area may be modeled as pasture on the native soil.
- Where "step forming" is used on a slope, the square footage of roof that can be modeled as pasture must be reduced to account for lost soils. In "step forming," the building area is terraced in cuts of limited depth. This results in a series of level plateaus on which to erect the form boards. The following equation (suggested by Rick Gagliano of Pin Foundations, Inc.) can be used to reduce the roof area that can be modeled as pasture.

$$A_1 - \frac{dC(.5)}{dP} X A_1 = A_2$$

A_1 = roof area draining to up gradient side of structure
dC = depth of cuts into the soil profile
dP = permeable depth of soil (The A horizon plus an additional few inches of the B horizon where roots permeate into ample pore space of soil)
A_2 = roof area that can be modeled as pasture on the native soil

- If roof runoff is dispersed down gradient of the structure in accordance with the design criteria and guidelines in BMP T5.10 of the 2005 SMMWW AND there is at least 50 feet of vegetated flow path through native material or lawn/landscape area that meets the guidelines in Section 6.2: Amending Construction Site Soils, the tributary roof areas may be modeled as landscaped area.

7.6.2 Limitations

- To minimize soil compaction, heavy equipment cannot be used within or immediately surrounding the building. Terracing of the foundation area may be accomplished by tracked, blading equipment not exceeding 650 psf.

7.7 Bioretention Areas (Rain Gardens)

The design criteria provided below outlines basic guidance on bioretention design specifications, procedures for determining infiltration rates, and flow control guidance. For details on design specifications see Section 6.1: Bioretention Areas.

7.7.1 Design Criteria

Soils

- The soils surrounding bioretention facilities are a principle design element for determining infiltration capacity, sizing, and rain garden type. The planting soil mix placed in the cell or swale is a highly permeable soil mixed thoroughly with compost amendment and a surface mulch layer.
- Soil depth should be a minimum of 18 inches to provide acceptable minimum pollutant attenuation and good growing conditions for selected plants.
- The texture for the soil component of the bioretention soil mix should be a loamy sand (USDA Soil Textural Classification). Clay content for the final soil mix should be less than 5 percent. The final soil mix (including compost and soil) should have a minimum long-term hydraulic conductivity of 1.0 inch/hour

per ASTM Designation D 2434 (Standard Test Method for Permeability of Granular Soils) at 80 percent compaction per ASTM Designation D 1557.

- The final soil mixture should have a minimum organic content of approximately 10 percent by dry weight.
- The pH for the soil mix should be between 5.5 and 7.0.

Mulch layer

- Bioretention areas can be designed with or without a mulch layer.

Compost

- Material must be in compliance with WAC chapter 173-350 Section 220 and meet Type 1, 2, 3 or 4 feedstock.
- pH between 5.5 and 7.0.
- Carbon nitrogen ratio between 20:1 and 35:1 (35:1 CN ratio recommended for native plants).
- Organic matter content should be between 40 and 50 percent.

Installation

- Minimize compaction of the base and sidewalls of the bioretention area. Excavation should not be allowed during wet or saturated conditions. Excavation should be performed by machinery operating adjacent to the bioretention facility and no heavy equipment with narrow tracks, narrow tires or large lugged, high pressure tires should be allowed on the bottom of the bioretention facility.
- On-site soil mixing or placement should not be performed if soil is saturated. The bioretention soil mixture should be placed and graded by excavators and/or backhoes operating adjacent to the bioretention facility.

Plant materials

- Plants should be tolerant of ponding fluctuations and saturated soil conditions for the length of time anticipated by the facility design and drought during the summer months.
- In general, the predominant plant material utilized in bioretention areas are facultative species adapted to stresses associated with wet and dry conditions.

Maximum ponding depth

- A maximum ponding depth of 12 inches is recommended.
- A maximum surface pool drawdown time of 24 hours is recommended.
- Ponding depth and system drawdown should be specified so that soils dry out periodically in order to:
    - o Restore hydraulic capacity to receive flows from subsequent storms.
    - o Maintain infiltration rates.
    - o Maintain adequate soil oxygen levels for healthy soil biota and vegetation.
    - o Provide proper soil conditions for biodegradation and retention of pollutants.

7.7.2 Limitations

- A minimum of 3 feet of clearance is necessary between the lowest elevation of the bioretention soil, or any underlying gravel layer, and the seasonal high groundwater elevation or other impermeable layer, if the area tributary to the rain garden meets or exceeds any of the following limitations:
  - o 5,000 square feet of pollution-generating impervious surface; or
  - o 10,000 square feet of impervious area; or
  - o ¾ acre of lawn and landscape.
- If the tributary area to an individual rain garden does not exceed the areal limitations above, a minimum of 1 foot of clearance is adequate between the lowest elevation of the bioretention soil (or any underlying gravel layer) and the seasonal high groundwater elevation or other impermeable layer.

7.7.3 Runoff Model Representation

Pothole Design (Bioretention Cells)

The rain garden is represented as a pond with a steady-state infiltration rate. Proper infiltration rate selection is described below. The pond volume is a combination of the above ground volume available for water storage and the volume available for storage within the planting soil mix. The latter volume is determined by multiplying the volume occupied by the planting soil mix by the soil's percent porosity. Use 40 percent porosity for bioretention planting mix soils recommended in Section 6.1.2.3: Bioretention components. That volume is presumed to be added directly below the surface soil profile of the rain garden. The theoretical pond dimensions are represented in the Pond Information/Design screen. The Effective Depth is the distance from the bottom of the theoretical pond to the height of the overflow. This depth is less than the actual depth because of the volume occupied by the soil. Approximate side slopes can be individually entered. On the Pond Information/ Design screen, a button asks: "Use Wetted Surface Area?" Pushing that button is an affirmative response. Do not push the button if the rain garden has sidewalls steeper than 2 horizontal to 1 vertical.

Rain gardens with underlying perforated drain pipes that discharge to the surface can also be modeled as ponds with steady-state infiltration rates. However, the only volume available for storage (and modeled as storage as explained herein) is the void space within the imported material (usually sand or gravel) below the invert of the drain pipe.

Linear design: (bioretention swale or slopes)

Swales

Where a swale design has a roadside slope and a back slope between which water can pond due to an elevated, overflow/drainage pipe at the lower end of the swale, the swale may be modeled as a pond with a steady state infiltration rate. This method does not apply to swales that are underlain by a drainage pipe.

If the long-term infiltration rate through the imported bioretention soil is lower than the infiltration rate of the underlying soil, the surface dimensions and slopes of the swale should be entered into the WWHM as the pond dimensions and slopes. The effective depth is the distance from the soil surface at the bottom of the swale to the invert of the overflow/drainage pipe. If the infiltration rate through the underlying soil is lower than the estimated long-term infiltration rate through the imported bioretention soil, the pond dimensions entered into the WWHM should be adjusted to account for the storage volume in the void space of the bioretention soil. Use 40 percent porosity for bioretention planting mix soils recommended in Section 6.1.2.3: Bioretention components. For instance, if the soil is 40 percent voids, and the depth of the imported soils is 2 feet throughout the swale, the depth of the pond is increased by 0.8 feet. If the depth of imported soils varies within the side slopes of the swale, the theoretical side slopes of the pond can be adjusted.

This procedure to estimate storage space should only be used on bioretention swales with a 1 percent slope or less. Swales with higher slopes should more accurately compute the storage volume in the swale below the drainage pipe invert.

Slopes

Where a bioretention design involves only a sloped surface such as the slope below the shoulder of an elevated road, the design can also be modeled as a pond with a steady state infiltration rate. This procedure only applies in instances where the infiltration rate through the underlying soil is less than the estimated long-term infiltration rate of the bioretention planting soil mix. In this case, the length of the bioretention slope should correspond to the maximum wetted cross-sectional area of the theoretical pond. The effective depth of the theoretical pond is the void depth of the bioretention soil as estimated by multiplying the measured porosity times the depth of the bioretention soils. Use 40 percent porosity for bioretention planting mix soils recommended in Section 6.1.2.3: Bioretention components.

7.7.4 Infiltration Rate Determinations

The assumed infiltration rate for the pond must be the lower of the estimated long-term rate of the planting soil mix or the initial (a.k.a. short-term or measured) infiltration rate of the underlying soil profile. Using one of the procedures explained below, the initial infiltration rates of the two soils must be determined. Then after applying an appropriate correction factor to the planting soil mix placed in the rain garden, the designer can compare and determine the lower of the long-term infiltration rate of the planting soil mix and the initial infiltration rate of the underlying native soil. The underlying native soil does not need a correction factor because the overlying planting soil mix protects it. Below are explanations for how to determine infiltration rates for the planting soil mix and underlying soils, and how to use them with the WWHM.

7.7.4.1 Planting soil mix for the rain garden

1. Method for determining the infiltration rate for the planting soil mix in a rain garden with a tributary area of or exceeding any of the following limitations: 5,000 square feet of pollution-generating impervious surface; or 10,000 square feet of impervious surface; or ¾ acre of lawn and landscape:
   - o Use ASTM D 2434 Standard Test Method for Permeability of granular Soils (Constant Head) with a compaction rate of 80 percent using ASTM D 1557 Test Method for Laboratory Compaction Characteristics of Soil Using Modified Effort.
   - o Use 4 as the infiltration reduction correction factor.
   - o Compare this rate to the infiltration rate of the underlying soil (as determined using one of the methods below). If the long-term infiltration

rate of the imported soil is lower, enter that infiltration rate and the correction factor into the corresponding boxes on the pond information/design screen of the WWHM.

2. Method for determining the infiltration rate for the planting soil mix in a rain garden with a tributary area less than 5,000 square feet of pollution-generating impervious surface; and less than 10,000 square feet of impervious surface; and less than ¾ acre of lawn and landscape:
   - o Use ASTM D 2434 Standard Test Method for Permeability of granular Soils (Constant Head) with a compaction rate of 80 percent using ASTM D1557 Test Method for Laboratory Compaction Characteristics of Soil Using Modified Effort.
   - o Use 2 as the infiltration reduction correction factor.
   - o Compare this rate to the infiltration rate of the underlying soil (as determined using one of the methods below). If the long-term infiltration rate of the imported soil is lower, enter that infiltration rate and the correction factor into the corresponding boxes on the pond information/design screen of the WWHM.

7.7.4.2 Underlying soil

- Method 1: Use Table 3.7 of the 2005 SMMWW to determine the short-term infiltration rate of the underlying soil. Soils not listed in the table cannot use this approach. Compare this short-term rate to the long-term rate determined above for the bioretention-imported soil. If the short-term rate for the underlying soil is lower, enter it into the measured infiltration rate box on the pond information/design screen in the WWHM. Enter 1 as the infiltration reduction factor.
- Method 2: Determine the D_{10} size of the underlying soil. Use the "upperbound line" in Figure 4-17 of the WSDOT Highway Runoff Manual to determine the corresponding infiltration rate. If this infiltration rate is lower than the long-term infiltration rate determined for the bioretention planting soil mix, enter the rate for the underlying soil into the measured infiltration rate box on the pond/information design screen. Enter 1 as the infiltration reduction factor.
- Method 3: Measure the in-situ infiltration rate of the underlying soil using procedures (Pilot Infiltration Test) identified in Appendix III-D (formerly V-B) of the 2005 SMMWW. If this rate is lower than the long-term infiltration rate determined for the imported bioretention soil, enter the underlying soil infiltration rate into the corresponding box on the pond information/design screen of the WWHM. Enter 1 as the infiltration reduction factor.

7.7.5 WWHM Routing and Runoff File Evaluation

In WWHM2 (the most recent WWHM iteration), all infiltrating facilities must have an overflow riser to model overflows that occur should the available storage be exceeded. In the Riser/Weir screen for the Riser head, enter a value slightly smaller than the effective depth of the pond (e.g., 0.1 foot below the Effective Depth), and for the Riser diameter enter a large number (e.g., 10,000 inches) to ensure that there is ample capacity for overflows.

Within the model, route the runoff into the pond by grabbing the pond icon and placing it below the tributary "basin" area. Be sure to include the surface area of the bioretention area in the tributary "basin" area. Run the model to produce the effluent runoff file from the theoretical pond. For projects subject to the flow control standard, compare the flow duration graph of that runoff file to the target pre-developed runoff file for compliance with the flow duration standard. If the standard is not achieved a downstream retention or detention facility must be sized (using the WWHM standard procedures) and located in the field. A conveyance system should be designed to route all overflows from the bioretention areas to centralized treatment facilities, and to flow control facilities if flow control applies to the project.

7.7.6 Modeling of Multiple Rain Gardens

Where multiple rain gardens are scattered throughout a development, it may be possible to represent those as one rain garden (a "pond" in the WWHM) serving the cumulative area tributary to those rain gardens. For this to be a reasonable representation, the design of each rain garden should be similar (e.g., same depth of soil, same depth of surface ponded water, and approximately the same ratio of impervious area to rain garden volume).

7.7.7 Other Rain Garden Designs

Guidance for modeling other bioretention designs is not yet available. However, where compost-amended soils are used along roadsides the guidance in Section 7.2: Dispersion can be applied.

7.8 WWHM Instructions for Estimating Runoff Losses in Road Base Material Volumes that are Below Surrounding Grade

Pre-requisite

Before using this guidance to estimate infiltration losses, the designer should have sufficient information to know whether adequate depth to a seasonal high groundwater table, or other infiltration barrier (such as bedrock) is available. The minimum depth necessary is 3 feet as measured from the bottom of the base materials.

7.8.1 Instructions for Roads on Zero- to 2-percent Grade

For road projects whose base materials extend below the surrounding grade, a portion of the below grade volume of base materials may be modeled in the WWHM as a pond with a set infiltration rate.

First, place a "basin" icon in the "Schematic" grid on the left side of the "Scenario Editor" screen. Left clicking on the basin icon will create a "basin information" screen on the right in which you enter the appropriate pre-developed and post-developed descriptions of your project site (or threshold discharge area of the project site). By placing a pond icon below the basin icon in the Schematic grid, we are routing the runoff from the road and any other tributary area into the below grade volume that is represented by the pond.

The dimensions of the infiltration basin/pond to be entered in the Pond Information/Design screen are: the length of the base materials that are below grade (parallel to the road); the width of the below grade material volume; and the

Effective Depth. Note that the storage/void volume of the below grade base has to be estimated to account for the percent porosity of the gravel. This can be done by multiplying the below grade depth of base materials by the fractional porosity (e.g., a project with a gravel base of 32 percent porosity would multiply the below grade base material depth by 0.32). This is the Effective Depth. If the below grade base course has perforated drainage pipes elevated above the bottom of the base course, but below the elevation of the surrounding ground surface, the Effective Depth is the distance from the invert of the lowest pipe to the bottom of the base course multiplied by the fractional porosity.

Also in WWHM2, all infiltrating facilities must have an overflow riser to model overflows that occur should the available storage be exceeded. In the Riser/Weir screen, for the Riser head enter a value slightly smaller than the effective depth of the base materials (e.g., 0.1 foot below the Effective Depth), and for the Riser diameter enter a large value (e.g., 10,000 inches) to ensure that there is ample capacity should overflows from the trench occur.

On the Pond Information/Design screen, there is a button that asks, "Use Wetted Surface Area?" Pushing that button is an affirmative response. Do not push the button.

Using the procedures explained in Volume III, Chapter 3 and Appendix III-D of the 2005 SMMWW, or in Section 4-5.2 of the 2004 WSDOT Highway Runoff Manual, estimate the long-term infiltration rate of the native soils beneath the base materials. If using Method 1 from Chapter III of the 2005 SMMWW, enter the appropriate "short-term infiltration rate" from Table 3.7 into the "measured infiltration rate" box on the "Pond Information Design" screen of WWHM. Enter the correction factor from that table as the "Infiltration Reduction Factor." If using Method 2, enter the appropriate long-term infiltration rate from Table 3.8 into the "measured infiltration rate" box. Enter 1 as the correction factor. Note that Table 3.8 is restricted to the soil types in the table. For soils with a D_{10} size smaller than .05 mm, use the "lowerbound" values from Figure 4-17 on page 4-56, Chapter 4 of the 2004 WSDOT Highway Runoff Manual. If using Method 3, enter the measured in-situ infiltration rate as the "Measured Infiltration Rate" in the Pond Information/Design Screen. Also enter the appropriate cumulative correction factor determined from Table 3.9 as the "Infiltration Reduction Factor." Wherever practicable, Ecology recommends using Method 3, in-situ infiltration measurements (Pilot Infiltration Test) in accordance with Appendix III-D of the 2005 SMMWW.

Run the model to produce the overflow runoff file from the base materials infiltration basin. Compare the flow duration graph of that runoff file to the target pre-developed runoff file for compliance with the flow duration standard. If the standard is not achieved a downstream retention or detention facility must be sized (using the WWHM standard procedures) and located in the field. The road base materials should be designed to direct any water that does not infiltrate into a conveyance system that leads to the retention or detention facility.

7.8.2 Instructions for Roads on Grades Above 2 Percent

Road base material volumes that are below the surrounding grade and on a slope can be modeled as a pond with an infiltration rate and a nominal depth. Represent the below grade volume as a pond. Grab the pond icon and place it below the "basin" icon so that the computer model routes all of the runoff into the infiltration basin/pond.

The dimensions of the infiltration basin/pond to be entered in the Pond Information/Design screen are: the length (parallel to and beneath the road) of the base materials that are below grade; the width of the below grade base materials; and an Effective Depth of 1 inch. In WWHM2, all infiltrating facilities must have an overflow riser to model overflows should the available storage be exceeded. In the Riser/Weir screen, enter 0.04 foot (½ inch) for the Riser head and a large Riser diameter (e.g., 1000 inches) to ensure that there is no head build up.

Note: If a drainage pipe is embedded and elevated in the below grade base materials, the pipe should only have perforations on the lower half (below the spring line) or near the invert. Pipe volume and trench volume above the pipe invert cannot be assumed as available storage space.

Estimate the infiltration rate of the native soils beneath the base materials. See Section 7.8.1: Roads on zero to 2 percent grade for estimating options and how to enter infiltration rates and infiltration reduction factors into the "Pond Information/ Design" Screen of WWHM. Enter the appropriate information for the theoretical pond of ½-inch maximum depth.

On the Pond Information/Design screen, there is a button that asks, "Use Wetted Surface Area?" Pushing that button is an affirmative response. Do not push the button.

Run the model to produce the effluent runoff file from the base materials. Compare the flow duration graph of that runoff file to the target pre-developed runoff file for compliance with the flow duration standard. If the standard is not achieved a downstream retention or detention facility must be sized (using the WWHM standard procedures) and located in the field. The road base materials should be designed to direct any water that does not infiltrate into a conveyance system that leads to the retention or detention facility.

7.8.3 Instructions for Roads on a Slope With Internal Dams Within the Base Materials that are Below Grade

In this option, a series of infiltration basins are created by placing relatively impermeable barriers across the below grade base materials at intervals. The barriers inhibit the free flow of water down the grade of the base materials. The barriers must not extend to the elevation of the surrounding ground. Provide a space sufficient to pass water from upgradient to lower gradient basins without causing flows to surface out the sides of the base materials that are above grade.

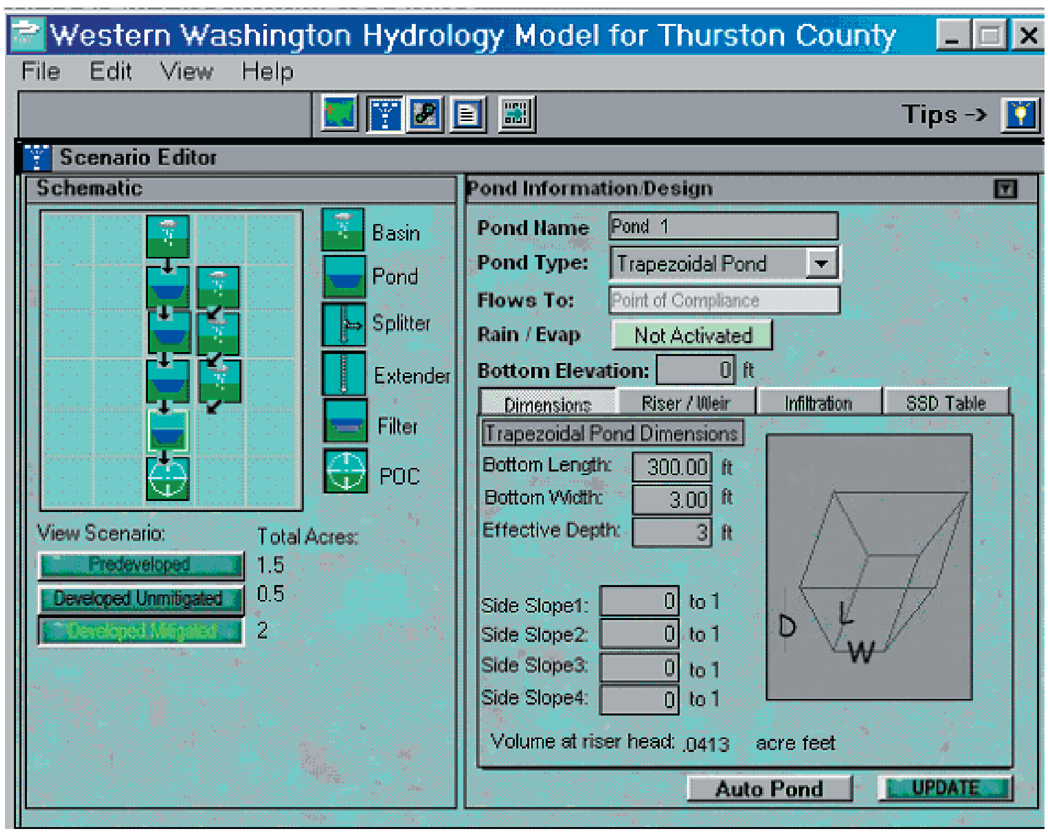
Each stretch of trench (cell) that is separated by barriers can be modeled as an infiltration basin. This is done by placing pond icons in a series in the WWHM. For each cell, determine the average depth of water within the cell (Average Cell Depth) at which the barrier at the lower end will be overtopped.

Specify the dimensions of each cell of the below grade base materials in WWHM on the screen which asks for pond dimensions. The dimensions of the infiltration cell entered in the Pond Information/Design screen are: the length of the cell (parallel to the road); the width; and the Effective Depth (in this case, it is okay to use the total depth of the base materials that are below grade).

Also in WWHM2, all infiltrating facilities must have an overflow riser to model overflows should the available storage be exceeded. For each trench cell, the available storage is the void space within the Average Cell Depth. The storage/void volume of the trench cell has to be estimated to account for the percent porosity of the base materials. For instance, if the base materials have a porosity of 32 percent, the void volume can be represented by reducing the Average Cell Depth by 68 percent (1 to 32 percent). This depth is entered in the Riser/Weir screen as the Riser head. The gross adjustment works because WWHM2 (as of March 2004) does not adjust infiltration rate as a function of water head. If the model is amended so that the infiltration rate becomes a function of water head, this gross adjustment will introduce error and therefore other adjustments should be made. For the riser diameter in the Riser/Weir screen, enter a large number (e.g., 10,000 inches) to ensure that there is ample capacity if overflows from the below-grade trench occur.

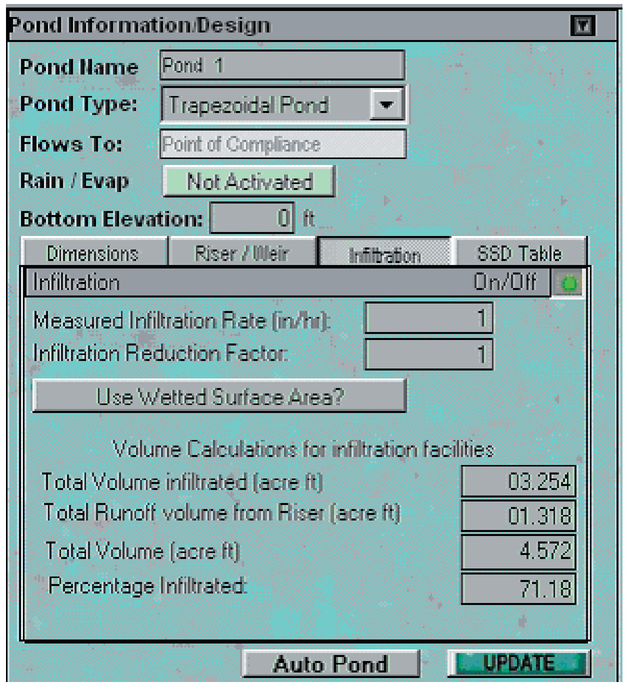
Each cell should have its own tributary drainage area that includes the road above it, any project site pervious areas whose runoff drains onto and through the road, and any off-site areas. Each drainage area is represented with a "basin" icon.

Up to four pond icons can be placed in a series to represent the below grade trench of base materials. The computer graphic representation of this appears as follows:



It is possible to represent a series of cells as one infiltration basin (using a single pond icon) if the cells all have similar length and width dimensions, slope, and Average Cell Depth. A single "basin" icon is also used to represent all of the drainage area into the series of cells.

On the Pond Information/Design screen (see screen below), there is a button that asks, "Use Wetted Surface Area?" Pushing that button is an affirmative response. Do not push the button if the below grade base material trench has sidewalls steeper than 2 horizontal to 1 vertical.



Using the procedures explained above for roads on zero grade, estimate the infiltration rate of the native soils beneath the trench. Also as explained above, enter the appropriate values into the "Measured Infiltration Rate" and "Infiltration Reduction Factor" boxes of the "Pond Information/Design" screen.

Run the model to produce the effluent runoff file from the below grade trench of base materials. Compare the flow duration graph of that runoff file to the target pre-developed runoff file for compliance with the flow duration standard. If the standard is not achieved a downstream retention or detention facility must be sized (using the WWHM standard procedures) and located in the field. The road base materials should be designed to direct any water that does not infiltrate into a conveyance system that leads to the retention or detention facility.

8 Hydrologic Analysis

In this chapter...

- *Emerging techniques for modeling LID*

Several methods of hydrologic analysis have been developed for modeling low impact development (LID) designs. Single event models have been most commonly used and a national method based on the Soil Conservation Service TR-55 model is available through the U.S. Environmental Protection Agency (EPA publication 841-B-00-02).

Single event methods, however, have limitations for modeling western Washington stormwater facilities. For example, a single event method does not account for the effects of storms that occur just before or after a single storm event and the associated antecedent soil moisture conditions.

The Washington Department of Ecology (Ecology) recommends that local jurisdictions in western Washington adopt the Western Washington Hydrologic Model (WWHM), an HSPF (Hydrologic Simulation Program-Fortran)-based model. Ecology recommends WWHM for several reasons, including:

- WWHM uses long-term and local precipitation data that accounts for various rainfall regimes in western Washington.
- The modeling methodology better accounts for previous storm events and antecedent soil moisture conditions.
- The various land categories describing hydrologic factors that influence runoff characteristics are calibrated using data collected by the U.S. Geological Service (USGS) in western Washington watersheds.

While WWHM provides advantages for designing stormwater facilities in western Washington, there are challenges for applying the model to low impact development designs. LID utilizes multiple, small-scale stormwater controls that are distributed yet often connected throughout the development. Flows are directed to these facilities from small contributing areas and stormwater that is not infiltrated, evaporated or transpired in one facility is directed to the next. This presents two challenges when using WWHM in this design setting:

- WWHM has limited routing capability, and while the model has been expanded to allow routing through multiple facilities, the procedure remains time and computing intensive for the large number of facilities in LID projects (AHBL, 2004).
- Pervious land category values (PERLNDs) for WWHM are based on local USGS studies. Pervious surfaces and soil treatments in a low impact development include compost amended soil, bioretention areas with engineered soil mixes, and pervious pavement with aggregate storage. The LID pervious surface treatments, or land categories, will likely behave differently than the calibrated PERLNDs in the WWHM. Pilot projects and associated monitoring are needed to provide necessary data to help further calibrate the WWHM to these new strategies.

8.1 Emerging Modeling Techniques

8.1.1 Micro-Basin Characterization

AHBL Engineers in Tacoma developed a micro-basin characterization technique to compensate for the routing limitations of the WWHM:

- The project is divided into small basins according to topography, lot, and street layout and LID stormwater facility configuration (see Figure 8.1 for a conceptual representation of the basin delineation).
- The contributing area is based on the bioretention cell or segment of bioretention swale and the area that contributes surface flows to that cell or swale.
- Areas are derived from design plans for roof areas, driveways, landscaping, and undisturbed areas for each basin.
- Storm flows from the basin are then routed through the bioretention cell or portion of the bioretention swale.
- An equivalent basin is generated that has characteristics that match the outflow from the bioretention cell or segment of swale.
- After all individual basins are defined, they are combined and routed to the next facility or used for the final development runoff.
  (AHBL, 2004)

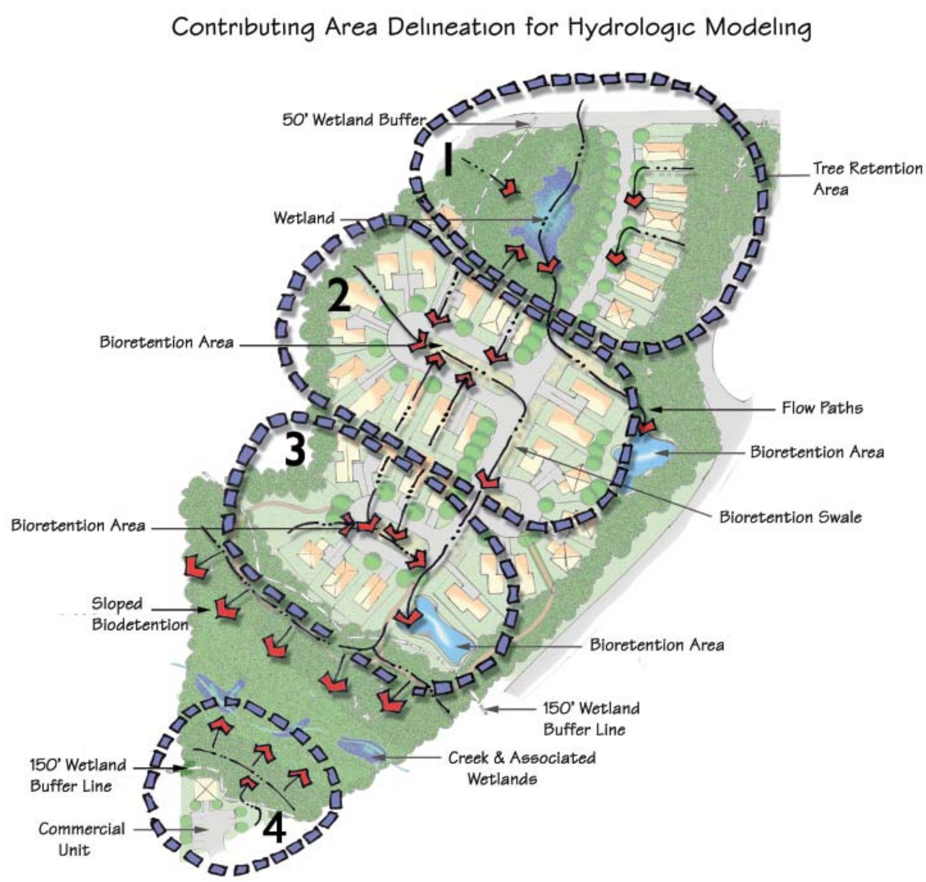


Figure 8.1 Basin delineation.

Graphic by AHBL Engineering

8.1.2 WWHM and LID Flow Control Credits

See Chapter 7: Washington Department of Ecology Low Impact Development Design and Flow Modeling Guidance for flow control credits when using bioretention, green roofs, rooftop rainwater harvesting, permeable paving, minimal excavation foundations, and dispersion techniques.

8.1.3 An Approach for Modeling Bioretention Swales and Compost Amended Soils

Herrera Environmental Consultants performed hydrologic modeling to evaluate the expected performance of a Natural Drainage System (NDS) for the High Point Revitalization Project in Seattle. The primary objectives of the hydrologic modeling were to evaluate compliance with overall stormwater performance goals for the site, cost effectiveness, and design optimization for the NDS.

Key elements of the proposed NDS include bioretention and conveyance swales that are distributed throughout the site within the public rights-of-way, disconnection of rooftop runoff from the storm drain system, and extensive use of compost amended soils.

Existing models are not ideally suited for examining the microscopic surface and subsurface dynamics of bioretention swales and their complex interaction with other stormwater management practices (e.g., rooftop dispersion and compost amended soil). Accordingly, Herrera developed new modeling techniques to more accurately assess the detailed performance of the bioretention swales at the city block-scale, as well as the cumulative performance of all elements of the NDS strategy for the entire High Point site.

The bioretention swales for High Point are complex in design, with multiple distinct layers governing their flow control capacity. These layers consist of a grass-lined or vegetated swale surface, a 6-foot thick engineered soil layer, and a 6-foot thick gravel under-drain layer. The swale is designed to retain stormwater at the surface long enough to allow infiltration into the underlying engineered soil layer. The engineered soil provides the primary mechanism for flow control. Stormwater is retained for longer periods of time and is exfiltrated through the sides of the swale to surrounding native soils. Moisture that does not exfiltrate within the engineered soil layer drains to the underlying gravel layer, which allows for additional exfiltration through the sides and bottom of the swale.

The bioretention swales were modeled in HSPF as a series of interconnected stage-storage-discharge relationships, or functional tables (FTABLEs). One FTABLE was used to represent each distinct layer of the swale. For the grass-lined or vegetated surface swale, FTABLE development was based on Manning's equation for open channels. The FTABLE for the engineered soil layer was of critical importance for predicting the overall performance of the bioretention swales, since this layer provides the primary flow control mechanism for the swales. This FTABLE was developed based on detailed modeling performed using MODRET software, which is a groundwater model capable of predicting dynamic surface water and groundwater interactions. The FTABLE for the under-drain layer was based on Darcy's Law for saturated flow through gravel. The FTABLEs for each layer were connected within HSPF, allowing for exfiltration to the native soils as well as one-way flow between layers (e.g., from the surface swale to the engineered soil layer, or from the engineered soil to the under-drain layer).

For the overall site-scale modeling, compost amended soils were modeled in HSPF as PERLNDs with lateral inflow from disconnected rooftop downspouts. Model parameters for these PERLNDs were modified from the USGS regional calibration parameters for till soils with grass cover in order to represent the enhanced infiltration offered by amended soils (Dinicola, 1990). The parameter adjustments were based on an HSPF calibration study by Kurtz (1996), which used data obtained from experimental plots at the University of Washington's Center for Urban Horticulture.

Runoff from rooftops was modeled as lateral inflow to lawns, or compost amended soil, down gradient from the downspouts. Lateral inflow is analogous to additional rainfall input to these receiving areas. For purposes of reflecting reasonable hydraulic loading rates, the areas receiving rooftop runoff were estimated using the following approach:

- Each building structure was assumed to have four downspouts contributing to the adjacent pervious area.
- Downspout discharge was assumed to spread at a 45 degree angle and sheet flow a distance of 10 feet onto the adjacent pervious area.

This modeling approach was successful for meeting the objectives of the study. Long-term monitoring of the site is scheduled to begin Fall 2004. Results from the monitoring study will be used to verify the modeling approach.

8.1.4 CH2M HILL LIFE™ Model

CH2M HILL developed the Low Impact Feasibility Evaluation (LIFE™) model specifically for evaluating the performance of various LID techniques. The LIFE™ model provides a continuous simulation of the runoff and infiltration from new or redeveloped areas, or from a watershed or sub-catchment with multiple land use categories utilizing the following inputs:

- Continuous rainfall data (typically in time increments of 1 hour or less) and evapotranspiration data (typically daily time increments) evaluated for time periods of one year or more.
- Site design parameters and land cover characteristics for each land category being modeled (e.g., road width, rooftop coverage, surface parking, etc.).
- Information on LID techniques that are applied for each land use type including:
    - Extent of source control application (e.g., percent of road and building lots with specific source controls).
    - Source control design parameters (e.g., area and depth of infiltration facilities, soil depth for green roofs, volume of rainwater harvesting cisterns, etc.).
- Soils information including:
    - Surface parameters (e.g., maximum water content, rooting depth of vegetation).
    - Subsurface parameters (e.g., saturated hydraulic conductivity).

The model provides total runoff volume, flow duration curves, and flow hydrographs as outputs to assess the performance of LID designs (CH2M HILL, 2004).

The LIFE™ model has not had extensive calibration. Pilot projects and associated monitoring will provide necessary data to help further calibrate the model to specific LID practices and expected overall performance of projects using multiple LID techniques.

Appendix 1

Street Tree List

The following list provides information on the growth patterns and favorable site characteristics for trees that are appropriate in the street landscape. Bioretention cells and swales located along streets may have specific soil and moisture conditions that differ from conventional roadside planting areas. Trees in this list may be applicable in bioretention areas depending on the physical setting and project objectives. See Appendix 3 for trees specifically recommended in bioretention cells or swales.

Local jurisdictions often have specific guidelines for the types and location of trees planted along public streets or rights-of-way. The extent and growth pattern of the root structure must be considered when trees are planted in bioretention areas or other stormwater facilities with under-drain structures or near paved areas such as driveways, sidewalks or streets. The city of Seattle, for example, has the following requirements for tree planting location:

- 3½ feet back from the face of the curb.
- 5 feet from underground utility lines.
- 10 to 15 feet from power poles.
- 7½ to 10 feet from driveways.
- 20 feet from street lights or other existing trees.
- 30 feet from street intersections.
- Planting strips for trees should be at least 5 feet wide.

Trees included in the "small" tree section of this list typically remain at or below a 30-foot mature height, which is compatible (unless indicated otherwise) with clearances for most overhead utility/electrical lines. Some jurisdictions may not recommend planting street trees that are fruit bearing or are otherwise "messy." Contact local authorities to determine if there are guidelines or restrictions to consider when making tree selections in your area.

Minimum ranges for planting strip widths are included and are compiled from various local and regional jurisdiction recommendations. Generally, larger planting widths are recommended for optimal tree health and longevity. Under certain circumstances, the use of root barriers or root guards may assist in preventing or delaying damage to adjacent paved surfaces. Consult a certified arborist for specifications and information on root barriers and installation.

Note on conifers: Jurisdictions often recommend very large planting areas for conifers due to potential visibility or safety issues associated with lower limbs. If properly trimmed and maintained, however, conifers can be incorporated safely into the urban streetscape and provide excellent year-round interception of precipitation.

Indicates a tree that does well in wet areas | * Denotes native species

SMALL TREES (under 30 feet in height)

Space evenly every 20 to 30 feet

Species/ **Common Name**	**Exposure**	**MatureHt./ Spread**	**Planting Strip Width**	**Comments**
Acer campestre Hedge maple	Sun/partial shade	To 30 feet/ To 30 ft. spread	4-5 feet	Deciduous; prefers moist, rich soils; slow growing tree tolerant of air pollution and soil compaction; yellow fall color; cultivars available including Queen Elizabeth maple ('Evelyn') with dark green, glossy foliage
*Acer circinatum** Vine maple	Sun/partial shade	20-25 feet/ 10 ft. spread	8 feet	Deciduous; prefers moist, well-drained soils; tolerates seasonal saturation and varying soil types; drought tolerant once established; bushy shrub or small tree; most often multi-trunked and does well in small groups; white flowers April-June; orange and red fall color
Acer ginnala Amur maple	Sun/partial shade	To 20 feet/ 20 ft. spread	4 feet	Deciduous; prefers moist, well-drained soils, but is tolerant of drought; is often multi-trunked, but can be pruned to a single stem; rounded form; fragrant, yellowish-white flowers in spring; cultivars are available such as 'Flame' and 'Embers' with differing fall colors
Acer griseum Paperbark maple	Sun/partial shade	15-25 feet/ 15-25 ft. spread	4 feet	Deciduous; prefers moist, well-drained soils, but is moderately drought tolerant; bronze peeling bark provides year-round visual interest; often multi-trunked, but can be trained to a single stem; scarlet fall color; slow growing; disease and pest resistant
Acer palmatum Japanese maple	Partial shade/Sun	15-25 feet/ 10-25 ft. spread	4 feet +	Prefers moist, well-drained soils; deciduous; slow to moderate growth rate; multi-trunked with spreading branches; intolerant of inundation but moderately drought resistant; vibrant fall colors; many cultivars available including 'Emperor I', 'Katsura', and 'Osakazuki'
Acer platanoides 'Globosum' Globe Norway maple	Sun/partial shade	15-20 feet/ 15-20 ft. spread	4-5 feet +	Moist soils preferred, but tolerates drought and seasonal inundation; tolerant of urban pollution; dense, compact, round form; slow-growing deciduous tree with brilliant fall color; shallow root system may make mowing under the tree slightly difficult; good selection for locations under power lines; another cultivar well suited for such a location is *A. platanoides* 'Almira,' reaching only 20-25 ft.
Acer triflorum Roughbark maple	Sun/partial shade	25-30 feet/ 20-25 ft. spread	Check with jurisdiction	Deciduous; prefers moist soils, but somewhat drought tolerant once established; apricot and gold fall color; rough, knobby trunk provides interest in winter; disease and pest resistant; non-aggressive roots do not damage sidewalks or driveways
Acer truncatum Purpleblow maple	Sun	20-25 feet/ 20-25 ft. spread	5 feet	Prefers moist, well-drained soil, but drought tolerant; very cold hardy deciduous tree; moderate growth rate; yellow flowers in spring; an additional maple cultivar of interest is 'Pacific sunset'

Species/ Common Name	Exposure	MatureHt./ Spread	Planting Strip Width	Comments
Amelanchier x *grandiflora* 'Autumn Brilliance' Serviceberry	Sun/partial shade	20-25 feet/ To 15 ft. spread	4 feet +	Moist to dry, well-drained soils; shrub or small tree; drought tolerant; white clustered flowers in spring; red or yellow fall color; also try 'Princess Diana' for bright red fall color and the slightly taller 'Robin Hill' (20-30 feet)
Carpinus caroliniana American hornbeam	Sun/partial shade	20-30 feet/ 20-30 ft. spread	4-6 feet	Deciduous; prefers moist, rich soils; grows near saturated areas but is only weakly tolerant of saturation; blooms March-May; slow growing; deep coarse laterally spreading roots; medium life span; also consider *Carpinus japonica* (Japanese hornbeam)
Cercis Canadensis Eastern redbud	Partial shade/sun	25 feet/ 30 ft. spread	4 feet +	Deciduous; prefers moist, rich soils; tolerant of shade; somewhat drought resistant, but not in full sun; purple-lavender flowers; medium longevity; often multi-trunked; shallow, fibrous roots become deeper on drier sites; fairly short-lived; blooms March-May
Cornus kousa var. 'Chinensis' Chinese kousa dogwood	Sun/partial shade	To 20 feet/ To 20 ft. spread	3 feet +	Prefers moist soils; tolerant of varying soil types; moderate growth rate; deciduous; white flowers in June and large red fruits that resemble a raspberry in September; red to maroon fall color; more disease resistant than other dogwoods; many additional cultivars available
Crataegus x *lavalii* Lavalle hawthorn	Sun	To 25 feet/ 15-20 ft. spread	4-5 feet	Deciduous; prefers moist, well-drained soil, but tolerant of varying soil types; bronze and coppery red fall color; white flowers in spring; fruit can be a bit messy
Malus spp. Flowering crabapple	Sun/partial shade	15-25 feet/ 6-15 ft. spread	4-5 feet	Tolerant of prolonged soil saturation; somewhat untidy; short lived; tolerant of drought and seasonally saturated soils; deciduous; white or faintly pink flowers in spring; numerous *Malus* species and cultivars provide a variety of foliage and flower colors, forms, and fruit. Many cultivars and varieties available including *M.* 'Adirondack' (to 10 ft. height), *M. floribunda* (Showy crab); *M.* 'Sugar Tyme' (to 18 ft. height); native *M. fusca** (Pacific crabapple) reaches 30-40 ft in height
Parrotia persica Persian ironwood	Sun/light shade	15-35 feet/ 15-30 ft. spread	4 feet	Moist to dry soils; drought tolerant when established, deciduous tree with moderate growth rate; brilliant fall color; often multi-trunked, but can be trained to have just one; tolerates urban pollution and soil compaction; surface roots do not generally cause problems; virtually disease and pest-free
Prunus serrulata 'Shirofugen' Japanese flowering cherry	Sun	To 25 feet/ To 25 ft. spread	4 feet	Deciduous flowering tree; moist, well-drained soils; double pink to white blooms in spring; vigorous grower; additional desirable choices include *P. serrulata* 'Snowgoose', 'Kwanzan', and 'Shirotae'
Quercus ilex Holly oak	Sun/partial shade	20+ feet/ 20 ft. spread	5 feet +	Prefers moist soils, but grows in varying soils; hearty, slow-growing evergreen tree; light pink flowers May-June; pruning will keep tree small for a hedge, without pruning may grow considerably larger – not appropriate under utility lines; tolerates salt water spray

MEDIUM TREES (30 to 50 feet in height)

Space evenly every 25 to 35 feet

Species/ **Common Name**	**Exposure**	**Mature Ht./ Spread**	**Planting Strip Width**	**Comments**
Acer platanoides 'Columnare' Columnare Norway maple	Sun/partial shade	40-50 feet/ 15-20 ft. spread	5-6 feet	Deciduous; adapts to varying soils; upright or columnar in form making this cultivar a better choice for narrow locations; tolerant of drought and seasonal inundation; tolerates urban pollution and displays brilliant fall color; shallow rooting necessitates locating at least 4-6 feet from sidewalks and driveways to prevent heaving of pavement
Acer rubrum Red maple	Sun/partial shade	35-50 feet/ 15-40 ft. spread	5-6 feet	Deciduous tree known for fall color; prefer wet or moist soils; tolerant of summer drought and urban pollutants; fast growing with roots that may heave sidewalks or interfere with mowing; many cultivars of varying heights available including: *A. rubrum*, 'Armstrong,' Bowhall', Karpick,' 'Scarsen,' and 'Red Sunset'
Carpinus betulus European hornbeam	Sun/shade	40-60 feet/ 30-40 ft. spread	5 feet	Deciduous tree; tolerant of urban pollution and poor soils; can also be used as a hedge or screen cultivars available and suggested include 'Fasigiata' (30-40 ft. height) and 'Franz Fontaine' (30-35 ft height)
Fraxinus americana 'Autumn Applause' Ash	Sun	To 40 feet/ 25 ft. spread	5-6 feet	Deciduous; prefers moist, well-drained soils; dense, wide spreading canopy; long-lived; purple fall color; moderate growth rate; also try *F. Americana* 'Junginger'
Fraxinus oxycarpa Raywood ash	Sun	25-50 feet/ 25 ft. spread	5 feet +	Deciduous; drought and variable soil tolerant; can take extreme temperatures; does not tolerate constant wind or fog; resists pests and disease better than do other ashes; inconspicuous flowers in spring
Fraxinus pennsylvanica Green ash/red ash	Sun	To 50 feet/ To 40 ft spread	4-5 feet +	Deciduous; prefers moist soils; fast growth rate; tolerant of wind, salt, seasonal drought and urban pollution; numerous cultivars including Patmore' (50-60 ft. height), 'Summit' (to 45 ft. height), and 'Urbanite' (to 50 ft. height)
Ginkgo biloba 'Autumn Gold' Maidenhair tree	Partial sun/partial shade	25-50 feet/ 25-30 ft. spread	5-6 feet	Moist soils; deciduous ornamental tree; fast growing and long-lived; tolerant of urban pollution, summer drought and winter inundation; showy fall color; grows in soils of varying quality; provides dense canopy; additional cultivars available
Gleditsia triacanthos inermis 'Shademaster' Thornless honeylocust	Sun/partial shade	To 45 feet/ 35 ft. spread	5-6 feet	Deciduous; prefers moist, rich soils, but will grow in varying soil types; a thornless cultivar tolerant of drought and seasonal inundation; adapts to urban pollution and displays vigorous growth; deciduous tree with showy yellow fall color; additional cultivars available such as 'Imperial,' which grows 30-35 feet, 'Moraine,' and 'Rubylace'
Koelreuteria paniculata Goldenrain tree	Sun/partial sun	20-35 feet/ 10-30 ft. spread	4 feet +	Deciduous; prefers moist well-drained soils, but is tolerant of poor soils; medium rate of growth and longevity; tolerant of periods of drought and seasonal inundation; tolerates urban pollution; provides a dense, wide-spreading canopy

Species/ Common Name	Exposure	Mature Ht./ Spread	Planting Strip Width	Comments
Platanus x *acerifolia* 'Liberty' London planetree	Sun	To 50 feet/ 45 ft. spread	8 feet	Prefers moist, rich soils, but tolerant of a variety of soils; tolerant of seasonal drought and inundation, urban pollution and poor soils; deciduous tree resistant to sycamore anthracnose, powdery mildew, and inward spread of wood decay due to trunk wounds; patchy ornamental bark; pruning of lower branches may be required for visibility; shallow roots can cause uplifting of sidewalks and pavement – use care when locating near pavement; also try 'Bloodgood' and 'Yarwood'
Pyrus calleryana 'Chanticleer' Flowering pear	Sun	To 40 feet/ 15 ft. spread	4-5 feet	Deciduous tree that grows well in a variety of soil types; orange to reddish fall color; white flowers in spring; additional cultivars of interest include *P. calleryana* 'Redspire' and 'Aristocrat'
Tilia cordata Littleleaf linden	Sun	30-50 feet/ 30 ft. spread	5-6 feet	Deciduous; prefers moist, well-drained soils, but tolerant of a variety of soil types; tolerant of wind and urban pollution; fast growing and long-lived; tolerates summer drought and seasonal inundation; provides a dense canopy; *C. cordata* is the hardiest linden; many forms available including, *T. cordata* 'Chancellor', 'Corzam', and 'Greenspire'

Large Trees (50 feet+ in height)

Space evenly every 35 to 45 feet

Species/ Common Name	Exposure	Mature Ht./ Spread	Planting Strip Width	Comments
*Abies grandis** Grand Fir	Sun/partial shade	100 feet/ 40 ft. spread	Check with jurisdiction	Evergreen; tolerant of fluctuating water tables and floods; medium rate of growth; root structure depends on site conditions – shallow in moist areas, deep taproot in drier conditions
Acer platanoides 'Emerald Queen' Emerald Queen Norway maple	Sun/partial shade	To 50 feet/ 40 ft. spread	5-8 feet	Deciduous; fast growing with an erect, spreading form; prefers moist soils, but is tolerant of summer drought and seasonal inundation; tolerates urban pollution; avoid locating near structures due to shallow, vigorous rooting; additional cultivars available including *A. platanoids* 'Parkway'
Acer pseudoplatanus Sycamore maple	Sun/partial shade	40-60 feet/ 25-40 ft. spread	5-8 feet	Deciduous; prefers moist, well-drained soils but is adaptable to may soil types; tolerates summer drought and seasonal inundation; tolerant of urban pollution with a moderate growth rate; sturdy, resistant to wind and salt spray; a number of cultivars are available including: *A. pseudoplatanus* 'Atropurpureum,' ' Brilliantissimum,' 'Cox' (Lustre), and 'Puget Pink'
Acer saccharum Sugar maple		60-75 feet/ 35 ft. spread	6 feet +	Deciduous; prefers moderately moist, well-drained soils; long-lived and tolerant of urban pollutants; slow to medium growth rate; needs large planting area; yellow and orange fall color; a variety of cultivars available including *A. saccharum* 'Legacy'
*Calocedrus decurrens** Incense cedar	Sun/partial shade	75-90 feet/ 10-20 ft. spread	Check with jurisdiction	Evergreen; tolerant of poor soils; drought tolerant after established; tolerant of wind and urban conditions; narrow growth habit makes this a good choice for smaller spaces and ideal for screening, fragrant tree; slow growing and long-lived
Cedrus deodara Deodar cedar		40-60 feet/ 20-40 ft. spread	Check with jurisdiction	Evergreen; prefers moist, well-drained soils, but drought tolerant when established; fairly fast growing and long-lived; dense, wide spreading canopy; attractive cultivars available
*Fraxinus latifolia** Oregon ash	Sun/partial shade	40-80 feet/ 30 ft. spread	6 feet +	Deciduous; saturated, ponded or moist soils; flood tolerant; small green-white flowers; tolerant of poor soils
Gleditsia triacanthos inermis Thornless honeylocust	Sun/partial shade	60-70 feet/ 40 ft. spread	5-6 feet	Deciduous; prefers moist soils, but will grow in poor soils; tolerant of drought, seasonal inundation, and urban pollution; occasionally fruit pods can create litter during winter months; thornless; cultivars available (see *G. triacanthos inermis* 'Shademaster' below in Medium trees)
Metasequoia glyptostroboides Dawn redwood	Sun	70-100 feet/ 25 ft. spread	5 feet +	Deciduous; prefers moist, deep, well-drained soils, but tolerates compacted and poor soils; long-lived, fast growing conifer; tolerant of seasonal inundation and drought; can grow in standing water; needles turn russet in the fall; needs large growing area; lower growing cultivars available such as *M. glyptostroboides* 'Gold Rush' and 'Sheridan Spire'

Species/ **Common Name**	**Exposure**	**Mature Ht./ Spread**	**Planting Strip Width**	**Comments**
Picea omorika Serbian spruce	Sun/partial shade	50-60 feet/ 20-25 ft. spread	Check with jurisdiction	Slow growing; tolerant of varying soils and urban pollution; moderately drought tolerant once established; elegant evergreen spruce, good for narrow locations; lower growing cultivars available
*Pseudotsuga menziesii** Douglas fir	Sun to shade	75-120 feet/ 40 ft. spread	Check with jurisdiction	Evergreen conifer; moist to dry soils; long-lived with a medium to fast rate of growth; tolerant of summer drought, winter inundation, and poor soils; withstands wind and urban pollution; provides a nice canopy, but potential height will restrict placement
Quercus bicolor Swamp white oak	Sun	60 feet/ 45 ft. spread	6-8 feet	Deciduous; grows in wet or moist sites, but is tolerant of drought conditions; withstands poorly drained soils; long-lived with moderate rate of growth
Quercus coccinea Scarlet oak	Sun	50-60 feet/ 45 ft. spread	6-8 feet	Deciduous; grows in a variety of soil types; long-lived with a moderate growth rate; tolerant of summer drought and urban pollution; does not tolerate saturated soils or shade; brilliant scarlet to red fall foliage
Quercus macrocarpa Burr Oak	Sun	70-80 feet/ 30-40 ft. spread	8 feet	Prefers moist soils, but is adaptable to varying soils; slow growing and long-lived; rugged looking deciduous tree; tolerant of seasonal drought and inundation; tolerates urban pollution and city conditions; provides a wide-spreading, dense canopy
Quercus phellos Willow oak	Sun/partial shade	60-70 feet/ 50 ft. spread	6 feet	Deciduous; prefers moist, well-drained soils, but grows in a wide range of soils types; long-lived tree with moderate growth rate and fibrous root system; tolerant of seasonal drought and inundation, as well as urban pollution; provides a wide-spreading, dense canopy; small delicate leaves
Quercus robur English oak	Sun	40-60+ feet/ 40 ft. spread	4-8 feet	Prefers well-drained soil; slow to moderate growth rate; long-lived deciduous tree; tolerant of seasonal drought and inundation; tolerates urban pollution, poor soils and constrained root space; susceptible to powdery mildew; many varieties and cultivars available including: 'Concordia,' 'Fastigiata,' 'Foliis Variegatis, and 'Westminster Globe.'
Quercus rubra Northern red oak	Sun/partial shade	60-75 feet/ 50 ft. spread	6-8 feet	Prefers moist, well-drained soils, but drought tolerant when established; tolerates seasonal inundation, urban pollution and salt spray; moderate rate of growth and longevity; provides a dense, wide-spreading canopy; susceptible to oak wilt fungus
Quercus shumardii Shumard's oak	Sun	To 70 feet/ 50 ft. spread	8 feet	Prefers moist, well-drained soils; deciduous, long-lived tree; tolerant of seasonal drought and inundation, urban pollution and poor soils
Taxodium distichum Bald cypress	Sun/partial shade	To 75 feet/ 40 ft. spread	Check with jurisdiction	Deciduous conifer; wet, mucky soils; tolerant of summer drought and seasonal flooding; will grow in poor soils; slow growing; long-lived with a wide-spreading canopy; roots do not appear to lift sidewalks as readily as other species; prune lower branches for sight-lines; cultivars include *T. distichum* 'Shawnee Brave'

Species/ **Common Name**	**Exposure**	**Mature Ht./ Spread**	**Planting Strip Width**	**Comments**
*Thuja plicata** Western red cedar	Partial shade/ shade	200 + feet/ 60 ft. spread	Check with jurisdiction	Moist to swampy soils; evergreen tree tolerant of seasonal flooding and saturated soils; a good tree for screening; long-lived; cultivars 'Pumilio' and 'Cuprea' are shorter versions, 'Aurea' and 'Atrovirens' have distinctive foliage
Tilia platyphyllos Bigleaf linden	Sun	60-80 feet/ 60 ft. spread	Check with jurisdiction	Prefers moist, well-drained soils, but grows in a variety of soil types; deciduous tree with medium growth rate; long-lived; tolerant of seasonal drought and inundation; tolerates urban pollutants; provides a wide-spreading, dense canopy; yellowish-white flowers attract bees
Ulmus ssp. Elm hybrids	Sun	50-60 feet/ 35-50 ft. spread	6-8 feet	Deciduous; prefers moist, well-drained soils, but drought tolerant; rapid grower; attractive yellow fall color; a hybrid elm resistant to Dutch elm disease; suggested hybrids include 'Accolade', 'Homestead' and 'Pioneer'
Umbellularia californica Oregon myrtle	Sun/partial shade	40-75+ feet/ To 50 ft. spread	Check with jurisdiction	Prefers moist, well-drained soils; slow growing evergreen tree with aromatic leaves; tolerates seasonal drought and inundation; tolerant of urban pollution; provides a wide-spreading, dense canopy; resistant to pests and disease; good for tall hedges or, when trunks are thinned, as a street tree; requires summer watering until established

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Appendix 2

Bioretention Design Examples

The following examples, from different locations in the U.S., illustrate a variety of concepts and specifications useful for developing bioretention facilities specific to local needs.

1. Bioretention Cell: Prince George's County, Maryland

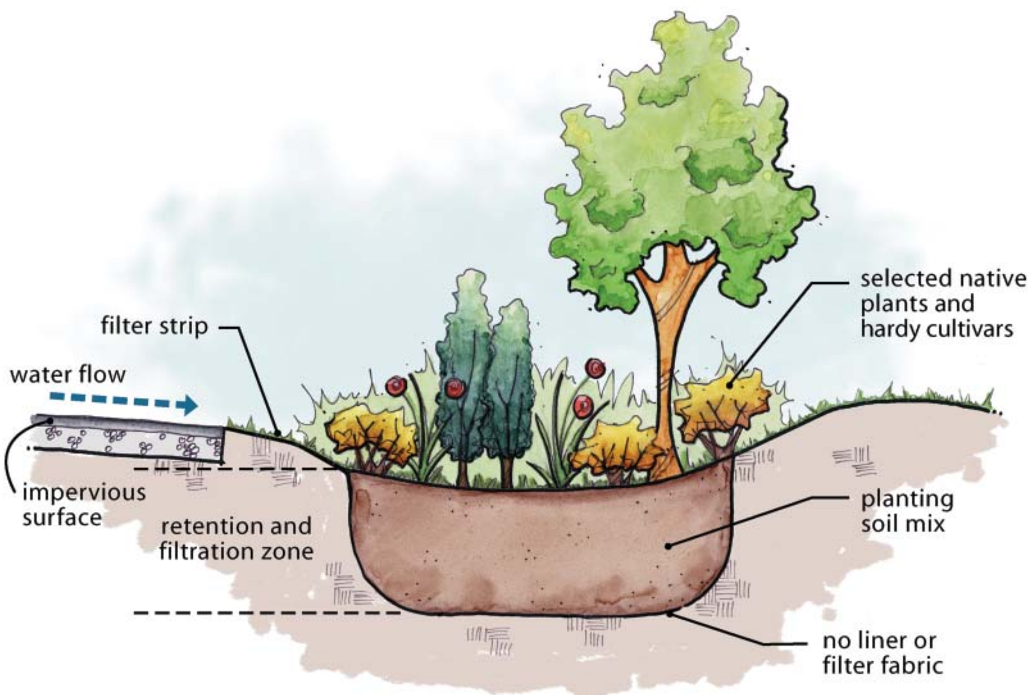

Figure 1 Typical bioretention design section.

Graphic by AHBL Engineering

Type of facility

- General application for infiltration and recharge, not recommended for contaminant hotspots.
- The initial bioretention design applied in the U.S. and the most simple design type.

Contributing area: 1-acre maximum with a maximum of ½-acre impervious area recommended.

Sizing: modified TR 55.

Flow path: off-line preferred, in-line permitted.

Planting soil depth: 2.5 feet minimum—allows for adequate filtration above native soil.

Soil:

Native soil (outside of excavated area)

- Minimum infiltration rate of 1 inch/hour.

Planting soil mix

- 50 to 60% sand, 20 to 30% leaf compost, and 20 to 30% topsoil.
- Infiltration rate not reported; however, recommended porosity for soil mix is approximately 25%.
- Topsoil is sandy loam, loamy sand or loam texture (USDA texture triangle).
- Maximum clay content < 5%.
- pH range 5.5 to 6.5.
- Uniform mix free of stones, stumps, roots or other similar material > 2 inches.
- Clean sand (0.02 to 0.04 inches) meeting AASHTO M-6 or ASTM C-33.

Comments

This is the initial planting soil specification developed for bioretention areas in the early 1990s and has been successfully applied in facilities operating for the past 10 years.

Pretreatment: provide grass or vegetated strip if space allows.

Under-drain: none

Gravel blanket: none

Filter fabric: none unless placed along sides to reduce lateral flows under adjacent pavement areas (e.g. median strip or parking lot island).

Mulch:

- 3-inch maximum, well-aged (12 months min.) shredded hardwood (shredded minimizes floating of material during surface water ponding), use fresh bark mulch when additional nitrogen retention desirable.

Compaction:

- Place soil in lifts of 12 to 18 inches.
- Do not use heavy equipment in bioretention basin.
- If compaction occurs at bottom of facility during excavation, rip to a minimum 12 inches and till 2 to 3 inches of sand into base before backfilling.
- If final grading of soil mix cannot be accomplished by hand, use light, low ground-contact pressure equipment.

Surface pool dewater: 3 to 4 hours.

System dewater: less than 48 hours.

Max ponding depth: 6 inches.

(Prince George's County, 2002)

2. Bioretention cell: Prince George's County, Maryland

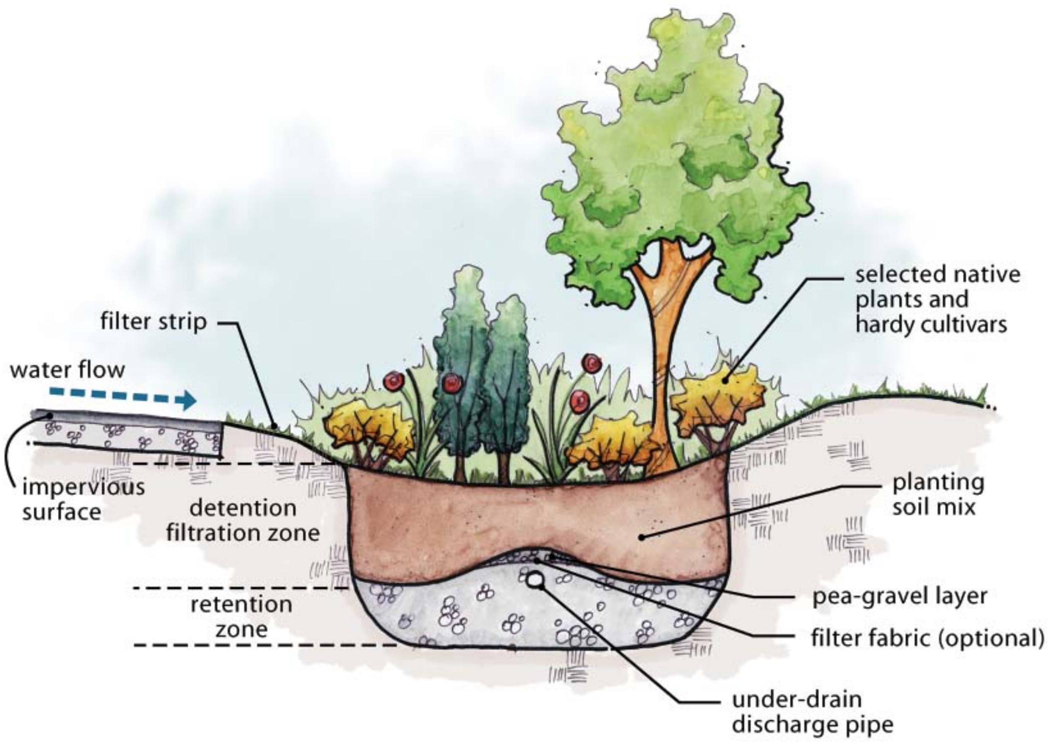

Figure 2 Bioretention design with elevated under-drain and fluctuating aerobic/anaerobic zone.
Graphic by AHBL Engineering

Type of facility:

- General application for infiltration, filtration, and recharge where high nitrogen loadings are anticipated.
- Design allows for a fluctuating aerobic/anaerobic zone below the raised under-drain discharge pipe.
- Design can be used for contaminant hotspot areas with liner.

Contributing area: 2-acre maximum with a maximum of 1-acre impervious area recommended.

Sizing: modified TR 55.

Flow path: off-line preferred, in-line permitted.

Planting soil depth: 2.5 feet minimum

Soil:

Native soil (outside of excavated area)

- Minimum infiltration rate can be less than 1 inch/hour with under-drain.

Planting soil (see Example #1)

Pretreatment: provide grass or vegetated strip if space allows.

Under-drain:

- 6 to 8-inch diameter rigid schedule 40, ½-inch perforations, 6 inches center to center.

Gravel blanket:

- Under-drain gravel bed: ½ to 1½-inch diameter washed stone AASHTO M-43.
- Pea gravel diaphragm (placed between planting soil and drain rock for improved sediment filtration): ¼ to ½-inch diameter washed stone ASTM D 448, 3 to 8 inches thick.

Filter fabric:

- Non-woven ASTM D-4491, permittivity 75 gal/min/ft^2 minimum, installed horizontally on top of the drain rock extending 1 to 2 feet either side of under-drain pipe located below.
- Filter fabric on bottom or sides of facility is not recommended unless used to restrict lateral or vertical flow.
- If pea gravel diaphragm is used, filter fabric can be placed between drain rock and diaphragm to impede direct gravitational flow.

Mulch:

- 3-inch maximum, well-aged (12 months min.) shredded hardwood (shredded minimizes floating of material during surface water ponding), use fresh bark mulch when additional nitrogen retention desirable.

Surface pool dewater: 3 to 4 hours.

System dewater: less than 48 hours.

Max ponding depth: 6 inches.

(Prince George's County, 2002)

3. Bioretention Swale: Seattle Public Utilities (SEA Street project)

Figure 3 SEA Street bioretention swale. *Photo by Colleen Owen*

Type of facility: Redesign of 660-foot existing street using bioretention swales within right-of-way for infiltration and conveyance.

Construction date: 1999 to 2000.

Contributing area: 2.3 acres (approximately 35% total impervious area).

Sizing: Santa Barbara Unit Hydrograph.

Flow path: in-line.

Planting soil depth: approximately 1 foot.

Soil:

Native soil

- Heterogeneous till-like material (not true lodgement till) with lens of silt, sand, and gravel material of varying permeability.

Planting soil

- Bottom of swales: 50% approved native soil and 50% decomposed organic compost by volume, thoroughly mixed. Remaining areas: 70 to 75% approved native soil and 25 to 30% compost by volume, thoroughly mixed.
- Infiltration rate not reported.

Comments

This soil specification has proven successful for infiltration requirements and plant growth and health at the SEA Street project; however, Seattle has modified the specification as noted in the Broadview Green Grid project (see example #4).

Pretreatment: none.

Under-drain:

- 6- to 8-inch slotted PVC pipe with surface drains set at designed flow depth elevations, solid iron pipe under driveways.
- Ultimate outfall to existing roadside ditch at end of block.
- Some areas lined with clay to restrict infiltration and possible subsurface flow to residential basements.

Gravel blanket: Seattle type 26 (sand gravel mix, see Section 6.1.2.3 Bioretention components for specification).

Filter fabric: none.

Mulch: 3-inch depth minimum (same as compost used for soil mix).

Compaction:

- No heavy equipment allowed in bioretention swale area during construction.
- No excavation during wet or saturated conditions.
- Soil installed in maximum lifts of 6 inches and foot compacted.

Surface pool dewater: not available.

System dewater: not available.

Max ponding depth: Live storage: 12 inches. Dead storage: 0 inches.

(Tackett, 2004; Seattle Public Utilities, 2000; personal communication, Tracy Tackett 2004)

4. Bioretention Swale: Seattle Public Utilities (Broadview Green Grid project)

Figure 4 Broadview green grid bioretention swale. *Photo courtesy of Seattle Public Utilities.*

Type of facility: Redesign of existing streets using bioretention swales within right-of-way for infiltration and conveyance (several blocks in length).

Construction date: 2003 to 2004.

Facility depth: 1 to 2.5 feet.

Contributing area: 2.9 to 3.7 acres (34 to 42% TIA) plus 32 acres (34% TIA) east-west streets. North-south street shown in Figure 4.

Sizing: XP-WSM

Flow path: in-line.

Soil:

Native soil (outside excavation area)

- C soils (SCS)

Planting soil mix

- Three different soil mixes are used in the Broadview Green Grid project depending on required infiltration rate, load bearing, and timing of installation.

1. Engineered Soil Mix

The Engineered Soil Mix is used in bioretention swale areas where higher infiltration rates and additional detention is desired. This mix is also used in road shoulder areas adjacent to bioretention/swales and is expected to maintain relatively good infiltration rates at 85% to 90% compaction.

- Design infiltration rate: 2 inches/hour.

Soil mix:

- 65% to 70% gravelly sand and 30% to 35% compost (see specification below).
- Gravelly sand gradation per ASTM D 422:

Sieve size	Percent Passing
2-inch	100
¾-inch	70-100
¼-inch	50-80
US No. 40	15-40
US No. 200	0-3

- The soil mixture should be uniform, free of stones, stumps, roots or other similar objects larger than 2 inches.
- On-site soil mixing or placement not allowed if soil is saturated or subject to water within 48 hours.
- Cover and store soil accordingly to prevent wetting or saturation.
- Test soil for fertility and micronutrients and, if necessary, amend mixture to create optimum conditions for plant establishment and early growth at rates recommended by an independent laboratory soil test.
- Place soil in lifts not exceeding 6 inches.

Comments

This soil specification maintains a higher infiltration rate at typical compaction rates. While the city of Seattle anticipates good performance from this specification, the mix may be slightly less optimum for plant growth than bioretention soil mixes 1 and 2 (see specification below) and has not been tested long-term for plant health performance.

2. Bioretention Soil Mix 1

Bioretention Soil Mix 1 uses on-site excavated soil mixed with compost.

Design infiltration rate: 0.3 to 1.0 inch/hour (varies with properties of native soils).

Soil mix:

- Approximately 65% approved on-site soil and 35% compost material thoroughly mixed.
- Excavated soil for mixing should be free of large woody debris or garbage (concrete or asphalt chunks, old pipe, etc.).
- Collect and test representative samples of excavated soil for gradation.
- Using on-site excavated soil is not appropriate for on-site soils with high clay content. The excavated soil should be sandy loam, loamy sand or loam texture (USDA texture triangle). The excavated soil can be amended with appropriate aggregate (e.g. sand) to achieve the appropriate texture.
- Cover and store soil accordingly to prevent wetting or saturation.
- Test soil for fertility and micronutrients and, if necessary, amend mixture to create optimum conditions for plant establishment and early growth at rates recommended by an independent laboratory soil test.
- Organic content of the soil mixture should be 8% to 12%.

Comments

On-site excavated soil, rather than imported soil, is specified as part of an overall sustainability strategy for Seattle. Using on-site excavated soil for the amended soil mix may reduce control over gradation, organic content, and final product performance, can increase project costs, and can complicate construction logistics when attempting to blend soil mix components in restricted space (personal communication, Tracy Tackett, 2004).

3. Bioretention Soil Mix 2

Bioretention Soil Mix 2 is mixed off-site and delivered ready for installation.

Design infiltration rate: 1 inch/hour.

Soil mix:

- 65% to 70% gravelly sand and 30% to 35% compost (see specification below).
- Gravelly sand gradation per ASTM D 422.

Sieve size	Percent Passing
US No. 4	100
US No. 6	88-100
US No. 8	79-97
US No. 50	11-35
US No. 200	5-15

- Maximum clay content should be less than 5%.
- Soil mixture should be uniform, free of stones, stumps, roots or other similar objects larger than 2 inches.
- On-site soil mixing or placement not allowed if soil is saturated or subjected to water within 48 hours.
- Cover and store soil accordingly to prevent wetting or saturation.
- Test soil for fertility and micronutrients and, if necessary, amend mixture to create optimum conditions for plant establishment and early growth at rates recommended by an independent laboratory soil test.
- Organic content of the soil mixture should be 8% to 12%.

Comments

The city of Seattle uses soil mix 2 during the wet season when maintaining dry native soil for mixing on-site is difficult. Bioretention soil mix 2 is a "vegetable garden mix" supplied by Cedar Grove Composting of Washington.

Compost material (for all 3 soil mixes)

- Material must be in compliance with WAC chapter 173-350 section 220 and meet Type 1, 2, 3 or 4 feedstock.
- See Section 6.2: Amending Construction Site Soils for compost specification.

Pretreatment: none.

Under-drain:

- 6 to 8-inch slotted PVC pipe, solid iron pipe under driveways.
- Under-drains connected to next downstream swale.

Gravel blanket: Seattle type 26 (sand gravel mix, see Section 6.1: Bioretention Areas for specification).

Filter fabric: none.

Mulch: 3-inch depth minimum. Compost used for mulch in bottom of swale and shredded tree trimmings in surrounding areas.

Compaction:

- No heavy equipment allowed in bioretention/swale area during construction.
- No excavation during wet or saturated conditions.
- Soil installed in maximum lifts of 6 inches and foot compacted.

Surface pool dewater: 24 hours.

System dewater: not reported.

Max ponding depth: 12 inches (total live and dead storage).

(Tackett, 2004; personal communication Tracy Tackett, 2004)

5. Sloped Bio*detention*: Austin, Texas

Figure 5 This sloped biodetention facility was a more cost-effective design for an Austin, Texas subdivision than a conventional pond. *Photo courtesy of Murphee Engineering.*

Type of facility: sloped biodetention using grassy vegetative barriers (hedgerows) on contour to detain storm flows and reduce pollutant loads.

Contributing area: not known.

Flow path: in-line.

Planting soil depth: 12-inch deep by 8-inch wide trenches excavated for planting vegetated barriers.

Soil:

Native soil

- C and D soils (SCS) on Karst formations.
- Infiltration rate not reported.

Planting soil:

- Native soil with slow release fertilizer.
- Infiltration rate not reported.

Pretreatment: rock berm used as a level spreader to distribute and release flow across slope and vegetative barriers down slope.

Under-drain: none.

Gravel blanket: not applicable.

Filter fabric: none.

Mulch: none.

Hedge plantings:

- Alamo switchgrass (*Panicum zizanioides*) in 8-inch wide rows on contour.
- Species should be adapted to local soil and climate conditions, easily established, long-lived, as well as have stiff stems that remain erect through the year. Grass species that can emerge through sediment deposits and resume growth from buried stem nodes, rhizomatous or stoloniferous growth habit are desired (Natural Resources Conservation Service, 2001).
- First row receiving discharges is double planted (one row a few inches down slope of the first row) using 4-inch slips on 4-inch centers.
- Planted at 110 stems per square foot.
- Area between hedgerows planted in grass for slope and soil stability and additional filtering.

Spacing: 25 feet between hedgerows (2 to 2.5% slope). Spacing will depend on slope.

Sizing and Hedgerow length:

- 2-year design storm (2.64 inches/3 hours) used for sizing.
- Hedgerows designed to manage 0.2 cfs discharge from contributing area per foot of hedgerow.

(Murphee, Scaief and Whelan, 1997)

Appendix 3

Bioretention Plant List

The following table includes both native and non-native plant species commonly available in the Puget Sound region and suitable for bioretention cells and swales. Individual site characteristics and goals may exclude some species or require modifications or additions to plant suggestions provided here.

Bioretention cells and swales generally feature three planting zones characterized by soil moisture and periodic inundation.

Zone 1: Area of periodic or frequent standing or flowing water. Zone 1 plants will also tolerate the seasonally dry periods of summer in the Pacific Northwest without extra watering and may also be applicable in zone 2 or 3.

Zone 2: Periodically moist or saturated during larger storms. Plants listed under Zone 2 will also be applicable in Zone 3.

Zone 3: Dry soils, infrequently subject to inundation or saturation. This area can be used to transition or blend with the existing landscape.

Special Considerations

Drought tolerance—Several plants included on the list do not tolerate dry conditions. For these plants, irrigation will be necessary during dry periods. In general, all plantings require watering during dry periods for the first two or three years after planting until established.

Placement of large trees—Consider height, spread, and extent of roots at maturity. Use caution in plant selection for areas with under-drain pipes or other structures. Lower limbs of plants placed close to a road or driveway may cause problems with visibility or safety. See Appendix 1: Street Trees for more information on tree selection and placement suggestions.

Phytoremediation—Appendix 5 includes a list of plants that have been studied for their ability to filter, absorb, and/or degrade specific contaminants. While most of these plants are not included in the following lists, varieties of some of the species known for phytoremediation are listed.

▶ ZONE 1

* denotes native species

TREES

Species/ Common Name	Exposure	Mature Size/ Spread	Time of Bloom	Comments
*Alnus rubra** Red alder	Sun/partial shade	30-120 feet/ 25 ft. spread		Prefers moist, rich soils, highly adaptable, drought tolerant; nitrogen fixer; rapid growing, relatively short-lived (60-90 years)
*Fraxinus latifolia** Oregon ash	Sun/partial shade	40-80 feet/ 30 ft. spread		Moist, saturated or ponded soils; flood tolerant; small green-white flowers
*Malus fusca** Pacific crabapple	Sun/partial shade	To 40 feet/ 35 ft. spread	Spring	Tolerant of prolonged soil saturation; produces fruit (do not plant near public walkways)
*Salix lucida** Pacific willow	Sun	40-60 feet/ 30 ft. spread		Wet soils; tolerates seasonal flooding; should not be planted in areas near pavement or underground structures

SHRUBS

Species/ Common Name	Exposure	Mature Size	Time of Bloom	Comments
*Cornus sericea** Red-osier dogwood Red-twig dogwood	Sun/partial shade	To 15 feet	May - June	Prefers wet to moist organically rich soils, but is adaptable; tolerates seasonal flooding; small white flowers; berrylike fruits
Cornus sericea 'Kelseyi' Dwarf dogwood	Sun	To 1.5 feet	June – August	Prefers wet to moist organically rich soils, but is adaptable; small white flowers; berrylike fruit; low growing, compact form; good ground cover
Cornus sericea 'Flaviramea' Yellow dogwood	Sun/partial shade	6-8 feet	May - June	Prefers wet to moist organically rich soils, but is adaptable; easily transplanted and grown; small, white flowers; yellow stems and reddish, purple fall color
Cornus sericea 'Isanti' Isanti dogwood	Sun/partial shade	4-5 feet	May - June	Prefers wet to moist organically rich soils, but is adaptable; deciduous shrub; tiny white flowers; red stems; purple fall color
*Lonicera involucrata** Black twinberry	Partial shade/shade	2-8 feet	April - May	Moist soils; prefers loamy soils; tolerant of shallow flooding; yellow, tubular flowers attract hummingbirds
*Myrica californica** Pacific wax myrtle	Sun/partial shade	To 30 feet	May - June	Evergreen shrub preferring moist soils; inconspicuous spring flowers; drought tolerant; if drought tolerance is not an issue try the smaller Washington native, *Myrica gale**
*Physocarpus capitatus** Pacific ninebark	Sun/partial shade	6-13 feet	May - June	Moist or dry soils; drought tolerant; snowball shaped; white flowers; seeds persist into winter
*Rosa pisocarpa** Clustered wild rose	Sun/partial shade	6-8 feet	May - July	Moist soils, tolerates seasonal flooding but also tolerant of dry conditions; pink clustered flowers; fruits persist
Salix purpunea 'Nana' Dwarf Arctic willow	Sun/partial shade	3-5 feet		Grows well in poor soils; moderately drought tolerant; small yellow flowers in the fall
*Spiraea douglasii** Douglas spirea Steeplebush	Sun/partial shade	4-7 feet		Moist or dry, to seasonally inundated soils; spikes of small, pink flower clusters

▶ ZONE 1

EMERGENTS

Species/ Common Name	Exposure	Mature Size	Time of Bloom	Comments
*Carex obnupta** Slough sedge	Sun/partial shade	1-5 feet		Moist to seasonally saturated soils; shiny foliage; excellent soil binder; drought tolerant
*Carex stipata** Sawbeak sedge	Partial shade	10 inches-3 feet		Wet soils; excellent soil binder
*Juncus effusus** Common rush	Sun/partial shade	1-2 feet	Summer	Wet soils; evergreen perennial; hardy and adaptable; drought tolerant; small, non-showy flowers
*Juncus ensifolius** Daggerleaf rush	Sun	12-18 inches		Wet soils; shallow water; excellent soil binder
*Juncus tenuis** Slender rush	Sun	.5–2.5 feet		Moist soils; tufted perennial
*Scirpus acutus** Hardstem bulrush	Sun	4-8 feet		Wet soils; favors prolonged inundation; excellent soil binder
*Scirpus microcarpus** Small-fruited bulrush	Sun/shade	2-4 feet		Wet soils; tolerates prolonged inundation; good soil binder; drought tolerant

▶ ZONE 2

TREES

Species/ Common Name	Exposure	Mature Size	Time of Bloom	Comments
Acer truncatum Pacific sunset maple	Sun	To 25 feet/ 20 ft. spread		Prefers moist, well-drained soils, but drought tolerant; very cold hardy; deciduous tree with moderate growth rate
*Amelanchier alnifolia** Western serviceberry	Sun/partial shade	10-20 feet/ 25 ft. spread	April - May	Moist to dry, well-drained soils; drought tolerant; large white flowers; purple to black berries; deciduous
*Corylus cornuta** Beaked hazelnut	Sun/partial shade	20–30 feet/ 15 ft. spread	April - May	Moist, well-drained soils; edible nuts; intolerant of saturated soils; catkins throughout winter add interest; deciduous
*Crataegus douglasii** Black hawthorn	Sun/partial shade	3-30 feet/ 25 ft. spread	Spring	Moist to dry, well drained, gravelly soils; small white flowers, black berries; 1" spines; forms thickets; deciduous
Fraxinus oxycarpa Raywood ash	Sun	25-50 feet/ 25 ft. spread	Spring	Drought tolerant; grows in varying soil types; deciduous; can take extreme temperatures; does not tolerate constant wind or fog; resists pests and disease better than other non-native ashes; inconspicuous flowers
*Rhamnus purshiana** Cascara sagrada	Sun/shade	20-40 feet/ 25 ft. spread		Moist to fairly dry soils; small greenish-yellow flowers; deciduous; sensitive to air pollution; yellow fall color
*Salix scouleriana** Scouler willow	Sun/partial shade	6-40 feet/ 15 ft. spread		Moist to dry soils; drought tolerant; deciduous tree; do not plant near paved surfaces or underground structures
*Salix sitchensis** Sitka willow	Sun/partial shade	3-26 feet/ 25 ft. spread		Moist soils; tolerates seasonal flooding; deciduous tree; do not plant near paved surfaces or underground structures
*Thuja plicata** Western red cedar	Partial shade/shade	200 feet+/ 60 ft. spread		Moist to swampy soils; tolerates seasonal flooding and saturated soils; long-lived; prefers shade while young

▶ ZONE 2

SHRUBS - Deciduous

Species/ Common Name	Exposure	Mature Size	Time of Bloom	Comments
*Acer circinatum** Vine maple	Filtered sun/shade	To 25 feet	Spring	Dry to moist soils; tolerant of shade and clay soils; excellent soil binder; beautiful fall color
Hamamelis intermedia Diane Diane witchhazel	Sun/partial shade	10-20 feet/ 10 ft. spread	January - March	Moist, fertile, acidic soil; showy fall color – yellow to yellow-orange; long-lasting, slightly fragrant, coppery-red flowers; not drought tolerant; may require watering in dry season
*Oemleria cerasiformis** Indian plum/Osoberry	Sun/partial shade	5-16 feet	February - March	Moist to dry soils; prefers shade; tolerates fluctuating water table
Philadelphus x lemoinei 'Belle Etoile' Mock-orange	Sun/partial shade	5-6 feet	May - June	Prefers moist, well-drained soils, high in organic matter, but soil and pH adaptable; easily transplanted and established; fragrant, large white flowers, tinged red at the base; other cultivars available
*Ribes lacustre** Black swamp gooseberry	Partial shade	1.5–3 feet		Moist soils; deciduous shrub; reddish flowers in drooping clusters; dark purple berries; *R. divaricatum** (Wild gooseberry) grows to 5 feet and is also an option; attracts butterflies, but is very thorny
*Rosa nutkana** Nootka rose	Sun/partial shade	6-10 feet	April - June	Moist to fairly dry soils; tolerates inundation and saturated soils; aggressive spreader; fruits persist; less thorny that *R. rugosa*
Rosa rugosa Rugosa rose	Sun	To 8 feet		Drought resistant; hardy, vigorous and aggressive; highly prickly; fragrant white to purple flowers; fruits persist
*Rubus parviflorus** Thimbleberry	Sun/partial shade	4-10 feet	May - June	Moist to dry soils; white flowers; red berries; makes thickets and spreads easily
*Rubus spectabilis** Salmonberry	Partial sun/shade	5-10 feet	February - April	Prefers moist, wet soils; good soil binder; magenta flowers; yellow/ orange fruit; early nectar source for hummingbirds; makes thickets
*Sambucus racemosa** Red elderberry	Partial sun/partial shade	To 20 feet	April - May	Moist to dry soils; small white flowers; bright red berries; vase shaped; pithy stems lead to "messy" form – prune for tidiness
*Symphoricarpos albus** Snowberry	Sun/shade	2-6 feet		Wet to dry soils, clay to sand; excellent soil binder; drought and urban air tolerant; provides good erosion control; spreads well in sun; white berries; flowers attract hummingbirds
*Vaccinium parvifolium** Red huckleberry	Partial shade/shade	4-10 feet		Slightly moist to dry soils; prefers loamy, acid soils or rotting wood; tolerant of dry, shaded conditions; red fruit; tricky to transplant

▶ ZONE 2

HERBACEOUS

Species/ Common Name	Exposure	Mature Size	Time of Bloom	Comments
*Aquilegia formosa** Western columbine	Sun/partial shade	1-3 feet	Spring	Moist soils of varying quality; tolerant of seasonal flooding; red and yellow flowers attract hummingbirds and butterflies
*Asarum caudatum** Wild ginger	Partial shade/shade	To 10 inches	Mid spring	Moist organic soils; heart-shaped leaves; reddish-brown flowers
*Aster chilensis** Common California aster	Sun	1.5 – 3 feet	June - September	Moist soils; white to purple flowers
*Aster subspicatus** Douglas aster	Sun	.5 – 2.5 feet	June - September	Moist soils; blue to purple flowers
*Camassia quamash** Common camas	Sun/partial shade	To 2.5 feet	May - June	Moist to dry soils; lots of watering needed to establish; loose clusters of deep blue flowers
Camassia leichtlinii Giant camas		2–4 feet	May - June	Moist to dry soils; lots of watering to establish; large clusters of white, blue or greenish-yellow flowers
*Iris douglasiana** Pacific coast iris	Sun/partial shade	1-2 feet	Spring	Tolerates many soils; withstands summer drought and seasonal flooding; white, yellow, blue, reddish purple flowers; fast growing; velvety purple flowers; vigorous
Iris foetidissima Gladwin iris	Sun/partial shade	1-2 feet	May	Moist to dry, well-drained soils; pale lilac flower; also called Stinking Iris
*Juncus tenuis** Slender rush	Sun	6 inches – 2.5 feet		Moist soils; yellow flowers
Iris sibirca Siberian Iris	Sun	1-2.5 feet	Late spring – early summer	Moist soils; deep blue, purple to white flowers
*Tellima grandiflora** Fringecup	Partial sun/shade	1-3 feet	March - June	Perennial preferring moist soils; yellowish-green to pink flowers
*Tiarella trifoliata** Foamflower	Partial sun/shade	To 1 foot	Early - mid summer	Moist soils; perennial with some drought tolerance after established; can form dense colonies; white flowers
*Tolmiea menziesii** Youth-on-age/Piggy-back plant	Partial shade/shade	1-2 feet	April - August	Moist soils; brownish-purple flowers; also makes and effective groundcover
Viola species* Violets	Partial shade/shade	6-12 inches	Late spring – early summer	Moist soils; yellow to blue flowers

▶ ZONE 3

TREES

Species/ Common Name	Exposure	Mature Size	Time of Bloom	Comments
Arbutus unedo Strawberry tree	Sun/partial shade	8-35 feet/ 8-20 ft. spread	November - December	Tolerant of extremes; tolerant of urban/ industrial pollution; white or greenish white flowers
*Calocedrus decurrens** Incense cedar	Sun	75-90 feet/ 12 ft. spread		Tolerant of poor soils; drought tolerant after established; fragrant evergreen with a narrow growth habit; slow growing
Chamaecyparis obtusa Hinoki false cypress	Sun/partial shade	40-50 feet/ 15-30 ft. spread		Moist, loamy, well-drained soils; very slow growing; prefers sun, but tolerates shade; does not transplant well or do well in alkaline soils. Note there are many alternative varieties of false cypress of varying sizes and forms from which to choose
Cornus spp. Dogwood	Sun/partial shade	20-30 feet/ 30 ft. spread	May	Reliable flowering trees with attractive foliage and flowers; may need watering in dry season; try *C. florida* (Eastern dogwood), or *C. nuttallii** (Pacific dogwood) or hybrid 'Eddie's White Wonder'. Also, *C. kousa* for small tree/ shrub which is resistant to anthracnose
Pinus mugo Swiss mountain pine	Sun/partial shade	15-20 feet/ 25-30 ft. spread		Prefers well-drained soil; slow growing, broadly spreading, bushy tree; hardy evergreen
Pinus thunbergiana Japanese black pine	Sun	To 100 feet/ 40 ft. spread		Dry to moist soils; hardy; fast growing
*Prunus emarginata** Bitter cherry	Sun/partial shade	20-50 feet/ 20 ft. spread	May - June	Dry or moist soils; intolerant of full shade; bright red cherries are attractive to birds; roots spread extensively
Prunus virginiana Choke cherry		15-25 feet/ 15-20 ft. spread	Late spring – Early summer	Dry or moist soils; deep rooting; attractive white fragrant flowers; good fall color
*Pseudotsuga menziesii** Douglas-fir	Sun	100-250 feet/ 50-60 ft. spread		Does best in deep, moist soils; evergreen conifer with medium to fast rate of growth; provides a nice canopy, but potential height will restrict placement
*Quercus garryana** Oregon white oak	Sun	To 75 feet		Dry to moist, well-drained soils; slow growing; acorns

SHRUBS

Species/ Common Name	Exposure	Mature Size	Time of Bloom	Comments
*Holodiscus discolor** Oceanspray	Sun/partial shade	To 15 feet	June - July	Dry to moist soils; drought tolerant; white to cream flowers; good soil binder
*Mahonia aquifolium** Tall Oregon grape	Sun/partial shade	6-10 feet	March - April	Dry to moist soils; drought resistant; evergreen; blue-black fruit; bright yellow flowers; 'Compacta' form averages 2 feet tall; great low screening barrier
*Philadelphus lewisii** Mock-orange	Sun/partial shade	5-10 feet	June - July	Adapts to rich moist soils or dry rocky soils; drought tolerant; fragrant flowers

▶ ZONE 3

SHRUBS **Species/ Common Name**	**Exposure**	**Mature Size**	**Time of Bloom**	**Comments**
Pinus mugo pumilio Mugho pine	Sun	3-5 feet/ 4-6 ft. spread		Adapts to most soils; slow growing and very hardy; newer additions with trademark names such as 'Slo-Grow' or 'Lo-Mound' are also available
Potentilla fruticosa Shrubby cinquefoil	Sun	To 4 feet	May - September	Moist to dry soils; several cultivars available with varying foliage and flower hues; try 'Tangerine' or 'Moonlight'
*Ribes sanguineum** Red-flowering currant	Sun/partial shade	8-12 feet	March - April	Prefers dry soils; drought tolerant; white to deep-red flowers attract hummingbirds; dark-blue to black berries; thornless
*Rosa gymnocarpa** Baldhip rose	Partial shade	To 6 feet	May - July	Dry or moist soils; drought tolerant; small pink to rose flowers

SHRUBS-Evergreen **Species/ Common Name**	**Exposure**	**Mature Size**	**Time of Bloom**	**Comments**
Abelia x grandiflora Glossy abelia	Partial Sun/Partial shade	To 8 feet/ 5 foot spread	Summer	Prefers moist, well-drained soils, but drought tolerant; white or faintly pink flowers
Arbutus unedo 'Compacta' Compact strawberry tree	Sun/partial shade	To 10 feet	Fall	Prefers well drained soils; tolerant of poor soils; good in climate extremes; white to greenish-white flowers; striking red-orange fruit
Cistus purpureus Orchid rockrose	Sun	To 4 feet	June - July	Moist to dry well-drained soils; drought resistant; fast growing; reddish purple flowers
Cistus salvifolius White rockrose	Sun	2-3 feet/ 6 ft spread	Late spring	Moist to dry well-drained soils preferred, but can tolerate poor soils; tolerant of windy conditions and drought; white flowers
Escallonia x exoniensis 'fradesii' Pink Princess	Sun/partial sun	5-6 feet	Spring - Fall	Tolerant of varying soils; drought tolerant when established; pink to rose colored flowers; good hedge or border plant; attracts butterflies
Osmanthus delavayi Delavay Osmanthus	Sun/partial shade	4-6 feet	March - May	Tolerant of a broad range of soils; attractive foliage and clusters of white fragrant flowers; slow growing
Osmanthus x burkwoodii Devil wood	Sun/partial shade	4-6 feet	March - April	Drought tolerant once established; masses of small, white fragrant flowers
Rhododendron 'PJM' hybrids	Sun/partial shade	To 4 feet	Mid – late April	Moist to fairly dry soils; well drained organic soil; lavender to pink flowers
Stranvaesia davidiana	Sun	6-20 feet	June	Moist soils; white flowers in clusters; showy red berries
Stranvaesia davidiana undulata	Sun	To 5 feet	June	Moist soils; lower growing irregularly shaped shrub; great screening plant
*Vaccinium ovatum** Evergreen huckleberry	Partial shade/ shade	3-15 feet	March	Moist to slightly dry soils; small pinkish-white flowers; berries in August

▶ ZONE 3

GROUNDCOVER - Evergreen

Species/ Common Name	Exposure	Mature Size	Time of Bloom	Comments
*Arctostaphylos uva-ursi** Kinnikinnik	Sun/partial shade		April - June	Prefers sandy/rocky, well-drained soils; flowers pinkish-white; bright red berries; slow to establish; plant closely for good results
*Gaultheria shallon** Salal	Partial shade/ shade	3-7 feet	March - June	Dry and moist soils; white or pinkish flowers; reddish-blue to dark-purple fruit
*Fragaria chiloensis** Wild/Coastal strawberry	Sun/partial shade	10 inches	Spring	Sandy well drained soils; flowers white; small hairy strawberries; evergreen; aggressive spreader
Helianthemum nummularium Sunrose	Sun	To 2 feet/ 2 ft. spread	May - July	Prefers well-drained soils, but will tolerate various soils; low-growing, woody sub shrub; many varieties are available with flowers in salmon, pink, red, yellow and golden colors
Lavandula angustifolia Lavender	Sun/partial shade	To 1.5 feet	June - August	Adaptable to various soils; blue, lavender, pink to white flowers, semi-evergreen aromatic perennial
*Mahonia nervosa** Cascade Oregon grape/Dull Oregon grape	Partial shade/ shade	To 2 feet	April – June	Dry to moist soils; drought resistant; evergreen; yellow flowers; blue berries
Mahonia repens Creeping mahonia	Sun/partial shade	3 feet	April - June	Dry to moist soils; drought resistant; yellow flowers; blue berries; native of Eastern Washington
*Penstemon davidsonii** Davidson's penstemon	Sun	To 3 inches	June - August	Low growing evergreen perennial; prefers well-drained soils; drought tolerant; blue to purple flowers

PERENNIALS & ORNAMENTAL GRASSES

Species/ Common Name	Exposure	Mature Size	Time of Bloom	Comments
*Achillea millefolium** Western yarrow	Sun	4 inches – 2.5 feet	June - September	Dry to moist, well-drained soils; white to pink/reddish flowers; many other yarrows are also available
Anaphalis margaritaceae Pearly everlasting	Sun/partial shade	To 18 inches		Drought tolerant perennial; spreads quickly; attracts butterflies
*Bromus carinatus** Native California brome	Sun/partial shade	3-5 feet		Dry to moist soils; tolerates seasonal saturation
Carex buchannii Leather leaf sedge	Sun/partial shade	1-3 feet		Prefers well-drained soils; copper-colored foliage; perennial clumping grass; tolerant of a wide range of soils; inconspicuous flowers
Carex comans 'Frosty curls' New Zealand hair sedge	Sun/partial shade	1-2 feet	June - August	Prefers moist soils; finely textured and light green; compact, clumping perennial grass; drought tolerant when established; inconspicuous flowers

PERENNIALS & ORNAMENTAL GRASSES

Species/ Common Name	Exposure	Mature Size	Time of Bloom	Comments
Coreopsis spp.	Sun	1-3 feet		Dry to moist soils; drought tolerant; seeds attract birds; annual and perennial varieties; excellent cut flowers
Echinacea purpurea Purple coneflower	Sun	4-5 feet		Prefers well drained soils; hardy perennial; may need occasional watering in dry months
*Elymus glaucus** Blue wildrye	Sun/partial shade	1.5-5 feet		Dry to moist soils; shade tolerant; rapid developing, but short lived (1-3 years); not good lawn grass
*Dicentra formosa** Pacific bleeding-heart	Sun/shade	6-20 inches	Early spring - early summer	Moist, rich soils; heart-shaped flowers
*Erigeron speciosus** Showy fleabane	Sun/partial shade	To 2 feet	Summer	Moist to dry soils; dark violet or lavender blooms; fibrous roots
Festuca ovina 'Glauca' Blue fescue	Sun/partial shade	To 10 inches	May - June	Prefers moist, well-drained soils; blue-green evergreen grass; drought tolerant; shearing will stimulate new growth
*Festuca idahoensis** Idaho fescue	Sun/partial shade	To 1 foot		Bluish-green bunching perennial grass; drought tolerant
*Fragaria vesca** Wood strawberry	Partial shade	To 10 inches	Late spring - early summer	Dry to moist soils; white flowers
Gaura lindheimeri Gaura	Sun	2.5-4 feet		Perennial; fairly drought tolerant and adaptable to varying soil types; long blooming period
*Geum macrophyllum** Large-leaved avens	Sun/partial shade	To 3 feet	Spring	Moist, well-drained soil; bright yellow flowers; other *Geum* cultivars available, some which may require supplemental watering
Geranium maculatum Spotted geranium	Sun/shade	To 1.5 feet	July	Moist, well-drained soils; low perennial; pale pink, blue to purple flowers
Geranium sanguineum Cranesbill	Sun/partial shade	To 1.5 feet	May - August	Moist soils; deep purple almost crimson flowers
Helichrysum italicum Curry Plant	Sun	To 2 feet	Summer	Moist or dry soils; hardy evergreen perennial; a good companion to lavender; bright yellow flowers; fragrant
Helictotrichon sempervirens Blue oat grass	Sun/partial shade	1-1.5 feet	June - August	Tolerant of a variety of soil types but prefers well-drained soil; clumping bright blue evergreen grass; bluish white flowers
Hemerocallis fulva Day lilies	Sun/partial shade	1-4 feet	Summer	Tolerant of a variety of soil types; easy to grow and tolerant of neglect; hardy perennial; entire plant is edible
Heuchera americana Coral bells (alumroot)	Sun/partial shade	1-2 feet	June - August	Moist to dry, well-drained soils; never wet; easily transplantable perennial; red, greenish-white flowers; may need supplemental watering in dry season
Heuchera micrantha 'Palace purple' (alumroot)	Sun/partial shade	1-2 feet	June - August	Moist, well-drained soils; bronze to purple foliage in shade; small, yellowish-white flowers; perennial, evergreen; a number of other species and varieties are available. Try *H. sanguinea* for bright red flowers
Lupinus spp.* Lupines	Sun	3-5 feet	March - September	Moist to dry soils; various native varieties; blue to purple, violet to white flowers; both native and non-native varieties

PERENNIALS & ORNAMENTAL GRASSES

Species/ Common Name	Exposure	Mature Size	Time of Bloom	Comments
*Lupinus bicolor** Two-color lupine	Sun	4 inches- 1.5 feet	Spring	Dry gravelly soils; small-flowered; annual
*Lupinus latifolius** Broadleaf lupine	Sun	To 1 foot	June - August	Dry to moist soils; perennial; bushy herb; bluish flowers
*Lupinus polyphyllus** Large-leafed lupine	Sun	To 3 feet	Spring - summer	Dry to moist, sandy to gravelly soils; perennial
*Maianthemum dilatatum** False lily-of-the-valley	Partial shade/ shade	3-12 inches	Spring	Prefers moist soils; small, white flowers; light-green to red berries
Pennisetum alopecuroides Fountain grass	Sun/partial shade	1-2 feet	August - September	Moist, well-drained soils; tolerant of many soil types; clump-forming grasses. A number of varieties are available in different heights and bloom times. Try *P. caudatum* (White-flowering fountain grass) and *P. alopecuroides* cultivars 'Hameln' and 'Little Bunny' (Dwarf fountain grass)
Pennisetum orientale Oriental fountain grass	Sun/partial shade	1-3 feet	June - October	Prefers moist, well-drained soils; somewhat drought tolerant; small clumping, blooming grass, showy pink flowers; fountain grasses will benefit from annual shearing in late winter/early spring, but not required
Penstemon fruticosus Shrubby penstemon	Sun	8–10 inches	May	Prefers well-drained soils; evergreen perennial; drought tolerant; violet-blue flowers 1" long attract hummingbirds
*Polystichum munitum** Swordfern	Partial shade/ Deep shade	2-4 feet		Prefers moist, rich soil conditions, but drought tolerant; large evergreen fern
*Potentilla gracilis** Graceful cinquefoil	Sun	1-2 feet	July	Moist to dry soils; yellow flowers
Rudbeckia hirta Black-eyed susan	Sun/partial shade	3-4 feet	Summer	Moist to dry soils; showy flowers, hardy and easy to grow; several other varieties are available
*Smilacina racemosa** False Solomon's seal	Partial sun/shade	1-3 feet	April - May	Moist soils; creamy white flowers; red berries
*Solidago canadensis** Canadian goldenrod	Sun/partial shade	1-2 feet	Late summer - early fall	Dry to moist soils; yellow flowers

Bog Garden Plants

A bog garden presents a unique design option for managing stormwater on site. A lined depression filled with an organic soil mix and wetland vegetation can be an attractive method for promoting evaporation and transpiration of collected runoff. A functioning bog garden generally displays no standing water, but soils are saturated much of the time, necessitating facultative wetland plant selections.

To select plant species appropriate for a bog garden refer to those listed in this appendix, **Zone 1**, as well as those found in the following table. The list below includes additional native and non-native plant species (not listed in the bioretention plant list) that have been successfully applied in Pacific Northwest bog gardens. It may be necessary to provide additional water to the bog system during seasonal dry periods due to a lack of stormwater runoff.

As with any system, plant species in a bog garden setting have various preferences for moisture and sun. Check listed comments below and research plant needs to optimize growth in the conditions specific to individual bog garden systems.

Bog Garden

Species/ Common Name	Exposure	Mature Size	Time of Bloom	Comments
*Adiantum aleuticum** Western maidenhair fern	Shade/partial shade	1-2 feet		Moist to wet soils; graceful, delicate fern; vivid bright green with black stems; spreads through creeping rhizomes; often called *A. pedatum*, but this refers to the related East Coast maidenhair fern; also try *A. capillis-veneris* (Venus-hair fern)
*Andromeda polifolia** Bog rosemary	Sun/partial shade	1-1.5 feet	Spring	Moist to wet soils; low-growing evergreen shrub; white to pink flower clusters; ornamental varieties include 'Blue Ice', 'Grandiflora' and 'Nana'
*Blechnum spicant** Deer fern	Shade/partial shade	1-3 feet		Moist to wet soils; has both evergreen and deciduous leaves; prefers soils high in organic material; is sensitive to frost
Carex spp. Sedges	Sun/shade	varies		A number sedge choices are great options for a bog garden setting; two are listed in Zone 1 of this appendix, but there are many alternative species to investigate, including *Carex mertensii** (Mertens' sedge) and *C. lyngbyei** (Lyngby's sedge)
*Eleocharis palustris** Creeping spike-rush	Sun	To 3.5 feet		Wet soils to shallow water; perennial forming small clumps
*Empetrum nigrum** Crowberry	Sun	To 8 inches	Early spring	Dry to wet/boggy soils; low-growing evergreen shrub; small purplish flowers and purplish-black berries
*Equisetum hyemale** Scouring-rush	Sun/partial shade	2-5 feet		Moist to wet soils; hollow-stemmed, evergreen perennial; spreads through creeping rhizomes; vigorous and persistent; with high silica content; also *E. scirpoides* (Dwarf horsetail); use both with caution – *Equisetum* can be very invasive and difficult to remove once established
*Gaultheria ovatifolia** Oregon wintergreen/ Western teaberry	Partial shade	To 1 foot	Late spring - summer	Moist to wet soils; low-growing evergreen shrub; pink or whitish flowers and red berries; also *G. humifusa** (Alpine wintergreen)
*Glyceria elata** Tall mannagrass	Sun/partial shade	3-4.5 feet		Moist to wet soils; loosely tufted perennial, spreads through creeping rhizomes; also try the taller *G. grandis** (Reed mannagrass)

Bog Garden

Species/ Common Name	Exposure	Mature Size	Time of Bloom	Comments
Gunnera manicata Gunnera	Sun/partial shade	4-6 feet/ 4-8 ft. spread		Moist to wet organic soils; prefers humid setting; non-native from Brazil and Columbia needing mulching protection in the winter; also referred to as 'giant rhubarb'; huge rounded leaves; needs plenty of space; also *G. tinctoria* from Chile
Hakonechloa macra Japanese forest grass	Shade/partial shade	1-3 feet		Prefers moist, rich soil; slowly spreading perennial grass; green leaves turn coppery orange in the fall
Hosta Plantain lily	Shade/partial sun	To 2.5 feet	Summer	Prefer moist, rich soil; many varieties and hybrids available in a various sizes, foliage textures and colors; thin spikes of blue or white flowers; some are tolerant of sun, but most prefer shade
Juncus spp. Rushes	Sun/shade	varies		As with the *Carex* species, there are a number of native rushes that would work well in a bog garden. Three options are listed in Zone 1 of this appendix. Others to investigate include *Juncus mertensianus** (Mertens' rush) and *J. acuminatus** (Tapered rush)
*Kalmia occidentalis** Swamp-laurel	Sun	.5-2 feet	Spring - early summer	Also known as *K. polifolia,* prefers moist soils; low shrub with aromatic leaves; rose-purple flowers; also try *K. microphylla** (Western bog-laurel) a mat-forming, evergreen shrublet; generally found in wet subalpine conditions
*Ledum groenlandicum** Labrador tea	Shade/partial sun	1.5–4.5 feet	Summer	Moist to boggy soils; evergreen shrub with small white flower clusters; foliage aromatic when crushed
Ligularia dentata Bigleaf ligularia	Shade/partial shade	3–5 feet	Summer	Moist to wet soils; large-leaved, clumping perennial; yellow-orange blooms; not tolerant of high heat or low humidity; try *L. dentata* cultivars 'Othello' and 'Desdemona'; also *L. przewalskii* (Shavalski's ligularia) and *L. stenocephala* (Narrow-spiked ligularia)
*Linnaea borealis** Twinflower	Shade/partial shade	4-6 inches	June - September	Moist or dry soils; evergreen perennial; pink, fragrant, trumpet-like flowers; trailing ground cover; try *L. borealis* on the less saturated margins of a bog garden; may be difficult to establish
Lobelia cardinalis Cardinal flower	Sun/partial shade	2-4 feet	Summer	Wet to moist, rich soils; clumping perennial; tubular, bright red, inch-long flowers; also try *L. siphilitica* (Blue lobelia), another perennial with blue flowers
*Lysichiton americanum** Skunk cabbage	Shade/partial shade	2-3 feet	March	Prefers wet soils; deciduous perennial; has odor that some consider to be skunky especially when blooming; yellow hooded fleshy flower spike; great leaves dominate
Matteuccia struthiopteris Ostrich fern	Sun/shade	To 6 feet		Moist, rich soils; hardy northern fern; clumping narrowly at base with foliage spreading to 3 feet in width
Mimulus spp. Monkey-flower	Sun/partial shade	1-3 feet	Spring- summer	Wet soils; perennial or annual that reseeds nicely and keeps spreading; many species available including natives, *M. guttatus** (Yellow monkey-flower) and *M. tilingii** (Mountain monkey-flower); also *M. lewisii** with rose-red to pale-pink flowers

Bog Garden Species/ Common Name	Exposure	Mature Size	Time of Bloom	Comments
*Myrica gale** Sweet gale	Sun/partial shade	To 4 feet		Moist to wet soils; aromatic, deciduous perennial shrub; glossy green leaves; a nitrogen fixing species
Oplopanax horridum Devil's club	Shade/partial sun	3-10 feet		Moist to wet soils; forms extensive clumps; aggressive grower, but huge palmate leaves highly decorative; clusters of small whitish flowers; wand-like stems have sharp spines
Osmunda cinnamomea Cinnamon fern	Sun/partial shade	2-5 feet		Moist to wet soils; large deciduous fern; unfolding 'fiddlehead' fronds are edible
*Oxycoccus oxycoccos** Bog cranberry	Sun	4-16 inches		Moist to wet soils, prefers *Sphagnum* moss mats, peat and acidic conditions; evergreen, low-creeping vine-like shrub; pink to red flowers; red berries; shade intolerant
*Polystichum munitum** Sword fern	Shade/partial shade	2-5 feet		Moist soils; large evergreen fern; dark green fronds with dagger shaped leaflets; hardy and easy to grow
*Potentilla palustris** Marsh cinquefoil		To 3 feet		Moist to wet soils; perennial with reddish-purple flowers; stems both prostrate and ascending
*Ribes divaricatum** Wild gooseberry	Partial shade/shade	1.5-6.5 feet		Prefers wet or moist soils; green or purple flowers and smooth, dark purple berries; a hedge or screen provides good habitat for birds and wildlife; beware prickly spines; also try *R. lacustre** (Black gooseberry)
*Salix arctica** Arctic willow	Sun/shade	To 2 feet	Spring	Moist soils; deciduous, prostrate or trailing shrub; leaves are dark green on the bottom and lighter on top; brownish to pink flowers; see Zone 1 of this appendix for details on *S. purpurea* 'Nana'
*Trientalis arctica** Northern starflower	Shade/partial shade	To 8 inches		Wet, boggy soils; small perennial; star-shaped white flowers, or with a pink tinge

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Appendix 4 Bioretention Cell and Bioretention Swale Research: Flow Control and Pollutant Removal Capability

REFERENCE	STUDY SETTING	SUMMARY	FINDINGS	COMMENTS
Davis, A.P., Shokouhian, M., Sharma, H., & Minami, C. (2001 January/February). Laboratory study of biological retention for urban stormwater management. *Water Environment Research, 73,* 5-14.	Laboratory	Two laboratory-scale bioretention boxes were constructed with perforated pipes at 2 different depths to collect effluent. Synthetic stormwater runoff was applied at specific flow rates and durations, and pollutant removal assessed. Soil composition: sandy loam (pH 6.4, CEC 2.9 meq/100 g soil, organic matter content 0.6%) with shredded hardwood bark mulch topcoat. Boxes included creeping juniper plantings.	Pollutant removal: • Copper: 89 to 98%. • Lead and Zinc: > 97 to 98% (lower ports below detectable limits). • Ammonium: -8 to 54% upper ports, 60 to 79% lower ports. • Nitrate: -96% upper port, 24% lower port, (large box only). • Phosphorous: 16 to 73% upper and mid ports, 71 to 81% lower ports.	• High metal removal in upper layers of large and small box. Removal did not increase much with depth. • Significant metal accumulation found in mulch layer samples. • Nutrient removal more variable than metals. Removal increased with depth. • 98 effluent samples taken from upper and lower pipes in the small box and 80 samples from the large box.
Davis, A..P., Shokouhian, M., Sharma, H., Minami, C., & Winogradoff, D. (2003 January/February). Water quality improvement through bioretention: Lead, copper, and zinc removal. *Water Environment Research, 75,* 73-82.	Laboratory and field	Two laboratory-scale bioretention boxes were constructed with perforated pipes at 2 different depths to collect effluent. Synthetic stormwater runoff was applied at varying flow rates, flow durations, metal concentrations, and pH to assess pollutant removal. Soil composition: sandy loam topped with 2.5 cm of mulch. Boxes included creeping juniper plantings. Additionally, synthetic stormwater runoff was applied and effluent measured at 2 field sites with bioretention facilities.	Pollutant removal: Lab • Copper: 87% to 98%. • Lead: 92% to 98%. • Zinc: 85% to 98%. Field Greenbelt facility: • Copper: 97%, lead: 95%, zinc: 95%. Largo facility: • Copper: 43%, lead: 70%, zinc: 64% cadmium: 27%, total phosphorous: 87%, TKN: 67%, nitrate: 15%.	Lab: • Removal for metals was excellent and similar to initial study (see above). • Removal at upper ports was affected slightly by flow rate and duration. • Removal at lower ports was not affected by flow rate and duration. • Removal at upper ports was affected slightly by pH and concentration. • Removal at lower ports was not affected by flow, pH and concentration (soil likely buffering pH changes). Field: • Greenbelt facility showed good agreement with lab analysis. • Largo removal was significantly lower and speculatively attributed to Greenbelt being an older facility with mature groundcover and having a higher fraction of fines in the soil.

REFERENCE	STUDY SETTING	SUMMARY	FINDINGS	COMMENTS
Kim, H., Seagren, E.A., & Davis, A.P. (2003, July/August). Engineered bioretention for removal of nitrate from stormwater runoff. *Water Environment Research, 75*, pp. 355-367.	Laboratory	A laboratory pilot-scale bioretention cell engineered with an anoxic zone at bottom of cell was constructed to assess nitrate removal potential (this phase was part of a larger nitrate removal study). A sand layer mixed with newspaper (electron donor for denitrification process) was placed at bottom of cell and used as a saturated anoxic zone. Synthetic stormwater was applied to the cell and effluent collected after passing through sand layer.	Pollutant removal: • First 2-3 hours no nitrate or nitrite observed in effluent during applications at 7 and 42 days after system inoculation. • After 2-3 hours removal for nitrate and nitrite were 70% to 80% for the 7 to 8-hour stormwater applications.	• No nitrate or nitrate in the effluent for the first 2 to 3 hours likely attributed to the following: The amount of effluent released during that period was water stored in system from previous application; accordingly, that water had a longer period exposed to the anoxic zone favorable to denitrification. • Pilot-scale bioretention cell performance suggests that incorporating an anoxic zone in the bottom of bioretention area can be effective for removing nitrate.
Horner, R., Lim, H., & Burges, S.J. (2002, November). *Hydrologic monitoring of the Seattle Ultra-Urban stormwater management projects* (Water Resources Series Technical Report No. 170). Seattle, WA: University of Washington.	Field	660 feet of residential road was narrowed and linear bioretention/ bioswales were installed within the right-of-way. A v-notch weir installed at the ultimate outfall of the project measured surface flow volumes and timing. Flows for the conventional pre-construction street were compared to the retrofit design.	Pre-construction (March-July 2000): • Rainfall: 7.96 inches. • Runoff: 4979 cubic feet. Post construction (March-July 2001): • Rainfall: 9.00 inches. • Runoff: 132 cubic feet. Oct 20 2003 record storm event: • Rainfall: 4.22 inches (32.5 hour storm duration). • Runoff: none.	• Approximately 97% reduction in surface flow volume was recorded from pre- to post-construction conditions. • Contributing area is approximately 2.3 acres and total impervious area is approximately 35%. Total rooftop contribution reaching the streets, swales and monitoring station is not known.

REFERENCE	STUDY SETTING	SUMMARY	FINDINGS	COMMENTS
Hon G, E., Seagren, E., Davis, A. P. (2002, June). Sustainable Oil and Grease Removal from Stormwater Runoff Hotspots using Bioretention. Paper for the 74th *Annual Conference and Exhibition of the Pennsylvania Water Environment Association*. State College, PA.	Laboratory	The research examined the capacity of a mulch layer to capture oil and grease (O&G) via sorption and filtration. Simulated stormwater runoff carrying selected hydrocarbons was applied to a bench-scale "reactor" with a 3-cm thick leaf compost layer. Stormwater was applied at a rate of 4 cm/hr for 6 hours resulting in a naphthalene concentration of 1.7-2.4 mg/L. To distinguish biodegradation and other removal pathways, experiments with and without microbe populations were conducted. Mulch samples were analyzed for contaminants, volatilized hydrocarbons captured, and microbial population counts conducted to correlate with biodegradation rates.	During simulated storm event: • Approximately 90% removal of dissolved naphthalene from aqueous phase via sorption. After storm event (37 and 40 hours): • Abiotic experiment: approximately 32% removal via biodegradation in the mulch layer. • Biotic experiment: approximately 72% removal via biodegradation in the mulch layer. After storm event (74 hours): • Biotic experiment: approximately 95% removal via biodegradation in the mulch layer. Losses due to volatilization were negligible.	• Naphthalene, in dissolved and particulate-associated phases, was selected because of its toxicity and common presence in stormwater. • Research was designed to test bioretention in automotive-intensive hotspots such as gas stations. • The native microbial population in the mulch was capable of biodegradation and inoculation with specific microorganisms to degrade O&G was not necessary. • The change in microbial numbers corresponded to the loss of naphthalene (i.e., microbial numbers were highest when the most naphthalene was degraded).

Appendix 5

Phytoremediation

The presence of vegetation can have various effects on contaminants in soil or water. Studies indicate that vegetated soils are capable of more effective degradation, removal, and mineralization of total petroleum hydrocarbons (TPHs), polycyclic aromatic hydrocarbons (PAHs), pesticides, chlorinated solvents, and surfactants than are nonvegetated soils (US EPA, 2000). Certain plant roots can absorb or immobilize metal pollutants including cadmium, copper, nickel, zinc, lead, and chromium, while other plant species are capable of metabolizing or accumulating organic and nutrient contaminants. An intricate and complex set of relationships and interactions between plants, microbes, soils, and contaminants make these various phytoremediation processes possible.

The term phytoremediation is a combination of the Greek prefix *phyto*, for plant, and the Latin root *remidium*, "to correct or remove an evil". Defined, phytoremediation is the utilization of vascular plants, algae, and fungi to control, break down, or remove wastes, or to encourage degradation of contaminants in the rhizosphere, or root region of the plant (McCutcheon & Schnoor, 2003). Phytoremediation processes are most effective where contaminants are present at low to medium levels, as high contaminant levels can inhibit plant and microbial growth and activity (US EPA, 2000).

Metals, organics, and inorganic contaminants in stormwater and soils can be subject to:

- Degradation.
- Extraction by the plant.
- Containment within the plant.
- A combination of these mechanisms.

Plant processes that promote the removal of contaminants from soil and water are either direct or indirect. Direct processes include plant uptake into roots or shoots and transformation, storage, or transpiration of the contaminant (Hutchinson et al., 2003). Indirect plant processing involves the degradation of contaminants by microbial, soil, and root interactions within the rhizosphere (Hutchinson).

1. Degradation *(rhizodegradation, phytodegradation, phytovolatilization)*

Table 1 Phytoremediation processes contributing to degradation or transformation of contaminants in soil and water.

Type	Process	Appropriate contaminants
Rhizodegradation (Plant-assisted bioremediation, phytostimulation)	Plant exudates and other processes enhance soil bacterial growth, spur degradation by mycorrhizal fungi and microbes, and add aeration channels and oxygen to soils	Petroleum hydrocarbons, BTEX, PAHs, PCP, perchlorate, pesticides, PCBs and other organic compounds
Phytodegradation	Aquatic and terrestrial plants take up, store and biochemically degrade or transform organic compounds	Chlorinated solvents, methyl bromide, atrazine, DDT, tetrabromoethene, tetrachloroethane, dichloroethene, Cl and P-based pesticides, PCBs, phenols, anilines, nitriles, nutrients
Phytovolatilization	Plants take up volatile metals and organic compounds and transpire or diffuse contaminant or modified form of contaminant out of roots, leaves or stems	Arsenic, tritium, Se, mercury, m-xylene, chlororbenzene, tetrachloromethane, trichloromethane, trichloroethane, and other chlorinated solvents

(Adapted from information in US EPA, 2000)

The rhizosphere, or area of soil 1 mm from the plant root, is a dynamic and intricately complex environment (Olson et al., 2003). Increased microbial activity and biomass in this area of plant-microbe interaction has become recognized as the "rhizosphere effect" and is critical for rhizosphere bioremediation to take place (Olson et al.). Plant roots exude enzymes and other organic substances. These releases dramatically enhance microbial numbers and metabolic activity, and increase contaminant degradation and the availability of substances for uptake by the roots (Christensen-Kirsh, 1996). The process of breaking down an organic contaminant in soils through active microbial behavior enhanced by the rhizosphere is known as *rhizodegradation* (McCutcheon & Schnoor, 2003).

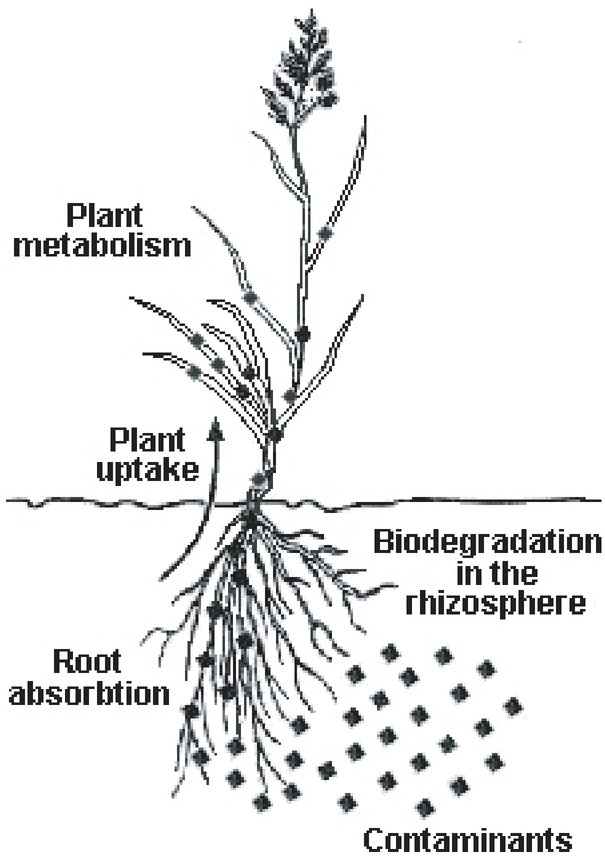

Figure 1 Illustration of basic phytoremediation pathways

The amount and type of compounds released into the soil, and the rhizosphere impacts on associated microbial communities, are specific to plant species (Olson et al., 2003). A synergistic relationship that promotes the exchange of water and nutrients is often established between plant roots and specialized soil fungi or mycorrhizae. This relationship also enhances plant growth (Banks et al., 2000).

Though plants are generally not capable of actually taking in and utilizing highly absorbed contaminants, such as PAHs, the presence of vegetation has been shown to accelerate the degradation of hydrocarbons by enhancing microbial activity (Banks et al., 2000). Root systems can encourage microbial degradation of large molecular organic contaminants (such as PAHs) that tend to bind to soil particles by activating otherwise dormant areas in the soil (Hutchinson et al., 2003). In some instances, the exuded enzymes are capable of detoxifying organic compounds without microbial assistance, a process known as *phytodegradation* (McCutcheon & Schnoor, 2003).

Plants transform certain contaminants through oxidation and reduction reactions, a conjugation phase (foreign compound joined by a plant sugar amino acid, thisol, or glutathione molecule), and deposition of the conjugates into vacuoles and cell walls (Dzantor & Beauchamp, 2002; Subramanian & Shanks, 2003).

The availability of a contaminant for uptake and transformation is also dependant upon the age of the contaminant and certainly the plant species (US EPA, 2000). This process of breaking down contaminants by plant metabolic activity is referred to as phytodegradation or *phytotransformation;* these terms can also apply to the breakdown of contaminants outside the plant through the release of enzymes produced by the plant and which result in the transformation of the compound (US EPA, 2000).

2. Extraction *(phytoextraction/phytomining, rhizofiltration, phytovolatilization)*

Table 2 Processes involving plant uptake or extraction of contaminants from soils or water.

Type	Process	Appropriate Contaminants
Phytoextraction (Phytomining)	Chemicals taken up with water by vegetation; harvested shoots could be smelted or metals otherwise extracted	Metals, metalloids, radionuclides, perchlorate, BTEX, PCP, organic chemicals not tightly bound to soil particles
Rhizofiltration	Contaminants taken up, sorbed, or precipitated by roots and/or shoots; sorbed to fungi, algae and bacteria	Metals, radionuclides, organic chemicals, nitrate, ammonium, phosphate, and pathogens
Phytovolatilization	Plants take up volatile metals and organic compounds and transpire or diffuse out of roots, leaves or stems	Se, tritium, As, Hg, m-xylene, chlororbenzene, tetrachloromethane, trichloromethane, trichloroethane, and other chlorinated solvents

(Adapted from information in US EPA, 2000)

Depending on the plant type and the contaminant, direct uptake can be considered either a passive and/or an active process (Chiou, 2002). The principal process is passive transport, with the primary transport medium, external water and soil water, carrying the contaminant into the plant. Active transport requires the plant to expend energy and generally applies to nutrients and other organic and inorganic ions required and extracted by the plant (Chiou).

Plants actually need metals, such as zinc and copper, as well as nutrients, to grow. When soil surrounding plant roots is deficient in essential elements, plants will exhibit symptoms indicative of deficiency (loss of leaf color, withering, dead spots, etc.) (Stern, 2000). Some plants, however, referred to as hyperaccumulators, make no distinction between heavy metals (such as cadmium or selenium) and those metals nutritionally necessary for growth (Raskin & Ensley, 2000; Stern). These plants absorb the metals through the root structure and store them in cell vacuoles, where tissues have been measured to contain 1,000 to 10,000 ppm of various heavy metals (Stern).

Potentially hazardous metals present in stormwater, such as zinc, copper, cadmium, and lead, can be absorbed by both terrestrial and aquatic plant roots as well as the shoots of submersed plants (Fritoff & Greger, 2003). The retention time and interactions with other elements in the water affect the bioavailablity of metals within a vegetated system exposed to stormwater (Fritoff & Greger). Metals may be contained by physical sequestration or accumulation in roots of non-harvestable plants.

The most important component of extractive phytoremediation is the availability of the compound (Dzantor & Beauchamp, 2002). The lipophilicity (fat-solubility), or distribution of a chemical from the soil solution to the lipids in the plant cell, is the primary controlling factor in the ability of plants to absorb and translocate organic chemicals (Hutchinson et al., 2003). Once transported into the plant cells, the chemical can be metabolized in a process very similar to mammalian metabolism; thus plants utilizing this process are frequently referred to as “green livers” (Dzantor & Beauchamp).

Using a process called *phytovolatilization,* elemental contaminants can be taken up, transformed to a volatile form, and transpired through roots, stems, or leaves (Doucette, Bugbee, Smith, Pajak, & Ginn, 2003). Selenium, for example, can be transformed into volatile dimethyl selenide, not known to represent any health risk once transported through air. Volatile organic compounds can be taken up and directly transpired or diffused through roots, stems, and foliage (Doucette et al.). Application or use of phytovolatilization requires a thorough examination of potential health risks associated with air transport of the contaminant or modified form of the contaminant in the atmosphere.

3. Containment/Immobilization *(phytostabilization, rhizofiltration)*

Table 3 Immobilization or containment processes preventing contaminant movement, leaching or transport.

Type	Process	Appropriate Contaminants
Phytostabilization	Vegetation prevents erosion and sorbed contaminant transport; often involves revegetating an area where natural vegetation cannot be sustained due to high contaminant concentrations	Metals, phenols, tetrachloromethane, trichloromethane, and other chlorinated solvents
Rhizofiltration	Contaminants taken up, sorbed, or precipitated by roots and/or shoots; sorbed to fungi, algae and bacteria	Metals, radionuclides, organic chemicals, nitrate, ammonium, phosphate, and pathogens

(Adapted from information in US EPA, 2000)

Root and microbial interactions can immobilize organic and some inorganic contaminants by binding them to soil particles and, as a result, reduce migration of the contaminant to groundwater (Christensen-Kirsh, 1996). The process of holding contaminated soils in place with vegetation, minimizing disturbance of contaminants bound to soil particles, and preventing contaminant movement is referred to as **phytostabilization** (McCutcheon & Schnoor, 2003).

The process where heavy metal contaminants in water are absorbed or precipitated onto or into plant roots is referred to as **rhizofiltration**. The plant may or may not actually take in and translocate the contaminant. The contaminant can be contained, immobilized or accumulated within or on the root structure. Generally this application is associated with contaminants carried in water rather than contaminated soil particles (US EPA, 2000). This process is heavily dependant on pH levels of the solution and harvesting of plants used in this process will often be necessary to reduce the reintroduction of the contaminant into soils or water.

Plant Selection Considerations

Use of native plant species for phytoremediation is generally favored; natives require less maintenance and present fewer environmental and human risks than do non-native or genetically altered species. Non-native species that require fertilizers or large amounts of irrigation will contribute to, rather than reduce, negative effects of stormwater runoff. Properly selected native plant communities are most tolerant of soils, climatic conditions, and seasonal cycles of inundation and drought. However, particular non-native plants may work best in remediation of a specific contaminant and can be safely used under circumstances where the possibility of invasive behavior has been eliminated (US EPA, 2000).

Scientific studies using phytoremediation techniques have focused almost entirely on monoculture trials, while ecosystem and plant community uses and effects remain largely unexplored. The drawbacks of phytoremediation efforts relying on monocultures are increased susceptibility to disease and other natural events damaging the plants, as well as reduced ecological diversity and wildlife habitat benefits (Marmiroli & McCutcheon, 2003).

Limiting Conditions

The primary factors that limit the effectiveness of phytoremediation are climate conditions, particularly temperature, and contaminant exposure to the plant root zone. In temperate regions, dormant periods for many plants that coincide with high precipitation periods may limit contaminant uptake during periods when pollutant loads are potentially largest (Christensen-Kirsh, 1996). Effective phytoremediation requires that root systems extend into the contaminated region or that the contaminants be brought within range of the rhizosphere (US EPA, 2000).

Microbial populations and their level of activity are strongly influenced by soil pH levels and water availability. Most biological activity occurs in soils with pH levels between 5 and 10 (Hutchinson et al., 2003). Low pH levels are optimal for metal availability, but can have adverse effects on vegetation. Microbial activity is maximized when 60 percent of soil pore space is filled with water. Activity is nearly absent with low water availability. Saturated soils have limited available oxygen, forcing a decline in microbial activity (Hutchinson et al.).

The physical characteristics of soil, such as percentages of clay and/or sand, can alter the availability of oxygen, nutrients, and water for plant and microbial use. Soils with high clay content, for example, have lower hydraulic conductivity and diffusion coefficients, and can render contaminants unavailable to microorganisms. The presence of vegetation can promote the development of soil structure, increase microbial activity within the rhizosphere, and, as a result, enhance the transport of water, nutrients, and contaminants through the soils system (Hutchinson et al., 2003). Adding organic amendments, such as compost, to disturbed urban soils can increase plant root growth, improve water-holding capacity of the soil, and encourage a wide variety of soil organisms.

The importance of optimizing the productivity and interactions between plants and microbes cannot be overstated, and the success of most phytoremediation applications (volatilization, extraction, stabilization, transformation, phytodegradation and rhizodegradation) will be largely dependant on this dynamic relationship (Olson et al., 2003).

Phytoremediation efforts can also be influenced by the presence of multiple contaminants, which, in combination, can inhibit pollutant processing. Understanding which contaminants are present is necessary to inform decisions regarding appropriate plant and soil selection (Dzantor & Beauchamp, 2002).

Concerns and Considerations

Utilization of some phytoremediation techniques, such as the extraction and sequestration of heavy metals in plant tissues, may require harvesting and proper disposal or recycling of contaminated vegetation. Most phytoremediative plants, however, do not accumulate significant levels of contamination and do not require specific treatment or disposal (US EPA, 2000). Existing natural vegetation on sites receiving stormwater runoff likely extract, metabolize, and/or degrade many contaminants (US EPA, 2000). However, the complexity of interactions between variables, such as plant communities, climatic conditions, soils, and combinations of contaminants will undoubtedly prohibit a comprehensive understanding of all interactions at every site for some time to come.

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Appendix 6

Sampling of Plant Species Studied for Phytoremediation

The following is a sampling of plant species that have been studied for phytoremediation. Some plants on this list may not be well suited for growing conditions in Puget Sound. A number of plants with identified phytoremediative abilities have not been included on this list because they are an invasive or potentially invasive weed in Washington state. These plants include such species as:

Amorpha fruticosa	(Indigo bush)	Accumulates lead
Azolla pinnata	(Water velvet)	Biosorbs metals
Bacopa monnieri	(Water hyssop)	Accumulates metals
Hydrilla verticillata	(Hydrilla)	Hyperaccumulates metals
Myriophyllum aquaticum	(Parrot feather)	Transforms and degrades a variety of contaminants
Phragmites australis	(Common reed)	Used in reed bed treatment systems (native genotypes do exist that are not considered invasive)

Related native species may not react to contaminants in the same manner as those specified. Different cultivars of the same species and various species of the same genus may differ in reactions and responses to climatic factors (McCutcheon, 2003).

GRASSES/LEGUMES

Species/Common Name	Contaminant	Process	Comments
Agropyron smithii Western wheat grass	Hydrocarbons	Rhizodegradation	Perennial grass used in pastures/lawns; shown in studies to enhance degradation of TPH and PAHs in soils (McCutcheon & Schnoor, 2003).
Agrostis castellana Colonial bentgrass	Metals	Hyperaccumulation	Perennial *A. castellana* has been shown to accumulate As, Pb, Zn, Mn and Al.
Bouteloua gracilis Blue gamma grass	Hydrocarbons	Rhizodegradation	Used for low-water use lawn and pasture grass. Has shown promise in grass mixes to enhance degradation of PAHs in soils (McCutcheon & Schnoor, 2003).
Buchloe dactyloides Buffalo grass	Hydrocarbons	Rhizodegradation/ Accumulation	Perennial grass; low maintenance, drought tolerant lawn requiring little/no mowing. In studies has been shown to reduce TPH and PAHs in soil (McCutcheon & Schnoor, 2003).
Cerastium arvense Field chickweed	Cadmium	Uptake/ Accumulation	Tufted perennial, white flowers. A Northwest (NW) native, a recent study on Vashon Island indicated uptake of cadmium (Institute for Environmental Research and Education, 2003). Additional chickweed varieties found in the NW include *C. beringianum* (Bering chickweed) and *C. fischerianum* (Fisher's chickweed).
Claytonia perfoliata Miner's lettuce	Cadmium	Uptake/ Accumulation	A somewhat succulent annual with white or pink flowers. Also known as *Montia perfoliata*. A smaller attractive variety is *Montia spathulata*. A recent study on Vashon Island indicated uptake and accumulation of cadmium (Institute for Environmental Research and Education, 2003).
Cynodon dactylon Bermuda grass	Hydrocarbons	Rhizodegradation/ Accumulation	Lawn grass; minimum maintenance but needs mowing and can be invasive. In studies where mixed with other grasses, it has reduced TPH and PAHs in soils (McCutcheon & Schnoor, 2003).

GRASSES/LEGUMES

Species/Common Name	Contaminant	Process	Comments
Elymus Canadensis Canadian wild rye	Hydrocarbons	Rhizodegradation/ Accumulation	In combination with other grasses, was shown to reduce PAHs in soils (McCutcheon & Schnoor, 2003). *E. mollis* is a NW native wild rye.
Festuca arundinacea Tall fescue	Pyrene, PAHs	Rhizodegradation/ Phytoextraction	Introduced perennial grass common in the NW; studies have shown enhanced degradation of recalcitrant PAHs (McCutcheon, 2003). Also helpful in uptake of nutrients: nitrogen, phosphorus and potassium (Christensen-Kirsh, 1996).
Festuca rubra Red fescue	Hydrocarbons	Rhizodegradation	Perennial grass often used in lawn mixes; Studies have shown enhanced degradation of TPH and PAHs (McCutcheon & Schnoor, 2003).
Lolium perenne English ryegrass	Hydrocarbons/ Nutrients	Rhizodegradation/ Uptake	Perennial grass shown to uptake nutrients and to significantly enhance degradation of TPH and PAHs in soils (McCutcheon & Schnoor, 2003).
Lupinus albus White lupin	Arsenic	Rhizoaccumulation	A nitrogen fixing legume capable of growth in acidic soils with low nutrient availability. A recent study indicated an ability to take up arsenic, primarily stored in the root structure (Esteban, Vazquez & Carpena, 2003). A number of lupine varieties are native to the NW, including: *Lupinus arcticus* (Artic lupine), *L. littoralis* (Seashore lupin), *L. nootkatensis* (Nootka lupine), and *L. polyphyllus* (Large-leaved lupine).
Lotus corniculatus Birds-foot trefoil	Hydrocarbons	Rhizodegradation/ Accumulation	An introduced European annual herb; when mixed with grasses was shown to reduce TPH and PAHs in soils (McCutcheon & Schnoor, 2003). This plant is generally not recommended for introduction into constructed wetlands of the Puget Sound region (Azous & Horner, 2001).
Melilotus officinalis Yellow sweet clover	Hyrdocarbons	Rhizodegradation	Tall, sweet smelling annual; *M. alba* is more common in NW region. When mixed with other grasses was shown to degrade TPH in soils (McCutcheon & Schnoor, 2003). Also helpful in uptake of nutrients: nitrogen, phosphorus and potassium (Christensen-Kirsh, 1996).
Panicum virgatum Switch grass	Hydrocarbons	Rhizodegradation	Enhances degradation of PAHs in soils (McCutcheon & Schnoor, 2003). *P. occidentale* is a species found in the NW.
Stellaria calycantha Northern starwort	Cadmium	Uptake/ Accumulation	Low sprawling perennial. A number of varieties are common in the NW, including, *S. longifolia* (Long-leaved starwort) and *S. longipes* (Long-stalked starwort). A recent study on Vashon Island indicated uptake and accumulation of cadmium (Institute for Environmental Research and Education, 2003).
Stenotaphrum secundatum St. Augustine grass	Hydrocarbons	Rhizodegradation	Perennial grass often used in lawns; coarse-textured. Decreases TPH and PAHs in soils (McCutcheon & Schnoor, 2003).
Trifolium pratense Red clover	Hydrocarbons	Rhizodegradation	Introduced perennial herb common in the NW. When mixed with other grasses was shown to degrade TPH in soils (McCutcheon & Schnoor, 2003).
Trifolium repens White clover	Hydrocarbons PCBs	Rhizodegradation/ Metablolization	Introduced perennial herb, deep rooting; enhances microbial activity and degradation of PAHs. Nitrogen fixer, and PCB metabolizer.
Vicia spp. Vetch	Nutrients/ Metals	Uptake	Perennial herb, takes up nutrients (nitrogen, phosphorus and potassium); *V. faba* has been shown to accumulate Al (McCutcheon & Schnoor, 2003).

OTHER FORBES

Species/Common Name	Contaminant	Process	Comments
Achillea millefolium Yarrow	Cadmium	Uptake/ Accumulation	Perennial aromatic herb native to the NW. Also known as *A. borealis*. A recent study on Vashon Island indicated uptake and accumulation of cadmium (Institute for Environmental Research and Education, 2003).
Allium schoenoprasum Chives	Cadmium	Hyperaccumulation	Perennial onion relative. A recent agricultural study in Israel indicated Cd was accumulated in roots and leaves (Khadka, Vonshak, Dudai & Golan-Goldhirsh, 2003).
Atriplex hortensis Garden Orach	PCBs	Metabolism	Of the spinach family, Orache is an extremely variable species; *A. patula* (Spearscale), *A. subspicata* and *A. patula* common in the NW. Shows promise transforming PAH and Graden Orach metabolizes PCBs (McCutcheon & Schnoor).
Brassica juncea Indian mustard	metals	Rhizofiltration/ Hyperaccumulation	Various species applicable for removing heavy metals (Pb, Zn, Ni, Cu, Cr, Cd and Ur) from soil or water (McCutcheon & Schnoor, 2003); B. campestris (also known as *B. rapa*) and *B. camestris* are common annual herb species in the NW.
Brassica rapa Field mustard	Cadmium, Zinc	Hyperaccumulation	Known to accumulate metals.
Digitalis purpurea Common Foxglove	Cadmium	Phytoextraction	A recent study on Vashon Island indicated uptake of cadmium; *D. lanata* (Grecian foxglove) shown to transform digitoxigenin (McCutcheon & Schnoor, 2003).
Helianthus annuus Sunflower	Metals PAHs	Extraction/ Metabolism Rhizodegradation	The common sunflower has been the subject of numerous studies and is used to extract heavy metals (Pb, Ur, Sr, Cs, Cr, Cd, Cu, Mn, Ni and Zn). Has shown promise in degrading PAHs in soil (McCutcheon & Schnoor, 2003).
Pteris vittata Brake fern	Arsenic	Hyperaccumulation	P. vittata accumulates arsenic in its above ground shoots (Caille et al., 2003).
Senecia glaucus	Crude Oil	Rhizodegradation	Observed to rhizodegrade crude oil in Kuwait; *Senecio triangularis* (Arrow-leaved groundsel), *S. pseudoarnica* (Beach groundsel), and *S. intergerrimus* (Western groundsel) are among the related perennial herbs in the NW.
Solidago hispida Hairy golden rod	Metals	Hyperaccumulation	Shown to accumulate Al. *Solidago* species shows promise for metabolizing TCE (McCutcheon & Schnoor, 2003). Related NW species include S. Canadensis(Canada goldenrod) and *S. multiradiata* (Northern goldenrod).
Thlaspi caerulescens Alpine pennycress	Cadmium, Zinc, Nickel	Hyperaccumulation	This plant is well recognized for its ability to hyperaccumulate metals. *T. arvense* (Field pennycress) is a common NW annual weed.

TREES, SHRUBS and VINES

Species/Common Name	Contaminant	Process	Comments
Acer rubrum Red maple	Leachate	Uptake	Fairly fast growing deciduous trees that have been utilized to uptake landfill leachate along with hybrid poplars (McCutcheon & Schnoor, 2003). NW species include *A. macrophyllum* (Oregon maple), *A. circinatum* (Vine maple), and *A. glabrum* (Rocky mountain maple).
Betula pendula European white birch	PAHs PCBs	Phytodegradation	Attractive European native, has been shown in laboratory tests to degrade PAHs and PCBs in solution (McCutcheon & Schnoor, 2003).
Gleditsia triacanthos Honey locust	Lead	Phytoextraction	Common honey locust (many cultivars available) has shown promise in the extraction and accumulation of lead (Gawronski, 2003).
Ilex spp. Holly	Cadmium	Accumulation	Evergreen shrub or tree. Recently shown to take up and accumulate cadmium (Institute for Environmental Research and Education, 2003).
Liquidambar styraciflua American sweet gum	Perchlorate	Phytodegradation/ Rhizodegradation	A native of the eastern U.S., grows to 60 ft., and is tolerant of damp soils. Has shown promise for phytoremediation of perchlorate (McCutcheon & Schnoor, 2003).
Maclura pomifera Osage orange	PCBs	Rhizodegradation	A deciduous tree that can withstand heat, cold, wind, drought, and poor soil. Roots have been shown to stimulate PCB-degrading bacteria in the soil (McCutcheon & Schnoor, 2003).
Morus rubra Mulberry	PAHs PCBs	Rhizodegradation	The mulberry is one of a few trees producing phenolic compounds stimulating PCB-degrading bacteria, and thus enhance the degradation of this pollutant. Mulberry has also been shown in the lab to degrade PAHs (McCutcheon & Schnoor, 2003).
Populus spp. Poplars	Chlorinated solvents, PAHs, atrazine, DDT, carbon tetrachloride	Phytodegradation/ Phytovolatilization Phytoextraction	Deciduous trees known for deep rooting and rapid growth. The focus of major attention in the field of phytoremediation, hybrids and clones have been developed for very fast growth and colonization. Poplars can absorb nutrients, such as nitrogen, at a high rate and are used in treatment of land applications of wastewater (McCutcheon & Schnoor, 2003). Known to take up and transform TCE from groundwater (McCutcheon & Schnoor, 2003). Varieties tested include *P. deltoids* (Eastern cottonwood), *P. trichocarpa* (Black cottonwood), *P. simonii* (Chinese poplar) and *P. nigra* (Lombardy poplar). *P. trichocarpa* is a NW native.
Populus tremula Aspen	Pb	Extraction	*P. tremula*, *P. treumloides* (Trembling aspen), and hybrids have shown potential to remediate contaminated water, either from the soil or water table, esp. the extraction of lead (McCutcheon & Schnoor, 2003).
Rosa spp. Paul's scarlet rose	Organic contaminants	Phytodegradation	Paul's scarlet rose is a red, natural climbing rose that can metabolize tetrachlorinated PCB 77. There are, of course many varieties. *R. gymnocarpa* (Dwarf rose) and *R. nutkana* (Nootka rose) are two Washington natives.

TREES, SHRUBS and VINES SPECIES/COMMON NAME	CONTAMINANT	PROCESS	COMMENTS
Salix spp. Willow	Perchlorate	Phytodegradation/ Rhizodegradation Phytoextraction	Deciduous trees or shrubs needing plenty of water. *S. caroliniana* (Coastal plain willow) and *S. nigra* (Black willow) shown to uptake and degrade percholate in soils as well as phytoextract metals (Cd, Zn and Cu). Additional *Salix* ssp. and hybrids have extracted metals (Cr, Hg, Se and Zn) (McCutcheon & Schnoor, 2003). Species in the NW include, *S. commutata* (Undergreen willow), *S. lucida* (Pacific willow), and *S. sitchensis* (Sitka willow). A study on Vashon Island indicated uptake/accumulation of cadmium by *S. scouleriana* (Scouler's willow) (Institute of Env. Research & Ed., 2003).
Viola spp. Violets	Metals	Phytoextraction/ Hyperaccumulation	Perennial flowering plants with many varieties. *Hybanthus floribundus* (Shrub violet) from Australia, has been found to accumulate high concentrations of metals. A study on Vashon Island, WA found violets growing naturally to have accumulated cadmium (Institute for Environmental Research and Education, 2003). The many varieties in the NW include: *V. adunca* (Early blue violet), *V. langsdorfii* (Alaskan violet), *V. palustris* (Marsh violet), and *V. glabella* (Yellow wood violet).

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Appendix 7 Permeable Paving Research: Infiltration Performance Over Time and Maintenance Strategies

REFERENCE	STUDY SETTING	SUMMARY	FINDINGS	COMMENTS
Porous Asphalt				
Fwa, T.F., Tan, S.A., & Guwe, Y.K. (1999). Laboratory evaluation of clogging potential of porous asphalt mixtures (Paper No. 99-0087). In *Transportation Research Record: Journal of the Transportation Research Board.* No. 1681, pp. 43-49.	Laboratory	Soil was washed into four different porous asphalt mixtures. Permeability (K) was measured after each clogging attempt until the change in permeability was negligible.	Mix 1: initial K = 300.88 in/hr terminal K = 22.00 in/hr Mix 2: initial K = 820.22 in/hr terminal K = 457.20 in/hr	Analysis utilized falling head test that increases infiltration rates; however, rates for optimum mixes far exceed any design storm infiltration need. All mixes currently used on Singapore roadways are apparently used as a topcoat application.
Wei, I.W. (1986). *Installation and evaluation of permeable pavement at Walden Pond State Reservation – Final report.* Report to the Commonwealth of Massachusetts, Division of Water Pollution Control (Research Project 77-12 & 80-22). Boston, MA: Northeastern University, Department of Civil Engineering.	Field evaluation of Walden Pond State Park parking lot in Massachusetts.	Various asphalt mixes were installed in different locations in the new parking lot and evaluated for infiltration rates using sprinkler systems and collection wells.	Best performing mixes: 1978 1980 1981 K mix: 40 in/hr 38 in/hr 37 in/hr J3 mix: 28 in/hr 4 in/hr 13 in/hr	Test plots were exposed to traffic, but not the heaviest loads in the overall parking area. No maintenance program.
St. John, M.S., & Horner, R.R. (1997). *Effect of road shoulder treatments on highway runoff quality and quantity.* Seattle, WA: Washington State Transportation Center (TRAC).	Field evaluation of road shoulder treatments in Washington state.	Three types of road shoulder treatments (conventional asphalt, gravel, and porous asphalt) were installed on a heavily traveled two-lane road. Flow-weighted composite samples were collected and runoff quality and quantity was evaluated.	After one year of use the porous asphalt shoulders showed no signs of clogging and had an average infiltration rate of 1750 in/hr.	During the year of monitoring approximately 4.2 ft^3 of sand was applied per test section length for routine sanding operations. No maintenance program reported for the porous asphalt shoulders.
Cahill, Thomas, Cahill Associates. Personal communication, April, 2003.	Interview Tom Cahill concerning their porous asphalt installations.	Cahill Associates has installed approximately 80 porous asphalt surfaces (mostly parking lots and recreation facilities) over the past 20 years. Visual inspections are conducted during rain events.	Visual inspections indicate no failures of any installations and Cahill estimates that oldest surfaces are functioning at 80% of initial capacity.	Cahill stresses that proper installation and strict sediment control are critical. Cahill installations use a perimeter infiltration gallery (hydrologically connected to storage under paved surface) as a backup if asphalt infiltration rate is degraded.
Hossain, M., Scofield, L.A., & Meier, W.R. (1992). Porous pavement for control of highway runoff in Arizona: Performance to date. In *Transportation Research Record No. 1354,* Transportation Research Board, National Research Council, Washington, D.C., pp. 45-54.	Field evaluation near Phoenix, Arizona.	Structural integrity and permeability were evaluated for a 3,500 ft-long porous pavement test section installed on the three northbound lanes of Arizona State Route 87 near Phoenix.	• Initial permeability (1986): 100 in/hr. • After 5 years of service (1990): 28 in/hr.	The porous asphalt has performed well in a heavy traffic (highway) application with "no cracking or significant surface deformation having occurred during the 5 years of service."

REFERENCE	STUDY SETTING	SUMMARY	FINDINGS	COMMENTS
Permeable Pavers				
Borgwardt, S. (1994). *Expert Opinion.* Hannover, Germany: University of Hannover, Institute for Planning Green Spaces and for Landscape Architecture.	Field evaluation of two train station parking lots in Europe. One lot was two years old and the other five years old.	Sprinklers applied simulated rainfall on test section and measured infiltration utilizing infiltrometer (double ring method). Infiltration rates at 60 minutes are used to represent saturated conditions. Grain size distribution was evaluated to correlate paver design with infiltration rate.	• 2-yr old lot: infiltration rate = 2.84 in/hr after 60-min sprinkling. • 5-yr old lot: infiltration rate = 5.70 in/hr after 60-min. of sprinkling.	Higher infiltration rate for the older as compared to the newer installation likely due to application of sand on top of gravel in drainage openings and fines introduced from inadequately washed aggregate base material in newer parking lot. No reported maintenance program.
Smith, D.R. (2000). *Permeable interlocking concrete pavements: Selection, design, construction, maintenance.* Washington, D.C.: Interlocking Concrete Pavement Institute.	Literature review.	Design, construction, maintenance, and infiltration capacity guidelines developed by the Institute's technical committee from literature review.	Smith recommends 1.1-in/hr infiltration rate and a CN of 65 (all soil types) for permeable interlocking concrete pavements. Infiltration rate is for a 20-year life span.	
Borgwardt, S. (1997 February). Performance and fields of application for permeable paving systems. *Concrete Precasting Plant and Technology,* pp. 100-104.	Field evaluation of various driving surfaces in Europe.	Several permeable driving surfaces of various ages were evaluated using a drip infiltrometer.	Reports a durable infiltration rate of 4.25 in/hr.	No reported maintenance programs.
Pratt, C.J., Mantle, D.G., & Schofield, P.A. (1989). Urban stormwater reduction and quality improvement through the use of permeable pavements. *Water Science and Technology, 21,* pp. 769-778.	Field evaluation of experimental plots.	A 4.6m-wide by 40m-long by 350mm-deep (on average) parking area was excavated and divided into 4 trial areas. Each trial area was filled with a different type base aggregate and water quality and quantity measurements taken from under-drains. The wearing course was cement paving blocks and plots were lined with an impermeable membrane.	Three periods were measured during 30 days with a total rainfall of 80.5mm. The 350mm of various sub-base stone and pavers reduced the following amounts of the total precipitation: • Granite: 25% • Limestone: 39% • Blast furnace slag: 45% • Gravel: 37%	

REFERENCE	STUDY SETTING	SUMMARY	FINDINGS	COMMENTS
Brattebo, B.O., Booth, D.B. (2003, November). *Long-term stormwater quantity and quality performance of permeable pavement systems.* Water Research, 37, 4368-4376.	Field evaluation in Puget Sound.	Two plastic grid systems (1 filled with soil and grass and 1 with gravel), a concrete block lattice filled with soil and grass, and concrete blocks with gravel filled cells were installed in a parking lot in the city of Renton, WA. Each stall was evaluated for infiltration capability, infiltrate water quality, and durability. Two parking stalls with each type of permeable paving material and a conventional asphalt stall, for a control, were installed in 1996.	Surface runoff was measured throughout Nov. 2001 and from Jan. to early March 2002. Total rainfall during the collection period was 570mm delivered in 15 distinct precipitation events. The most intense storm event delivered 121mm of rain in 72 hours. The permeable stalls infiltrated virtually all stormwater. Surface runoff occurred for 6 events (other measurable surface runoff was detected, but attributed to leaks in the system). The most significant runoff volume of the 6 events was 4mm during the largest storm noted above (3% of total precipitation).	The permeable parking facility was monitored for the first year following construction. This study is a follow up to that work. The parking stalls were used constantly during the 6 years previous to this monitoring cycle. None of the permeable paving surfaces showed signs of major wear.
Dierkes, C., Kuhlmann, L., Kandasamy, J., & Angelis, G. (2002, September). Pollution retention capability and maintenance of permeable pavements. In *"Global solutions for urban drainage", Proceedings of the Ninth International Conference on Urban Drainage.* Portland, OR.	Field evaluation.	The infiltration rate of a parking stall in a 15-year old permeable paver installation in a shopping center was determined. The stall was then excavated to examine contaminant levels in the underlying base aggregate and soil. Stall was selected with high content of spilled oil on surface. A drip infiltrometer was used to measure infiltration rates.	The paving structure consisted of: pavers with 1-3 mm joints, 5-8 cm thick bedding material (2-5 mm), and a 20-25 cm base of crushed stone (8-45 mm). Infiltration rate: 440 liters/second/hectare in the central region of the stall and 2000l iters/second/hectare at the edges of the stall.	
Clausen, J.C., & Gilbert, J.K. (2003, September). *Annual report: Jordan Cove urban watershed section 319 national monitoring program project.* Storrs-Mansfield, CT: University of Connecticut, College of Agriculture and Natural Resources.	Field evaluation in southeastern Connecticut.	Two conventional asphalt, two conventional crushed aggregate, and two permeable paver (UNI group Eco-Stone) driveways were monitored during a 12-month period for runoff, infiltration rate, and pollutant discharge. Trench drains at the bottom of the driveways with tipping buckets measured runoff volume. Infiltration rates were assessed using 2 methods: a single ring infiltrometer and a perforated hose for a flowing test. Contributing area for each driveway and land cover type (roof, lawn, etc.) was assessed.	Infiltration rates for the permeable pavers: • Infiltrometer 2002: 7.7 in/hr. • Infiltrometer 2003: 6.0 in/hr. • Flowing infiltration 2003: 8.1 in/hr. • Runoff coefficient for pavers (runoff depth/rainfall depth) = 24%.	No maintenance program reported. The Eco-Stone driveways were two years old at the time of the study.

REFERENCE	STUDY SETTING	SUMMARY	FINDINGS	COMMENTS
Pervious Concrete				
Wingerter, R., & Paine, J.E. (1989). *Field performance investigation: Portland Cement Pervious Pavement.* Orlando, FL: Florida Concrete and Products Association.	Laboratory and field evaluation in Florida.	Test slabs of pervious concrete were poured, 18" cores removed, and infiltration rates tested. Cores were then clogged by adding 2" of sand and pressure washing for 1.5 hrs. Existing porous concrete installations were also evaluated by coring and measuring infiltration rates and percent of void space infiltrated by fines.	Laboratory core • Pre-clogging infiltration rate = 23.97 in/min. • Post-clogging infiltration rate with 1" sand remaining on surface = 3.66 in/min and 10.22in/min with sand removed from surface. Field tests • Naples FL restaurant parking lot 6.5 yrs. old: infiltration rate = 4 in/min, 3.4% infiltrated by fines. • Fort Myers parking area 8 yrs. old: infiltration rate = 7 in/min, 0.16% infiltrated by fines.	Analysis utilized falling head test that increases infiltration rates, however, rates far exceed any design storm infiltration need. No reported maintenance programs.
Maintenance				
Balades, J.D., Legret, M., & Madiec, H. (1995). Permeable pavements: Pollution management tools. *Water Science and Technology, 32,* 49-56.	Field evaluation in France.	Various street cleaning techniques were applied to different permeable pavements, including parking lots and roads with heavy traffic. Infiltration rates measured before and after cleaning.	Sweeping followed by suction: • Highly clogged surfaces (< 14 in/hr) no improvement. • Partially clogged surfaces (112–140 in/hr) original infiltration rates (210.60–224.64 in/hr) were obtained after two passes. Suction only • 1st site: initial infiltration rate = 7.02 in/hr, after two passes infiltration rate = 28.08 in/hr. • 2nd site: initial infiltration rate = 210.60 in/hr, after two passes infiltration rate = 280.80 in/hr. High pressure wash with suction • Shopping mall: initial infiltration rate = 9.83 in/hr (parking area) and 28 in/hr (roadway), after two passes infiltration rates = 84.24 in/hr for both parking and roadway. • Residential road: initial infiltration = approximately 0 in/hr, after treatment infiltration rate = 112 in/hr.	The analysis does suggest that restoring a percentage or all of the initial infiltration rate of a permeable pavement installation is possible. However, the type of permeable surface and the cleaning technique applied to that specific surface was not reported.

REFERENCE	STUDY SETTING	SUMMARY	FINDINGS	COMMENTS
Gerrits, C., & James, W. (2001). *Restoration of infiltration capacity of permeable pavers.* Master's thesis, University of Guelph. Guelph, Ontario, Canada.	Field evaluation of pervious paver (Eco-Stone) parking lot surfaces at University of Guelph in Ontario.	110 9m x 9m plots in the parking lot were tested for infiltration rates. Material in the drainage cells was excavated to various depths and tests repeated to evaluate regenerating infiltration capacity. Plots were categorized by low, medium and high average daily traffic, and paver bedding material. Parking lot was approximately 8 years old at time of research. Lot is sanded and plowed for snow during winter.	• 3" gravel bed: low traffic: initial = 5.85 in/hr excavate 20 mm = 7.8 in/hr med traffic: initial = 0.58 in/hr excavate 20 mm = 7.80 in/hr • 4" sand bed: low traffic: initial = 0.35 in/hr excavate 20 mm = 0.94 in/hr med traffic: initial = 0.12 in/hr excavate 20mm = no change	Authors find that vacuuming upper 5-20 mm of drainage cell material can regenerate infiltration, and that amounts of material removed to improve infiltration rates can be achieved by modern street sweeping equipment. Sand bed with high traffic most difficult to regenerate and medium traffic with gravel bed easiest to regenerate. Areas with pine needles and vegetation on drainage cells had higher infiltration rates than plots without vegetation material.
Dierkes, C., Kuhlmann, L., Kandasamy, J., & Angelis, G. (2002, September). Pollution retention capability and maintenance of permeable pavements. In *"Global solutions for urban drainage", Proceedings of the Ninth International Conference on Urban Drainage.* Portland, OR.	Field evaluation.	A high-pressure wash and vacuum street cleaning machine was used to clean a school yard permeable paver installation (approximately 4 yr old). The pavers were 10 cm x 20 cm x 8 cm installed on a 2-5 mm pea gravel leveling layer, and the joints filled with 1-3 mm basalt aggregate. Infiltration rates before and after cleaning were evaluated using a drip infiltrometer.	• Infiltration rate before cleaning at 3 selected points: less than 1 mm/second/hectare. • Infiltration rates after cleaning at same 3 points: 1545-5276 liters/second/hectare.	

Appendix 8

Permeable Hot-mix Asphalt Sample Specification

Origin: Cahill Associates, Westchester, Pennsylvania (Cahill Associates, Section 02725-General porous paving and groundwater infiltration beds, 2004).

Application: Parking lots with aggregate base for retention storage.

Soil infiltration rate: Required soil infiltration varies depending on contributing area, aggregate base storage and infiltration capacity, and design storm. In general, minimum long-term infiltration rate should be 0.1 inch/hour.

Figure 1 Parking installation, *Courtesy of Cahill Associates*

Top course: 2.5 inches thick

Aggregate grading:	U.S. Standard Sieve	Percent Passing
	1/2	100
	3/8	92-98
	4	32-38
	8	12-18
	16	7-13
	30	0-5
	200	0-3

Bituminous asphalt cement

- 5.75% to 6.00% by weight dry aggregate.
- Drain down of asphalt binder should be no greater than 0.3% in accordance of ASTM D6390.
- Use a neat asphalt binder modified with an elastomeric polymer to produce a binder meeting requirements of performance or PG 76-22 (PG recommendation for mid-Atlantic states).
- Elastomeric polymer is a styrene-butadiene-styrene or equal applied at a rate of 3% by total weight of the binder. Thoroughly blend polymer and binder at asphalt refinery prior to loading and transportation. The polymer modified asphalt binder should be heat and storage stable.
- Hydrated lime is added at a rate of 1.0% by weight of the total dry aggregate to mixes with granite stone to prevent separation of the asphalt from the aggregate and achieve a required tensile strength ratio of at least 80%. Hydrated lime should meet ASTM C 977.
- The asphalt mix should be tested for resistance to stripping by water in accordance with ASTM D 3625. If estimated coating area is not above 95%, anti-stripping agents should be added to the asphalt.

Asphalt installation

- Bituminous surface course mix is laid in one 2.5-inch lift directly over aggregate storage base.
- Laying temperature of the mix should be between 240 and 250 degrees Fahrenheit and ambient temperature should not be below 40 degrees Fahrenheit.
- Compaction of the surface course should occur when the surface is cool enough to resist a 10-ton roller. One or two passes is all that is required for proper compaction and additional rolling can cause a reduction in surface course porosity.

Aggregate base/storage bed material

- Coarse aggregate is 0.5- to 2.5-inch uniformly graded stone with a wash loss of no more than 0.5% (AASHTO size number 3).

Aggregate grading:	U.S. Standard Sieve	Percent Passing
	2 ½”	100
	2”	90-100
	1 ½”	35-70
	1”	0-15
	½”	0-5

- Choker base course aggregate should be 3/8- to 3/4-inch uniformly graded stone with a wash loss of no more than 0.5% (AASHTO size number 57).

Aggregate grading:	U.S. Standard Sieve	Percent Passing
	1 ½”	100
	1”	95-100
	½”	25-60
	4	0-10
	8	0-5

Aggregate base/storage installation

- Stabilize area and install erosion control to prevent runoff and sediment from entering storage bed.
- Existing subgrade under base should NOT be compacted or subject to excessive construction equipment traffic prior to installation.

- Storage bed should be excavated level to allow even distribution of water and maximize infiltration across parking entire area.
- Immediately before base aggregate and asphalt placement remove any accumulation of fine material from erosion with light equipment and scarify soil to a minimum depth of 6 inches.
- Geotextile fabric is a Mirafi 160N or approved equal. Overlap adjacent strips 16 inches and secure fabric 4 feet outside of storage bed to reduce sediment input to bottom of area.
- Install course (0.5 to 2.5 inch, AASHTO size number 3) aggregate in lifts no greater than 8 inches and lightly compact each lift.
- Install 1-inch choker course (No. 8 to 1.5-inch aggregate, AASHTO size number 57) evenly over surface of course aggregate base.
- Storage and infiltration bed depth will depend on infiltration rates, storage requirement and design storm; however, Cahill Associates often install 18- to 36-inch sections designed for full retention of storm flows.
- All erosion and sediment control should remain in place until area is completely stabilized with soil amendments, landscaping or other approved controls.

Backup systems

- For backup infiltration capacity (in case the asphalt top course becomes clogged) an unpaved stone edge is usually installed that is hydrologically connected to the storage bed (see Figure 2).

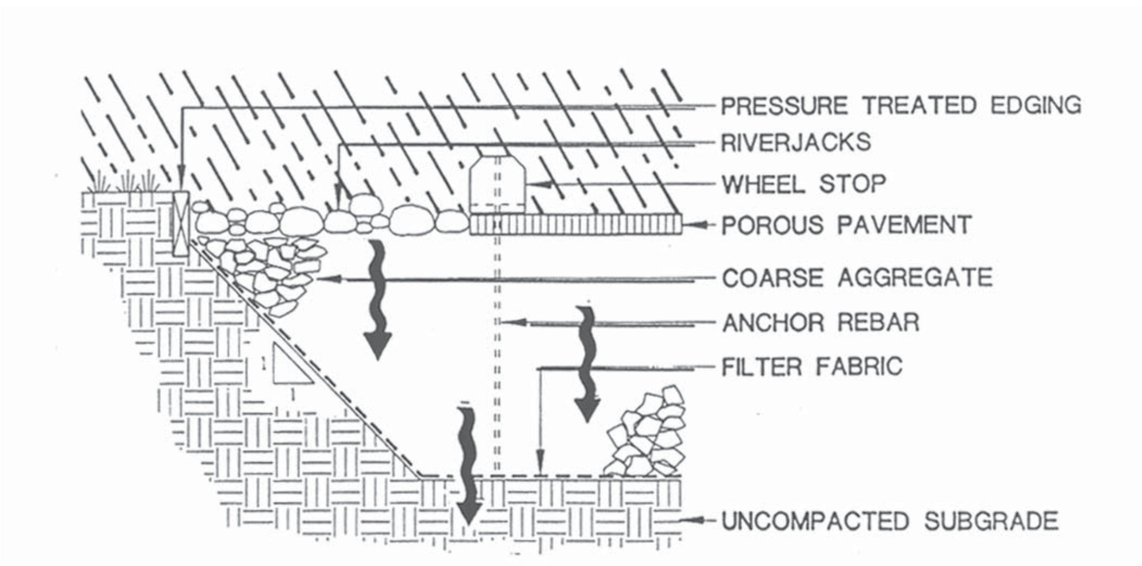

Figure 2 Backup infiltration system for permeable parking lot installations.
Graphic courtesy of Cahill Associates

- To ensure that the asphalt top course is not saturated from high water levels in the aggregate base (as a result of subgrade soil clogging), a positive overflow is usually installed.

Cahill Associates design some systems to infiltrate storm flows from adjacent buildings. Water is collected from roof downspouts, conveyed through a catch basin (to remove debris), and distributed in perforated pipes throughout the storage and infiltration aggregate base.

Appendix 9

Vegetated Roof Design Specification Example

Designers: Boxwood of Seattle, WA and Roofscapes Inc., Philadelphia, PA.

Roof location: Point Defiance Zoo animal health care facility, Tacoma. WA.

The specification that follows is provided by Boxwood of Seattle and Roofscapes, Inc., and was used in the construction of this vegetated roof.

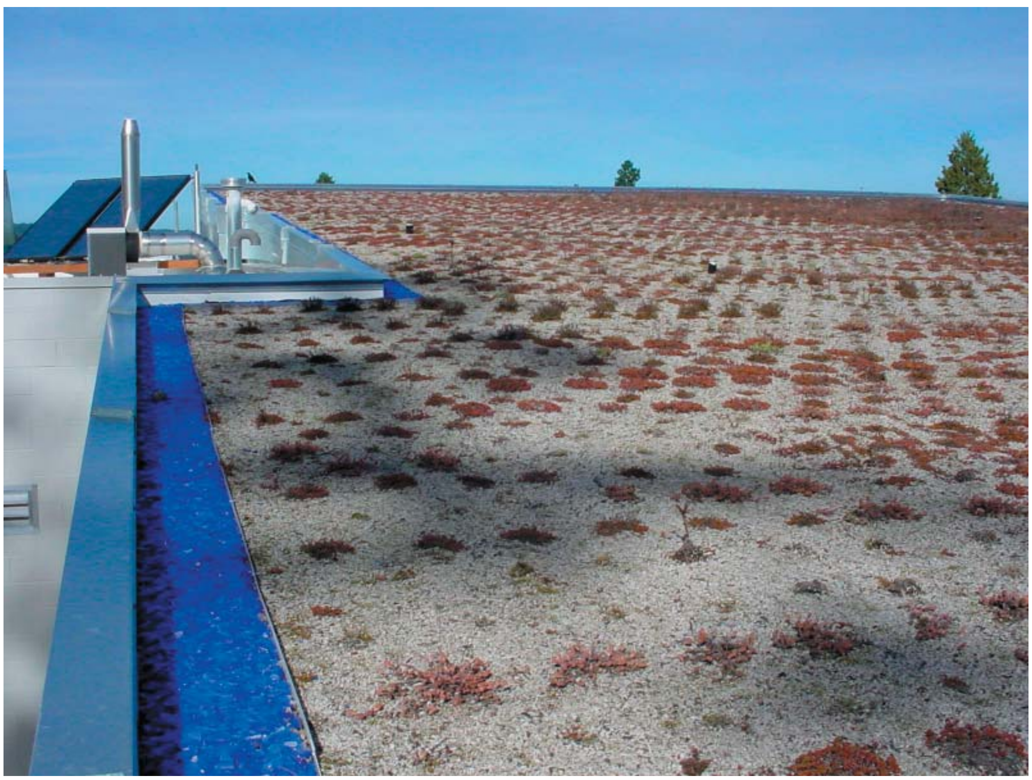

Figure 1 Vegetated roof at Point Defiance Zoo animal health care facility. *Photo by Curtis Hinman*

Summary

- The vegetated cover is a two-layer system, consisting of a 2.5-inch growth media layer installed over the Meadowflor™ drainage system. The weight of this system at Maximum Water Capacity and with rainfall runoff occurring is less than or equal to 15 pounds per square foot.
- The system is not irrigated. However, it may require periodic hand watering during the initial 12 months of the establishment period.

Thermoplastic Sheet Waterproofing Membrane

- Materials:
  - o Sarnafil G476 fiberglass reinforced membrane and compatible sealant.
  - o Minimum thickness: 60 mils.
  - o All roofing components should be compatible with the membrane.
- Quality Assurance:
  - o Only an approved contractor authorized by the manufacturer prior to bid should apply the waterproofing system.
  - o Installation of waterproofing membrane, flashing, membrane expansion joints, membrane containment grids, membrane protection layers, drainage layer and insulation should be the responsibility of the membrane applicator to ensure undivided responsibility.
  - o Obtain primary waterproofing materials, membrane, and flashing from a single manufacturer with not less than 10 years of successful experience in waterproofing applications. Provide other system components only as approved by manufacturer of primary materials.
  - o Waterproofing contractor should arrange with the membrane manufacturer to have the services of a competent field representative at the site to accept the substrate surface before installation of waterproofing materials. The field representative of the membrane manufacturer should check and test all heat-welded seams before the water test, and prior to installation of separation and protection layers.
  - o Before construction begins the owner, architect, contractor's field superintendent, waterproofing foreman, waterproofing membrane manufacturer's field representative, and other involved trades should meet to discuss waterproofing practices applicable to this project.
  - o There should be no deviation made from the contract specification or the approved shop drawings without prior written approval by the owner, the owner's representative and/or design professional, and membrane manufacturer.
  - o Water testing of the completed waterproofing system should be for a minimum of 24 hours. Water testing should be witnessed and confirmed in writing by the owner's representative and/or design professional, the waterproofing contractor, and membrane manufacturer.
  - o Trained and authorized personnel should complete all work.
- Installation
  - o The surface substrate should be clean, dry, free from debris, and smooth with no surface roughness or contamination. Broken, delaminated, wet or damaged insulation or recover boards should be removed and replaced.
  - o Overlap rolls by 3 inches. Shingle seam overlaps with the flow of draining rainwater when possible.
  - o Hot-air welding of seam overlaps:
    - ✓ Seams should be 3-inch when using an automatic machine welding, and 4-inch when hand welding.
    - ✓ All membrane to be welded should be clean and dry. Follow manufacturer's specifications for welding.
  - o Flashings: all flashings should be installed concurrently with the waterproofing membrane as the job progresses per manufacturer's directions. No temporary flashings will be allowed. All flashings should be inspected and accepted by the membrane manufacturer.
  - o Temporary cut off: when a break in the day's work occurs, install a temporary watertight seal by sealing the membrane to the deck or substrate. When work resumes, the contaminated membrane should be removed. If any water is allowed to enter under the completed waterproofing, the affected area should be removed and replaced at the contractor's expense.
  - o Membrane is incompatible with asphalt, oil-based and plastic-based cements, creosote and penta-based materials. If contact occurs, the material should be cut out and discarded. The

contractor should consult the manufacturer with respect to material compatibility, precautions, and recommendations.
  - o Contaminants, such as grease, fats, oils, and solvents, should not be allowed to come into direct contact with the waterproofing membrane.

Protection Fabric

- Material: 22-ounce per square yard polypropylene non-woven needled geotextile.
- The surface of the waterproofing system should be swept and washed.
- Until the drain sheet is installed, traffic over the working area should be strictly controlled and limited to essential personnel only.
- Heavily traveled areas (e.g., corridors for transporting material to the working areas) must be protected in a manner approved by the waterproofing installer.
- Suitably protect lay-down areas using ½-inch plywood over 1-inch sheets of expanded polystyrene, or similar sheathing material.
- Roll out the protection fabric on top of the completed waterproofing system.
- Overlap seams a minimum of 6 inches and tack seams using a hot-air welding gun (Leister, or equivalent).

MEADOWFLOR™ Drainage System

- The vegetated cover system should be underlain everywhere by the Meadowflor™ system. This consists of:
  - o Roofmeadow® perforated polyethylene drain sheet with adhered polypropylene separation fabric. The sheet is a dimpled sheet. The composite system satisfies the following specifications:

Membrane thickness	≥ 20 mil
Compressive strength	≥ 5,200 lb/ft^2
Tensile strength (ASTM-D4594)	≥ 1,000 lb/ft
Brittleness temperature (ASTM-D746)	≤ -50° F
Softening temperature	≥ 250° F
Transmissivity (between platens)	≥ 24 gal/min/ft
Permittivity (ASTM-D4491)	≥1.5 sec^{-1}
Height (varies according to position)	0.39 to 0.78 in

  - o Separation Fabric
    - ✓ Needled non-woven polypropylene geotextile fabric. This component should satisfy the following specifications:

Unit Weight (ASTM-D5261)	≥ 4.25 oz/yd^2
Puncture Resistance (ASTM-D4833)	≥ 35 lbs
Mullen Burst Strength (ASTM-D4632)	≥ 135 lb/in
Permittivity (ASTM-D4491)	≥ 1.5 sec^{-1}

- Install the drain sheet, together with separation sheet. The drain sheet should be installed with the studs and fabric layer facing up to enhance rapid drainage of the overlying media.
- Assemble the perforated conduit on top of the drain sheet, as shown on the drawings.
- Weigh down the drainage layer with temporary ballast, as necessary.

Border Elements

- Roofmeadow® cantilever, fabricated from 1/8-inch aluminum.
- Height: ≥ 0.25 inch higher than the top of the growth media layer.
- Base Length: 7 inches, or 1.5 times the height of the element, whichever is greater.
- Install border elements as required to prevent mixing of ballast and growth media.

Growth Media Layer

- Roofmeadow® Type M1 Extensive Growth Media. This material is a mixture of mineral and organic components that satisfies the following specifications:
  - o Void ratio at Field Capacity (0.333 bar) ≥ 15% (vol)
  - o Moisture content at Field Capacity ≥ 10% (vol)
  - o Maximum Water Capacity ≥ 20% (vol)
  - o Density at Maximum Water Capacity ≤ 62 lb/ft^3
  - o Saturated Hydraulic Conductivity ≥ 1.5 in/hr, and ≤ 15.0 in/hr
  - o Volatile fraction (organic matter) ≤ 10% (dry wt.)
  - o pH 5.5 - 7.9
  - o Soluble salts ≤ 0.30 mmhos/cm (1:20 dilution)
  - o Grain-size distribution of the <u>mineral fraction</u> (ASTM-D422)

Clay fraction (2 micron)	≤ 1%
Pct. Passing US#200sieve	≤ 5% (i.e., silt fraction)
Pct. Passing US#60 sieve	≤ 10%
Pct. Passing US#18 sieve	5 - 50%
Pct. Passing 1/8-inch sieve	20 - 70%
Pct. Passing 3/8-inch sieve	75 -100%

- Macro and micronutrients should be incorporated in the formulation in initial proportions suitable to support the specified planting.
- Thoroughly blend at a batch facility. Moisten, as required, to prevent separation and loss of fine particles during installation.
- Quality control samples should be collected and submitted for testing for each 100 CY provided to the job.
- Placing the growth media layer: The media should be dispensed at the roof level in a manner that will not suddenly increase the load to the roof. It should be immediately spread to the specified thickness, plus 10 percent (after moderate compaction).
- Set the media back from the curbs and parapets as directed in the specifications. The set back for this project is 12 inches. At the margins of the media spread a 2-foot wide strip of separation fabric.
- Cover the media layer with the wind blanket and secure, unless direct seeding (see below).
- Thoroughly soak with water using a sprinkler or hand sprayer. For a 4-inch growth media layer, expect to use about 30 gallons per 100 square feet.

Gravel Margin

- Fill the area between the flashed wall and growth media with gravel as specified.

Planting (plug installation)

- The following plant list should be installed. Any alternatives must be approved by the green roof installer.
- All extensive planting schemes must incorporate *Sedum* species. *Sedum* must represent at least 50 percent of the installed plants. Additionally, the plant mixture should include a minimum of four different species of *Sedum* in approximately equal quantities.
- Non-*Sedum* varieties should be selected that are adapted to the specific growing conditions.
- Plant installation should occur May-June or September-October, unless an active irrigation system is included.
- Plants should be established from 32-cell plugs propagated in sterile nursery medium, according to the plant provider's recommendations. Plugs larger than this can be used; however, the establishment rate is typically better with the smaller plants. The recommended minimum planting rate is 640 plants per 1000 square feet.
- Thoroughly soak the growth media prior to planting.
- The plugs should be set into the media to their full depth and the media pressed firmly around the installed plug. At the end of each day, soak those areas that have been newly planted.
- Do not mulch.

Plant List:

Allium schoenprasm

Delopserma nubigenum

D. cooperii

Echeveria sp.

Petrohagia saxifraga

Sedum floriferum

S. album

S. sexangulare

S. spurium roseum

S. pinofolium

S. reflexum

S. sarmentosum

S. boehmii (orostachys)

Sempervivum sp.

Wind Blanket

- Roofmeadow® photo/bio-degradable covering is used to protect the media from wind erosion during the 24-month plant establishment period. The provider must demonstrate that the wind blanket will remain securely in place during high winds and that it will not interfere with the growth of the plants. It must satisfy the following specifications:
    - o Aperture — $\geq$ 0.04 in, and $\leq$ 0.125 inch
    - o Tensile strength — (ASTM D4632) $\geq$ 20 lb
    - o Satisfies smolder resistance criteria — (FTMA-CCC-%-191B)
- The Roofmeadow® Wind Blanket includes a method for firmly securing the protective layer to the green roof system.

Glossary

Advection	Transfer or change of a property of the atmosphere (e.g., humidity) by the horizontal movement of a mass of fluid (e.g., air current).
Allelopathic	Suppression of growth of one plant species as a result of the release of a toxic substance by another plant species.
Ammonification	Process in which organic forms of nitrogen (e.g., nitrogen present in dead plant material compounds) are converted to ammonium ($NH4^{+}$) by decomposing bacteria.
Bankful discharge	Stream discharge that fills the channel to the top of the banks and just begins to spread onto the floodplain. Bankful discharges occur on average every 1 to 1.5 years in undisturbed watersheds and are primarily responsible for controlling the shape and form of natural channels.
Bedload	Sediment particles that are transported as a result of shear stress created by flowing water, and which move along, and are in frequent contact with, the streambed.
Biotic integrity	Condition where the biologic or living community of an aquatic or terrestrial system is unimpaired and species diversity and richness expected for that system are present.
Bole	Trunk of a tree.
California Bearing Ratio	Test using a plunger of a specific area to penetrate a soil sample to determine the load bearing strength of a road subgrade.
Cation exchange capacity	Amount of exchangeable cations that a soil can adsorb at pH 7.0 expressed in terms of milliequivalents per 100 grams of soil (me/100 g).
Compost maturity	Term used to define the effect that compost has on plant growth. Mature compost will enhance plant growth; immature compost can inhibit plant growth.
Compost stability	Level of microbial activity in compost that is measured by the amount of carbon dioxide produced by a sample in a sealed container over a given period of time.
Critical shear stress	Lift and drag forces that move sediment particles. Forces are created as faster moving water flows past slower water.
Denitrification	Reduction of nitrate (commonly by bacteria) to di-nitrogen gas.

Desorb	To remove (a sorbed substance) by the reverse of adsorption or absorption.
Diurnal oxygen fluctuations	Fluctuations in dissolved oxygen in water as photosynthetic activity increases during the day and decreases during the night.
Effective impervious area (EIA)	Subset of total impervious area that is hydrologically connected via sheet flow or discrete conveyance to a drainage system or receiving body of water. The Washington State Department of Ecology considers impervious areas in residential development to be ineffective if the runoff is dispersed through at least 100 feet of native vegetation using approved dispersion techniques.
Endocrine disruptors	Substances that stop the production or block the transmission of hormones in the body.
Evapotranspiration	Collective term for the processes of water returning to the atmosphere via interception and evaporation from plant surfaces and transpiration through plant leaves.
Exfiltration	Movement of soil water from an infiltration integrated management practice to surrounding soil.
Exudates	Substances exuded from plant roots that can alter the chemical, physical and biological structure of the surrounding soil.
Hydrologically functional landscape	Term used to describe a design approach for the built environment that attempts to more closely mimic the overland and subsurface flow, infiltration, storage, evapotranspiration, and time of concentration characteristic of the native landscape of the area.
Hydroperiod	Seasonal occurrence of flooding and/or soil saturation that encompasses the depth, frequency, duration, and seasonal pattern of inundation.
In-line bioretention	Bioretention area that has a separate inlet and outlet.
Invert	Lowest point on the inside of a sewer or other conduit.
Liquefaction	Temporary transformation of a soil mass of soil or sediment into a fluid mass. Liquefaction occurs when the cohesion of particles in the soil or sediment is lost.
Mycorrhizal	Symbiotic association of the mycelium of a fungus with the roots of a seed plant.
Nitrification	Process in which ammonium is converted to nitrite and then nitrate by specialized bacteria.
Off-line bioretention	Bioretention area where water enters and exits through the same location.

Phytoremediation	The utilization of vascular plants, algae and fungi to control, break down, or remove wastes, or to encourage degradation of contaminants in the rhizosphere (the region surrounding the root of the plant).
Reaction range	Length of the pin or pile in a minimal excavation foundation system that is in direct contact with and bears against the soil to support the above-ground structure.
Saturated hydraulic conductivity	Ability of a fluid to flow through a porous medium under saturated conditions; is determined by the size and shape of the pore spaces in the medium, their degree of interconnection, and by the viscosity of the fluid. Hydraulic conductivity can be expressed as the volume of fluid that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.
Seral stage	Any stage of development or series of changes occurring in the ecological succession of an ecosystem or plant community from a disturbed, un-vegetated state to a climax plant community.
Soil bulk density	Ratio of the mass of a given soil sample to the bulk volume of the sample.
Soil stratigraphy	Sequence, spacing, composition, and spatial distribution of sedimentary deposits and soil strata (layers).
Stage excursions	Departures, or changes, in pre-development water depth (either higher or lower) that occur after development takes place.
Threshold discharge area	Onsite area draining to a single natural discharge location or multiple natural discharge locations that combine within one-quarter mile downstream (as determined by the shortest flow path).
Time of concentration	Time that surface runoff takes to reach the outlet of a sub-basin or drainage area from the most hydraulically distant point in that drainage area.
Total impervious area (TIA)	Total area of surfaces on a developed site that inhibit infiltration of stormwater. The surfaces include, but are not limited to, conventional asphalt or concrete roads, driveways, parking lots, sidewalks or alleys, and rooftops.
Transmissivity	Term that relates to movement of water through an aquifer. Transmissivity is equal to the product of the aquifer's permeability and thickness (m^2/sec).
Tree canopy dripline	Outer most perimeter of a tree canopy; defined on the ground by a vertical line from the perimeter of the leaves of a tree canopy to the ground directly below.

Frequently used acronyms

AASHTO ....American Association of State Highway and Transportation Officials

ASTM.................American Society for Testing and Materials

CEC ....Cation exchange capacity

CN.....................Curve number

CRZ ....Critical root zone

IMPs ....Integrated management practices

SMMWW ....*Stormwater Management Manual for Western Washington*

USDA.................United States Department of Agriculture

WAC ....Washington Administrative Code

WWHM............Western Washington Hydrologic Model

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