Email to Stakeholders – Draft LID Manual
January 9, 2012

Dear Stormwater Management Professional:

WSU Extension and the Puget Sound Partnership are pleased to announce that the *Draft 2012 Low Impact Development Technical Guidance Manual for Puget Sound* (Draft LID Manual) is now available for broader stakeholder review. The Draft LID Manual is an update to the existing *2005 LID Technical Guidance Manual for Puget Sound*, and incorporates new national and regional information and results of recent research regarding LID practices.

The Draft LID Manual (text and graphics) is available at: http://www.psp.wa.gov/LID_manual.php. This web site also contains information about the process, timeline, and participants involved in developing the 2012 version of the Draft LID Manual.

Comments should be submitted by clicking on a link at the above web site and following instructions.

The review period will end at 5 pm on **Thursday, February 9, 2012**. No late comments will be accepted.

A few important points to remember:

- **Only comments received via the web-based tool listed on the above web site will be accepted. We are not able to accept comments that are submitted via e-mail; phone calls; or in hard copy.**

- Please refer to the cover letter from Curtis Hinman for additional important information regarding review of draft text and graphics, and remaining coordination needed among Ecology, WSU and the Partnership to complete the Draft LID Manual.

- Any questions regarding the review process should be directed to Bruce Wulkan at the Puget Sound Partnership: Bruce.Wulkan@psp.wa.gov, or 360-339-4626.

- The Partnership will post a document of comments received on the above listed website in March 2012.

Please note that the Draft LID Manual is being updated in coordination with the Department of Ecology's development of the *2012 Stormwater Management Manual for Western Washington*. The public comment period for that update process ends on February 3, 2012. If you have questions regarding the *Draft 2012 Stormwater Management Manual for Western Washington*, or would like to comment on it, please contact Carrie Graul at the Department of Ecology at (360) 407-7221, or carrie.graul@ecy.wa.gov . You may also visit: http://www.ecy.wa.gov/programs/wq/stormwater/wwstormwatermanual/2012draft/2012draftSWMMWW.html

If you would like to comment on the Department of Ecology's draft LID requirements in the draft Municipal Stormwater NPDES general permit, please see: http://www.ecy.wa.gov/programs/wq/stormwater/municipal/2012Reissuance.html.

Thank you for your contribution toward this effort.

Curtis Hinman
WSU Puyallup Research and Extension Center

Bruce Wulkan
Puget Sound Partnership

WSU Puyallup Green Stormwater Infrastructure
Research Program

January 9, 2012

Dear Stormwater Colleagues:

Thank you for taking the time to review the new version of the LID Technical Guidance Manual for Puget Sound (LID Manual). The art and science of LID or Green Stormwater Infrastructure is growing and evolving rapidly, so there are many significant changes in the 2nd edition.

Below are a few general points to keep in mind as you review the document:

- We have not done any significant proof reading for grammar and will begin the focused editing and layout once this review is complete. Accordingly, please do not focus on grammar, but rather technical, substantive content.
- Most but not all of the chapters or appendices are included. What is not included either does not need review (e.g. literature review matrices) or requires Ecology to complete their Permit and Stormwater Management Manual for Western Washington (SWMMWW) review.
- What is included for review:
  - Chapters 1-6 which includes the most current design guidelines for LID practices.
  - Appendices 1, 3, 4, 5.
- What is not included for your review:
  - Chapter 7 which is Ecology's design and flow control guidance. This is in Appendix III-C of the SWMMWW Volume 3. Once comments are received and Ecology updates that section we will include it in the LID Manual.
  - Appendix 2 (Bioretention literature review), Appendix 6 (Compost specification) and Appendix 7 (Permeable pavement literature review). The compost specification follows Washington's guidelines and is available on Ecology's website and 2 and 7 are simply references.
- Not all the graphics are included. We are still working on creating graphics and gathering photos. If you have graphics or images that would work well please include a note in your review and we will contact you. I suggest that you open the text document and the graphics document side by side and scroll through them simultaneously for easy viewing and commenting.
- Site analysis guidelines for determining subgrade infiltration rates have been changed significantly in the SWMMWW and in the LID Manual. The latest version that is specific to permeable pavement and bioretention is in the LID Manual.
- Ecology, WSU and the Partnership are still working on coordinating the SWMMWW and the LID Manual, so discrepancies exist between the two documents. During the review period and once the review is complete we will be bringing the two documents into alignment.

February 9th is the comment deadline. Comments should only be provided using the web tool. The link to the Partnership's web page for the LID Manual review is:

http://www.psp.wa.gov/LID_manual.php

I look forward to your comments,

Curtis Hinman

WSU Extension Faculty, Green Stormwater Infrastructure Specialist
WSU Puyallup Green Stormwater Infrastructure Program Lead
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Chapter 1: Introduction

In this chapter

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 40 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**.

Pull quote: Water budget studies of wet coniferous forests in western Washington, British Columbia, and the United Kingdom indicate that approximately 40 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,

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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).

1.2 Impacts of Urbanization

The conversion of the U.S. landscape to urban development is occurring rapidly. From 1954 to 1997 the urban land area grew from approximately 18.6 to 74 million acres, and during the later part of that time period (1982 to 1997) the population grew by 15 percent while developed land increased by 34 percent or 25 million acres. Analyzes of 22 metropolitan areas revealed that 95 percent of building permits were on green field sites (EPA, 2006).

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 1-1: water budget for Puget Sound lowland forest>

<Figure 1-2: satellite images of Puget Sound urbanization>

<Figure 1-3: water budget for typical suburban development>

Steams

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 also a leading cause for in-stream physical habitat degradation and initial loss of **biotic integrity** (May et al., 1997).

<Figure 1-4: urban vs rural stream hydrograph>

<Figure 1-5: channel cross section and progressive enlargement from urbanization>

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, 1999).

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 in the Puget Sound region 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.

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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, peak flow intensity and frequency, and channel erosion. • Increased fine sediment and urban water pollutant loads. • Increased fish passage barriers.
Increased fine sediment deposition	• Reduced inter-gravel 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 concentrations and 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). • Strong synergism degrading salmonid ability to avoid prey found for combinations of common pesticides at levels common in receiving waters. • Synergistic influence of multiple types of pollutants unknown. • Nutrients: excessive aquatic plant growth; excessive **diurnal oxygen fluctuations.**

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.

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<Figure 1-6: EIA and ratio of 10yr forested to 2yr urban flow>

A recent national study by USGS (2010) assessing levels of urbanization and the physical chemical and biological response of 2nd to 3rd order stream in nine metropolitan areas across the U.S. suggest that significant impacts occur at very low levels of watershed development. Macroinvertebrate assemblages were altered in basins that are perceived as relatively undisturbed, and the commonly proposed threshold of 5-10 percent maximum impervious area is not protective of stream invertebrates for conventional development patterns. Antecedent land use plays a role in how streams response to urbanization with macroinvertebrates responding relatively less to similar land use changes in areas affected by existing impacts of agriculture. The physical and chemical variables most associated with urbanization and macroinvertebrate response were: increased flashiness, conductivity, sulfate, chloride, pesticides, polycyclic aromatic hydrocarbons, and toxicity indices (define this).

Wetlands and lakes

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).

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- 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.

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:

- *Water quality treatment. (to be completed later)*
- *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, stormwater management and Market Implications*. Duration-control design standards in Washington Department of Ecology's (Ecology) 2012 *Stormwater Management Manual for Western Washington* require large 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. In this context, several analyses by (Horner, May, Livingston, Blaha, Scoggins, Tims, Maxted, 2001; May et al. 1997; USEPA , 2006; and cite) suggest that increasing density, strategically conserving native soils and vegetation are essential tools for protecting receiving waters from the impacts of urbanization.

1.4 Low Impact Development

The conventional, purely structural approach to manage stormwater runoff has limitations for recovering adequate storage, providing adequate treatment and creating 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** even in denser settings. 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.

1.4.1 Low Impact Development Definition

Low impact development is a stormwater and land use management strategy that strives to mimic pre-disturbance hydrologic processes of infiltration, filtration, storage, evaporation and transpiration by emphasizing conservation and use of on-site natural features, site planning, and distributed storm water management practices that are integrated into a project design. LID strategies can be applied to new development, urban retrofits, infrastructure improvements, and revitalization projects to protect aquatic resources.

1.4.2 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.

1.4.3 Flow Control Objective

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

1.4.4 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.

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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. However, initial monitoring of projects on soils with low permeability suggest that pre-development hydrology can be approximated with little or no surface flow release (Hinman, 2005). 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 to meet regulatory requirements. Properly designed and implemented LID applications will significantly reduce pond size requirements (Derry, Butchart and Graham, 2004 and Horner et al., 2002).

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 1-7: forest cover EIA and stream channel stability>

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, 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). And initial monitoring of projects on soils with low permeability suggest that pre-development hydrology can be approximated with little or no surface flow release in medium density settings (Hinman, 2005). 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 may be necessary for achieving the LID flow objective where higher density projects are located on soils with low infiltration rates.

1.4.5 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 the current version of Ecology's *Stormwater Management Manual for Western Washington* (SWMMWW).

This section will be completed when the review for the current NPDES permit and the SWMMWW is complete.

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1.4.6 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 minimizing site disturbance 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.
- Reduce the development envelope, minimize road networks (density) and reduce or eliminate road stream crossings.
- 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.

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- 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: Precision Site Preparation and Construction to Minimize Site Disturbance; 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 and the techniques covered in this manual.

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

X	Site assessment	**X**	Urban trees		Living walls
X	Site planning and design	**X**	Amending construction site soils		Downspout dispersion
X	Site phasing and fingerprinting	**X**	Porous asphalt		Filter strips
X	Preserving native soils and vegetation	**X**	Pervious concrete		Constructed wetlands
X	Precision site preparation and construction	**X**	Permeable plastic and concrete grid systems		Subsurface gravel wetland
X	Bioretention cells	**X**	Permeable pavers	**X**	Maintenance
X	Sloped biodetention	**X**	Vegetated roofs		Homeowner education
X	Bioretention swales	**X**	Roof rainwater harvesting systems		
X	Bioretention planters	**X**	Minimal excavation foundations		

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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.

1.4.7 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.

1.4.8 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:

- Adopting the current version 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)

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Chapter 2: Site Assessment

In this chapter

Comprehensive inventory and assessment of on-site and adjacent off-site conditions are the important first steps for designing and implementing a low impact development project. The inventory and assessment process will provide information necessary to implement the site planning and layout activities (examined in the next section) by identifying the current, and estimating the pre-disturbance conditions. Specifically, site hydrology, topography, soils, vegetation and water features are evaluated to identify how the site currently processes stormwater. Roads, lots and structures are aligned, and construction practices are implemented to preserve and utilize these features to retain natural hydrologic function. In most all cases, low impact development requires on-site inventory and assessment and cannot be properly planned and implemented through map reconnaissance alone.

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

Inventory and evaluation, to successfully implement a low impact development 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.

Site analysis can be divided into two broad categories of activities:

1. Gathering existing analyses, inventories and historic information about the site, which includes (but is not limited to):

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- Soil surveys (soil surveys provide very broad characterization of regional soils and are not adequate for making detailed design decisions).
- Soil analyses from adjacent properties.
- Historic records documenting filling/altering of wetlands or stream channels.
- Aerial photos.
- Maps and site reconnaissance verifying topography.
- Location of ground water protection areas and/or 1, 5 and 10 year time of travel zones for municipal well protection areas.
- A description of local site geology, including soil or rock units likely to be encountered, the groundwater regime, and geologic history of the site.

2. Site reconnaissance and characterization. The remainder of the Site Assessment chapter outlines the steps necessary to adequately characterize the hydrologic, geologic and biologic conditions onsite. This characterization will inform the overall design and location of infrastructure with the goal of preserving and using on site features to function in conjunction with IMPs to manage stormwater.

2.1 Stormwater Site Plans

The Stormwater Site Plan is the comprehensive report containing the technical information and analysis necessary for regulatory agencies to evaluate a proposed new development or redevelopment project for compliance with stormwater requirements. Contents of the Stormwater Site Plan will vary depending on the Minimum Requirements applicable to the project and individual site characteristics (see SWMMWW Vol 1 Chapter 2 for Minimum Requirements and thresholds triggering those requirements).

2.1.1 Site plans for projects required to meet Minimum Requirements 1-5

Projects triggering Minimum Requirements 1-5 are generally smaller projects ranging from a single family residence and up to 2-3 homes. The following provides the minimum analysis and technical information necessary to properly design and implement an LID project and for the regulatory agency to evaluate the new or re-development for compliance with stormwater requirements.

- A survey prepared by a registered land surveyor or project proponent showing:

- Existing public and private development, including utility infrastructure on and adjacent to the site.
- Minor hydrologic features, including seeps, springs, closed depression areas, drainage swales, and
- Major hydrologic features with a streams, wetland, and water body survey and classification report showing wetland and buffer boundaries consistent with the requirements of the jurisdiction.
- Flood hazard areas on or adjacent to the site, if present
- Geologic hazard areas and associated buffer requirements as defined by the jurisdiction.
- Aquifer and wellhead protection areas on or adjacent to the site, if present.
- Topographic features that may act as natural stormwater storage, infiltration or conveyance.

- Contours for the survey are as follows:
  - Up to 10 percent slopes, two-foot contours.
  - Over 10 percent to less than 20 percent slopes, five-foot contours.
  - Twenty percent or greater slopes, 10-foot contours.
  - Elevations shall be at 25-foot intervals.
- A soils report prepared by a licensed geotechnical engineer, licensed engineering geologist or project proponent. The report should identify:
  - Underlying soils on the site using soil surveys, soil pits and/or soil grain analyses (see http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm for soil survey information).
  - Infiltration rates of soil underlying rain gardens using the infiltration testing method outlined in the Rain Garden Handbook for Western Washington Homeowners. For bioretention areas or permeable pavement use septic style pit tests, small-scale PIT or grain size analysis (see section 2.2 for PIT and grain size analysis protocol).
- Determine if depth to groundwater under rain gardens or permeable pavement is within 1 foot of the bottom (subgrade surface) of the infiltration areas using a monitoring well or excavated pit. This analysis should be performed during the winter season.
- A survey of existing native vegetation cover by a licensed landscape architect, arborist, qualified biologist or project proponent identifying any forest areas on the site and a plan to protect those areas if part of a native soil and vegetation protection area (see Chapter 4: Vegetation and Soil Protection, Reforestation and Maintenance for details).

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- Preliminary drainage report consistent with the requirements of the jurisdictions storm-water management code.

2.1.2 Site plans for projects required to meet Minimum Requirements 1-9

Projects triggering Minimum Requirements 1-9 are larger projects that must comply with Ecology's water quality treatment and/or flow control requirements. The Site Plan requirements for more complex projects include elements in section 2.1.1 plus additional characterization, and that the analysis for those plans are performed by licensed professionals. The following provides the minimum analysis and technical information necessary to properly design and implement more complex LID projects and for the regulatory agency to evaluate the new or re-development for compliance with stormwater requirements.

- A survey prepared by a registered land surveyor showing:
  - Existing public and private development, including utility infrastructure on and adjacent to the site.
  - Minor hydrologic features, including seeps, springs, closed depression areas, drainage swales, and
  - Major hydrologic features with a streams, wetland, and water body survey and classification report showing wetland and buffer boundaries consistent with the requirements of the jurisdiction.
  - Flood hazard areas on or adjacent to the site, if present
  - Geologic hazard areas and associated buffer requirements as defined by the jurisdiction.
  - Aquifer and wellhead protection areas on or adjacent to the site, if present.
  - Topographic features that may act as natural stormwater storage, infiltration or conveyance.
- Contours for the survey are as follows:
  - Up to 10 percent slopes, two-foot contours.
  - Over 10 percent to less than 20 percent slopes, five-foot contours.
  - Twenty percent or greater slopes, 10-foot contours.
  - Elevations shall be at 25-foot intervals.
- A soils report prepared by a licensed geotechnical engineer or licensed engineering geologist. The report should identify:
  - Underlying soils on the site using soil pits and/or soil grain analyses.

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- Saturated hydraulic conductivity (Ksat) of site soils. Ksat should be assessed using small-scale or full-scale Pilot Infiltration Tests (PIT) or grain size analysis (see section 2.2 for general PIT and grain size analysis protocol, section 6.1.2.1 for grain size and small-scale PIT procedures specific to bioretention and section 6.3.2.1 for grain size and small-scale PIT specific to permeable pavement). Placement of infiltration tests should be carefully considered to reduce cost. A few strategically placed PIT are generally adequate for initial site assessment and for smaller sites. A more detailed soil assessment and additional Ksat testing may be necessary to direct placement of impervious surfaces such as structures away from soils that can most effectively infiltrate stormwater, and placement of permeable pavement and bioretention over those soils. The Ksat tests are also necessary as input to the runoff model to predict the benefits of the LID integrated management practices.

- If seasonal high groundwater cannot be confirmed to be greater than 5 feet below the bottom of the bioretention or permeable pavement (subgrade surface) monitoring wells should be placed strategically to assess depth to groundwater. This analysis should be performed for one year prior to construction (including one full winter season) using a continuously logging sensor and be performed by a licensed geotechnical engineer or licensed engineering geologist.
- If on site infiltration may result in shallow lateral flow (interflow) the conveyance and possible locations where that interflow may re-emerge should be assessed by a licensed geotechnical engineer or licensed engineering geologist. This will likely require placement of groundwater monitoring wells to determine existing groundwater gradients and flow.
- If a single bioretention facility serves a drainage area exceeding 1 acre, a groundwater mounding analysis should be done in accordance with section ??? of the SWMMWW.
- A survey of existing native vegetation cover by a licensed landscape architect, arborist or qualified biologist identifying any forest areas on the site that identifies species and condition of ground cover and shrub layer, as well as tree species, condition, **seral stage**, and canopy cover.
- Delineation of native soil and vegetation protection areas and a plan by a licensed landscape architect, arborist or qualified biologist for protection during construction (see Chapter 4: Vegetation and Soil Protection, Reforestation and Maintenance for details).
- Preliminary drainage report consistent with the requirements of the jurisdictions stormwater management code.

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2.2 Soil and subsurface characterization

Low Impact Development requires in-depth soil and possibly groundwater analysis in appropriate locations to determine operating infiltration rates and soil storage capacity for three primary reasons: 1) LID emphasizes evaporation, storage and infiltration of stormwater in smaller-scale facilities distributed throughout the site; 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; and 3) pre-development soil storage capacity provides baseline data for estimating post-development soil storage needs

Soil and subsurface characterization relies to a large extent on infiltration test pits and soil borings. The type and number of soil test pits and borings for initial site assessment are variable and site specific, however, some general guidelines are appropriate. A few strategically placed soil test pits is 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 for soil pit and soil borings recommendations for initial assessment. A more detailed soil pit assessment may be necessary once the preliminary site layout with location of LID stormwater controls is determined.

For recommendations on test frequency and correction factors specific to bioretention see Section 6.1.2.1 Determining subgrade and bioretention soil media design infiltration rates. For recommendations on test frequency and correction factors specific to permeable pavement see Determining sugrade infiltration rates under section 6.3.2.1 Common components, design and construction criteria for permeable pavement systems.

The methods below are used to determine the short-term (initial) saturated hydraulic conductivity rate for subgrade soil profile (existing) soils beneath bioretention areas and permeable pavement. The initial or measured saturated hydraulic conductivity with no correction factor may be used as the design infiltration rate if the qualified professional engineer deems the infiltration testing described below (and perhaps additional tests) are conducted in locations and at adequate frequency capable of producing a soil profile characterization that fully represents the infiltration capability where the bioretention or permeable pavement areas are located. For example, if the small-scale PITs are performed for all bioretention areas and the site soils are adequately homogeneous.

If deemed necessary by a qualified professional engineer, a correction factor may be applied to the measured saturated hydraulic conductivity to determine the long-term (design) infiltration rate. Whether or not a correction factor is used and the specific number used will depend on heterogeneity of the site soils and number of infiltration tests in relation to the number and type of infiltration areas (see section ??? for more details on correction factors). For bioretention areas, the overlying BSM provides excellent protection for the underlying native soil from sedimentation; accordingly, the underlying soil does not require a correction factor for influent control and clogging over time.

If a single bioretention facility serves a drainage area exceeding 1 acre, a groundwater mounding analysis should be done in accordance with section ??? of the SWMMWW.
Three infiltration tests are recommended for initial site assessment and subsequent detailed analysis if necessary. Specific tests are determined by site conditions and the type of LID infiltration practice.

1. In-situ small-scale pilot infiltration test method

The small-scale Pilot Infiltration Test (PIT) is similar to the large-scale PIT, but reduces cost and test time and is appropriate for LID facilities that (when designed properly) have lower hydraulic loads. Pilot Infiltration Tests provide the advantage of in-situ field test procedures that approximate saturated conditions and allow inspection of soil stratigraphy beneath the infiltration test. The test method is the following:

- Excavate the test pit to the estimated elevation at which the imported BSM will lie on top of the underlying native soil. Lay back the slopes sufficiently to avoid caving and erosion during the test.
- The horizontal surface area of the bottom of the test pit should be 12 to 32 square feet. It may be circular or rectangular, but accurately document the size and geometry of the test pit.
- Install a vertical measuring rod adequate to measure the full ponded water depth and that is marked in half-inch increments in the center of the pit bottom.
- Use a rigid diameter pipe with a splash plate on the bottom to convey water to the pit and reduce side-wall erosion or excessive disturbance of the pond bottom. Excessive erosion and bottom disturbance will result in clogging of the infiltration receptor and yield lower than actual infiltration rates. Use a 3 inch pipe for pits on the smaller end of the recommended surface area and a 4 inch pipe for pits on the larger end of the recommended surface area.

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- Add water to the pit so that there is standing water for at least 6 hours.
- At the end of the pre-soak period, add water to the pit at a rate that will maintain a 6-12 inch water level above the bottom of the pit over a full hour.
- Every 15 minutes, record the cumulative volume and instantaneous flow rate in gallons per minute necessary to maintain the water level at the same point (between 6-12 inches) on the measuring rod.
- After one hour, turn off the water and record the rate of infiltration in inches per hour from the measuring rod data until the pit is empty.
- A self-logging pressure sensor may also be used to determine water depth and drain-down.
- At the conclusion of testing, over-excavate the pit to see if the test water is mounded on shallow restrictive layers or if it has continued to flow deep into the subsurface.
- Data Analysis
    - Calculate and record the infiltration rate in inches per hour in 30 minutes or one-hour increments until one hour after the flow has stabilized.
    - Use statistical/trend analysis to obtain the hourly flow rate when the flow stabilizes. This would be the lowest hourly flow rate.
    - Apply appropriate correction factors to determine the site-specific design infiltration rate (see Table ??? for bioretention correction factors and Table ??? for permeable pavement corrections factors).

<figure 2-1: PIT test photo>

2. Soil grain size analysis method

The soil grain size analysis method can be used if the site has soils unconsolidated by glacial advance.

- Grain size should be analyzed for each defined layer below the top of the final bioretention area subgrade to a depth of at least 3 times the maximum ponding depth, but not less than 3 feet (1 meter).
- Estimate the saturated hydraulic conductivity in cm/sec using the following relationship (see Massmann 2003, and Massmann et al., 2003).

$$\log_{10}(K_{sat}) = -1.57 + 1.90D_{10} + 0.015D_{60} - 0.013D_{90} - 2.08\mathrm{f}_{\mathrm{fines}} \quad (1)$$

Where, D_{10}, D_{60} and D_{90} are the grain sizes in mm for which 10 percent, 60 percent and 90 percent of the sample is more fine and f_{fines} is the fraction of the soil (by weight) that passes the number 200 sieve (K_{sat} is in cm/s).

- If the licensed professional conducting the investigation determines that deeper layers will influence the rate of infiltration for the bioretentions area, soil layers at greater depths should be considered when assessing the site's hydraulic conductivity characteristics.
- Machinery or material stockpiles and associated compaction should not be allowed in bioretetion areas. Equation 1 assumes minimal compaction consistent with the use of tracked (i.e. low to moderate ground pressure) excavation equipment. If the soil layer being characterized has been exposed to heavy compaction, the hydraulic conductivity for the layer could be approximately an order of magnitude less than what would be estimated based on grain size characteristics alone (Pitt, 2003). In such cases, compaction effects must be taken into account when estimating hydraulic conductivity unless the project engineer determines that compaction (if present) has been mitigated. For clean, uniformly graded sands and gravels, the reduction in K_{sat} due to compaction will be much less than an order of magnitude. For well-graded sands and gravels with moderate to high silt content, the reduction in K_{sat} will be close to an order of magnitude. For soils that contain clay, the reduction in K_{sat} could be greater than an order of magnitude.
- Use the layer with the lowest saturated hydraulic conductivity to determine the short-term (measured) hydraulic conductivity.
- Apply appropriate correction factors to determine the site-specific design infiltration rate (see Table ??? for bioretention correction factors and Table ??? for permeable pavement corrections factors).

3. In-situ large-scale Pilot Infiltration Test (PIT) method

Large-scale in-situ PIT described below is the preferred method for estimating the short-term saturated hydraulic conductivity of the soil profile beneath permeable pavement facilities where water from adjacent impervious surfaces is directed to the pavement surface resulting in higher hydraulic loads. The test method is the following:

- The horizontal surface area of the bottom of the test pit should be approximately 100 square feet. Accurately document the size and geometry of the test pit.
- Install a vertical measuring rod (minimum 5-ft. long) marked in half-inch increments in the center of the pit bottom.

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- Use a rigid 6-inch diameter pipe with a splash plate on the bottom to convey water to the pit and reduce side-wall erosion or excessive disturbance of the pond bottom. Excessive erosion and bottom disturbance will result in clogging of the infiltration receptor and yield lower than actual infiltration rates.
- Add water to the pit at a rate that will maintain a water level between 6 and 12 inches above the bottom of the pit. A rotameter can be used to measure the flow rate into the pit.
  Note: The depth should not exceed the proposed maximum depth of water expected in the completed facility.
- Every 15-30 min, record the cumulative volume and instantaneous flow rate in gallons per minute necessary to maintain the water level at the same point (between 6 and 12 inches) on the measuring rod.
- Add water to the pit until one hour after the flow rate into the pit has stabilized (constant flow rate) while maintaining the same pond water level. (usually 17 hours)
- After the flow rate has stabilized, turn off the water and record the rate of infiltration in inches per hour from the measuring rod data, until the pit is empty.
- At the conclusion of testing, over-excavate the pit to see if the test water is mounded on shallow restrictive layers or if it has continued to flow deep into the subsurface.
- Data Analysis
  - Calculate and record the infiltration rate in inches per hour in 30 minutes or one-hour increments until one hour after the flow has stabilized.
  - Use statistical/trend analysis to obtain the hourly flow rate when the flow stabilizes. This would be the lowest hourly flow rate.
  - Apply appropriate correction factors to determine the site-specific design infiltration rate (see Table ??? for bioretention correction factors and Table ??? for permeable pavement corrections factors).

See section ???: Determining subgrade and bioretention soil media design infiltration rates and setion ???: Determining subgrade infiltration rates for permeable pavement for correction factors soil testingg specific to those practices.

The depth and number of test holes or test pits, and samples should be increased, if in the judgment of a licensed engineer with geotechnical expertise (P.E.), a licensed geologist, engineering geologist, hydrogeologist, or other licensed professional acceptable to the local jurisdiction, the conditions are highly variable and such increases are necessary to accurately

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estimate the performance of the infiltration system. The exploration program may also be decreased if, in the opinion of the licensed engineer or other professional, the conditions are relatively uniform and the borings/test pits omitted will not influence the design or successful operation of the facility. In high water table sites, the subsurface exploration sampling need not be conducted lower than two feet below the ground water table.

Prepare detailed logs for each test pit or test hole and a map showing the location of the test pits or test holes. Logs must include at a minimum, depth of pit or hole, soil descriptions, depth to water, presence of stratification. Logs must substantiate whether stratification does or does not exist. The licensed professional may consider additional methods of analysis to substantiate the presence of stratification that will

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.

If the ground water in the area is known to be less than 5 feet below the proposed facility, the ground water regime should be assessed . At a minimum, ground water monitoring wells should be installed to determine groundwater depth and seasonal variations, considering both confined and unconfined aquifers. Monitoring through at least one wet season is required, unless site historical data regarding ground water levels is available.

If on site infiltration may result in shallow lateral flow (interflow) the conveyance and possible locations where that interflow may re-emerge should be assessed by a licensed geotechnical engineer or licensed engineering geologist. In general, a minimum of three wells associated with three hydraulically connected surface or ground water features, are needed to determine the direction of flow and gradient. Alternative means of establishing the ground water levels

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may be considered. If the ground water in the area is known to be greater than 5 feet below the proposed facility, detailed investigation of the ground water regime is not necessary.

Special considerations are necessary for highly permeable gravel areas. Signs of high ground water 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 ground water 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).

2.3 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. Utilizing 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.

Inventory and assessment

In addition to identifying the 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 soil test pits do not provide sufficient information to determine depth to ground water, map ground water table height and sub-surface flow patterns in proposed development, infiltration, and dispersion areas using shallow monitoring wells. In many sites, shallow hand-augured monitoring wells can be installed at low cost.

For management of on-site hydrologic features see section 2.5: Riparian Management Areas, Chapter 1: Introduction, Chapter 3: Site Planning and Layout, and Chapter 5: Precision Site Preparation and Construction sections.

2.4 Native forest and soil protection 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.

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, condition, **seral stage**, and canopy cover.
- Identify underlying soils using soil pits and soil grain analysis to assess infiltration capability. 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 soil and vegetation protection areas see Chapters 4: Vegetation and Soil Protection, Reforestation and Maintenance and Chapter 5: Precision Site Preparation and Construction.

2.5 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 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

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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.

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:
  - Measure existing hydroperiods and estimate future hydroperiods resulting from proposed development.
  - Identify hydrologic pathways into and out of wetland.
  - Determine whether the wetland has breeding, native amphibians (conduct survey in spring).
  - Identify and delineate riparian buffer.

Management

If the wetland qualifies for protection, use LID strategies to increase stormwater infiltration and storage on the project site in order to meet the following guidelines (Azous and Horner, 2001).

- The increase or decrease of the pre-development mean monthly water level fluctuations should be maintained to less than 5 inches.
- 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.
- 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.

- Do not allow the total dry period (when pools dry down to the soil surface everywhere in the wetland) to increase or decrease by more than two weeks in any year.
- 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.
- 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.
    - See Guide sheets 3A through 3C in Appendix 1-D of the 2005 stormwater manual 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.

2.6 Riparian Management Areas (RMA)

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

- 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).

Adequately sized and maintained Riparian Management Areas can protect streams, lakes and wetland areas from some impacts of surrounding urbanization, as well as supply nutrients and materials to support healthy aquatic ecosystems.

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, 2.7: Floodplains, and Chapter 4: Vegetation Protection, Reforestation, and Maintenance for assessing the extent and quality of the RMAs in various settings.

Management

Riparian Management Areas 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.

2.7 Streams

Determining appropriate assessment and management protocol for stream channel corridors will require clear articulation of goals and objectives. Appropriate goals and objectives will likely be determined through the development application process involving government permitting entities, consultants and the developer. If the project is within a watershed with streams designated as high quality and sensitive, objectives for assessment and management strategies should include: 1) protect mature native riparian vegetation and soils; 2) protect diverse native stream habitat characteristics to support the native assemblage of stream life; and 3) maintain pre-development hydrology. Note: in urban settings, where stream function is

impaired and enhancement strategies are considered, special design strategies may be required to incorporate structural protection measures into habitat restoration goals. Any in-stream restoration efforts should not proceed without a clear understanding of the stream type, processes influencing the watershed and restoration reach, and upstream disturbance inputs that influence downstream activity.

Inventory and assessment

The following steps should be utilized as a starting point to adequately inventory and provide an assessment of any creeks, streams or rivers:

- Identify stream category by using DNR water typing classification system (WAC 222-16-030).
- Identify riparian area and fish and wildlife habitat requirements.
- Assess general stream corridor condition and determine if there is a need for more detailed assessment and specific management strategies.

Management

- Designate riparian management area widths according to best available science and local jurisdiction regulations.
- Map riparian management areas on all plans, and delineate riparian management areas on the site with silt, chain link or other appropriate fencing to protect soils and vegetation from construction damage.
- See Riparian Management Area section for additional management strategies.

2.8 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.

Inventory and Assessment

The following steps, at a minimum, should be used to inventory and provide an assessment of floodplain areas:

- Identify the 100-year floodplain and channel migration zone.

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- Inventory composition and structure of vegetation within the floodplain area.
- Indentify active channel.

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.

2.9 Sub-basin Delineation

Stormwater management in the LID context is based on a distributed approach. The project site and most importantly the development envelope is divided into sub-basins or small contributing areas that are managed in small-scale hydrologic and water quality treatment practices. This approach provides several advantages some of which include: the individual practices receive smaller hydraulic and pollutant loads; the small-scale practices can be arranged in the project efficiently and save space for other amenities compared to large ponds; and the LID practices can be designed into the project as community amendments. To effectively design within the distributed approach, consider the sub-basin delineation and how to integrate the small-scale stormwater management practices at the initial stages of the project design.

<figure 2-2: contributing area delineation >

2.10 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, and guide the road layout and overall location and configuration of the development envelope(s). See the Site Planning and Layout section for details on utilizing assessment information for site design.

<figure 2-3: site analysis map layers and composite map>

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Chapter 3: Site Planning and Layout

In this chapter...

Site assessment and site planning are iterative processes. Existing and native environmental conditions strongly influence the extent and location of the development envelope for an 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 minimizing and 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, housing type or commercial building given the existing character and possible future conditions. Architectural considerations and the mix of land use types (e.g. commercial and residential mixed use) 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 of the site layout and 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.

Density and stormwater management

Density within the context of regional and site planning has a very significant impact on stormwater management. Recent modeling studies suggest that increasing density is the most effective management strategy for reducing stormwater volume and associated pollutant loads per building. Jacob and Lopez (2009) found that doubling typical suburban densities to

8 dwelling units per acre did more to reduce volume and pollutant loads than most conventional BMPs, and at 64 dwelling units per acre, volume and pollutant loads were reduced more than essentially all conventional BMPs scenarios (population held constant). EPA (2006) also found that higher density scenarios generated less impervious cover and less stormwater runoff at the house and watershed scale. When coupled with sound open space, stream and wetland protection, reducing green field development and sprawl is a critical tool for protecting receiving waters. Given these and other community benefits that come from more compact growth and that the Washington Growth Management Act promotes development in urban cores, this chapter focuses to a large extent on techniques to management stormwater on small lots and higher density scenarios.

Regulatory context

The configuration of lots, the location of structures on parcels, road widths and other site layout considerations are influenced by several local codes and standards, including:

- Comprehensive Plan Goals and Policies.
- Zoning Code.
  - Landscaping, Native Vegetation, Tree Protection, and Open Space.
  - Impervious Surface Standards.
  - Bulk and Dimensional Standards.
  - Site Plan Review.
  - Parking.
- Development Code and Standards.
  - Clearing and Grading Standards.
  - Engineering and Street Standards.

There may be language within these codes and standards that discourages or prohibits LID strategies. For example existing lot setback, street width standards, parking requirements and density standards may lead to excessive impervious surface coverage. Integrating new codes and standards that allow LID practices and improve stormwater management is not the subject of this manual; however, guidelines for accessing existing code and implementing LID in local jurisdictions are available in *Integrating LID into Local Codes: A Guidebook for Local Governments* (Puget Sound Partnership, 2011).

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Initial delineation and site management

Assessment of natural resources outlined in the previous section will produce a site plan with a series of maps identifying streams, lakes, wetlands, buffers, steep slopes and other hazard areas, significant wildlife habitat areas, existing utilities and setbacks, 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 delineation and 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 construction 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 implementing the site plan.
- Meet and walk the property with equipment operators prior to clearing and grading to clarify construction boundaries and limits of disturbance (see Chapter ???: Vegetation Protection, Reforestation, and Maintenance and Chapter ???: Precision Site Preparation and Construction for more detailed information).

This chapter is organized under three main categories: (1) urban redevelopment and infill; (2) new suburban development; and (3) commercial. The first two categories are further divided into two sections that examine: (a) roads, driveways and parking; and (b) housing type, mixed use and lot layout. The third category, commercial, focuses on parking.

3.1 Urban redevelopment and infill

Infill development is the process of developing vacant or under-used parcels within existing urban areas that are already largely developed. Infill takes advantage of, and improves the tax base for, existing infrastructure and services including various transportation modes, sewer, water, and power. Other benefits can accrue with development in urban core areas by reducing transportation impacts and creating more vibrant neighborhoods with a mix of

housing types closer to services and employment (MRSC, 1997).

While the socio-economic benefits of infill can be significant, the reduction of green field and sensitive area conversion is one of the most effective stormwater management strategies for protecting streams, lakes and wetlands. Under conventional land use development the population increased by 36 percent in the Puget Sound region between 1970 and 1990. During the same period, the amount of developed land increased by 87 percent (Pivo and Lidman, 1990). In the Puget Sound lowlands most precipitation is transformed to ET or groundwater flow with 1% or less reaching fresh water as overland flow. Estimates for typical suburban overland flow range from 30-40%. As a result, reducing land development and using existing converted land in urban cores is one of the most cost effective stormwater volume reduction tools.

Stormwater regulations for infill have to balance adequate flow and water quality treatment guidelines in relation to the expense of those regulations that may discourage infill. And area available for stormwater storage, infiltration and treatment in denser development is limited. However, opportunities in roadways, parking areas, building sites, and the building envelope do exist to improve existing conditions in the urban setting.

3.1.1 Roads, Driveways and Parking

The overall objectives for LID redevelopment and infill road designs are:

- Reduce **total impervious area** (TIA) by reducing pavement coverage.
- Minimize effective impervious area (EIA) and concentrated surface flows on impervious surfaces by reducing or eliminating hardened conveyance structures (pipes or curbs and gutters).
- Infiltrate or slowly convey storm flows in roadside bioretention cells and swales, and through permeable paving and aggregate storage systems under the pavement.
- Slow and filter storm flows through bioretention planters.
- Incorporate trees and adequate planting soil galleries in the streetscape.
- Create connected street patterns to promote walking, biking and access to transit and services, as well as provide efficient fire and safety vehicle access.
- Create and use open space areas as a community amenity and to store and slow storm flows during the winter when the areas are less active.

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Road layout and streetscape

In developed urban cores road layout is often set within the historic development pattern. However, several design strategies within an existing streetscape are possible for improving stormwater management and enhancing community character:

- Bioretention in traffic calming designs and other open space associated with roadways (see Figure ???).
- Bioretention planters and trees in sidewalks and promenades (see Figure ???). See section ???: Bioretention for design details.
- Permeable pavement and bioretention in parking areas.
- Permeable pavement surrounding trees and associated subsurface planting soil structures (see Figure ???). See section ???: Urban Trees and section ???: Permeable Pavement for design details.

<Figure 3-1: Portland traffic calming>

<Figure3-2: Portland planter (12th and Montgomery) and planview graphic>

<Figure 3-3: Silva Cell project>

The Sherbourne project (see figures ???) is a residential infill project designed with a loop road along home frontages that provides good access for residents, as well as 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 3-4: Sherbourne plan view>

<Figure 3-5: Sherbourne picture>

For more strategies applicable to the road layout and width, sidewalks, driveways, and parking see section ???: Roads, Driveways and Parking for suburban development.

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

See Section ???: Permeable Pavement for details.

<Figure 3-6: Vancouver, B.C. alley>

3.1.2 Lot and Building Design

As density increases so does the percentage of surface flow associated with rooftops. At the same time, the available area to manage the roof water at the ground level decreases. Rainwater harvesting and green roofs are two strategies that become relatively more applicable in the dense urban core, particularly for commercial or multifamily complexes. For more information on rain water collection see section ??? and for vegetated roofs see section ???.

Bioretention and permeable paving systems are highly adaptable and can provide significant stormwater management benefits in an ultra-urban setting. Applicable strategies include Bioretention cells or planters adjacent to or attached to the building (for more information on bioretention planters see section ???) and permeable pavement courtyards and walkways. Permeable pavement can be particularly effective surrounding trees and associated subsurface planting soil structures (see section ???: Urban Trees for more information).

<Figure 3-7: Portland bioretention planter>

<Figure 3-8: Portland court yard bioretention>

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Preserving native soils and vegetation and incorporating LID practices in relatively dense residential infill is challenging, but achievable. Good site assessment, strategic design and careful construction sequencing are key processes for success. Particularly important in LID residential infill projects is to consider surrounding neighborhood character and design to integrate within that context. Danielson Grove provides a good case study for preserving native soils and vegetation and incorporating LID features in a dense residential infill project.

Project case study: Danielson Grove, Kirkland, WA

<Figure 3-9: Danielson Grove graphics>

Low impact development practices applied at Danielson Grove

Site Planning

- Clustering
- Use of open space
- Retained vegetation / soils
- Reduction of potable water use

Stormwater Management

- Reduction of impervious surfaces
- Use of amended top soil
- Bioretention
- Permeable pavement

Construction

- Shared infrastructure facilities
- Reduced grading impacts

Project Overview

Danielson Grove was completed in 2005 and built under the City of Kirkland's Innovative Housing Demonstration Project Ordinance. Sixteen cottage-style homes (700 to 1,500-square feet) are carefully arranged on individual fee simple lots ranging from 2,400 to 3,000 square feet. The project is located in an established traditional single family residential

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neighborhood with lots ranging in size from 7,000 to 10,000 square feet. The total project site area is 2.25 acres, zoned R-7200, generally flat sloping to the west, with approximately 40% of the pre-development site covered with native coniferous trees and understory plant material.

Site Planning

Danielson Grove was executed by a diverse design team consisting of the owner/builder, architect, civil engineer, landscape architect, geologist, arborist, governing jurisdiction, and the contractor. The importance of building a broad-based team early in the conceptual planning process and working collaboratively thru to the end of construction can not be overstated; particularly on infill redevelopment projects with increasing densities.

Creative clustering allowed the preservation of large undisturbed open spaces and saved approximately 40 existing trees, compared to just six which would have been sufficient to meet tree retention requirements under existing zoning. One benefit of these saved trees is the creation of a visual buffer with adjacent neighbors. Views onto the site are filtered through the mature stands of existing vegetation. Also, scale and orientation of the cottages was selected to further reduce impacts to the existing neighborhood. This was accomplished by moving houses back from and reducing their height close to street edges. Adjacent to the most heavily traveled public roadway is a one story community building which is visually inviting to pedestrians, but which also creates separation and privacy for the internal shared, common green space. Individual lot sizes and private outdoor space have been reduced in order to maximize retained vegetation and allow for larger areas of shared, common open spaces. As a result, approximately 41% of the site is set aside as open space. Of this, 10% is undisturbed soils and vegetation, and 22% is set aside as common open space.

The cottages front doors are organized around central common areas helping to create safe, friendly and usable spaces. An important component in developing the community is the use of low open fences along individual lot lines. These help separate and define public and private areas, while allowing a visual connection. To strengthen the development of this tight-knit community even further, all garages are detached with residents walking to their front door through the common areas. This encourages personal interaction for all residents.

The community is parked at 1.5 stalls per unit with each cottage having one assigned detached garage and sharing eight off-street stalls. In addition, there are approximately 25 on-street

parking stalls available to the community and visitors. By detaching the garages, the cottages have smaller footprints, making them more human in scale, and preventing the internal street from being dominated by garage doors. In addition, on-street parking is more efficient due to the reduction in individual garage driveway cuts.

Creating Community

With its smaller footprint homes, network of paths, “out back” garages, and inviting common spaces, Danielson Grove fosters a sense of community by encouraging interaction among its residents. The low, informal fences separate community and private spaces, while giving homeowners a sense of privacy and opportunity for individual expression.

This project defies its small size by offering its residents a variety of experiences. There is a hierarchy of exterior spaces – meandering walkways, expansive lawn, and large outdoor plaza for community gatherings, as well as small patios and seating nooks for individual use.

Stormwater Management

A network of porous paths meander through retained vegetation allowing water to filter and cleanse through native soils and plant roots before entering the storm system. Attractively designed bio-filtration swales are strategically placed between buildings to collect and treat roof and surface runoff. These features dramatically extend the length of time stormwater remains on the site, improving water quality, and maximizing the opportunity for infiltration, plant uptake and evapotranspiration. Ultimately, drainage is conveyed to a detention vault buried beneath the centrally located community building and plaza. The vault provides flow control, mimicking pre-development conditions by slowly releasing drainage to the public receiving system.

Porous pavers were used in the plaza area to allow the stormwater to drain directly into the detention vault.

The street right of way is 40 feet with a 22-foot section providing two traffic lanes and parking on one side. Instead of traditional concrete sidewalks on both sides of the public street, a single concrete sidewalk was constructed on one side of the street with a porous gravel walk on the other. Crushed gravel and porous concrete walkways were used under the existing conifer canopy to minimize root disturbance and maintain healthy root growth.

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All non-retained planting areas incorporated approximately 12 inches of amended compost tilled deeply into the existing soil structure to improve moisture holding capacity and add nutrients. In order to minimize water use, water-wise natives and locally naturalized plant material were used extensively. In addition, irrigation needs were minimized by limiting the use of lawn primarily to the central “commons” area.

Construction

Grading impacts were reduced by careful upfront site planning with a focus on saving existing trees and minimizing soil disturbance. This was accomplished by reducing building foundation foot prints, and co-locating utilities. Additionally, special attention was paid to matching existing grades. This minimized cuts and fills, reducing the amount of material needing to be hauled off or onto the site to establish design grades.

Utility infrastructure was designed to efficiently serve the project while minimizing site disturbance. Water and sewer lines were located only in areas that were already slated for disturbance. Water meters were clustered to minimize disturbance resulting from service line construction. Dry utilities were co-located under proposed sidewalks in joint trenches.

The Result

Danielson Grove is a neighborhood rich in detail, texture and vibrant color. The focus is on sensitivity to the environment and design for human scale and interaction. This combination results in a site that functions environmentally, socially and aesthetically.

Builder: The Cottage Company
Architect: Ross Chapin Architects
Civil Engineer: Triad Associates
Landscape Architect: Triad Associates

End of case study

3.2 New suburban development

The following applies to medium to high density suburban settings, planned communities and rural development.

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3.2.1 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).

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.
The overall objectives for LID new suburban road designs are:

- Reduce TIA by reducing the overall road network coverage.
- Reduce stream crossings with efficient road network design.
- 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 to promote walking, biking and access to transit and services, as well as provide efficient fire and safety vehicle access.
- Create and use open space areas as a community amenity and to store and slow storm flows during the winter when the areas are less active.

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. Figures ??? illustrate the grid and curvilinear road layouts and Table 3.1 summarizes the strengths and weaknesses of the grid and curvilinear approaches.

<Figure 3-10: grid road layout>

<Figure 3-11: curvilinear road layout>

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Table ??? 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.*

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; Center for Housing Innovation, 2000; CMHC, 2002). 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 (see Figure ???).

<Figure 3-12: hybrid road layout>

The road and pedestrian pathways in figures ??? and ??? illustrate multifunctional site layout. Specifically, 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.

<Figure 3-13: loop road design>

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.

<Figure 3-14: green street section>

The above design example illustrates that lot configuration, pedestrian accessibility, as well as efficient vehicle access influence road layout. The following are lot layout and pedestrian design strategies to create 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).
- Reduce front yard set-backs to reduce driveway length.
- 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).

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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.

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).

<get CO study>

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 ???.

<Figure 3-15: LID road sections>

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Table ??? 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*

Reducing the street width from 26 to 20 feet reduces TIA by 30 percent. In the road network represented in Figure ???, 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.

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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 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 ???.

<Figure 3-16: turnaround areas>

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 ???: 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 ??? and ???). 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 ??? provides two examples of queuing streets for local residential streets.

<Figure 3-17: queuing streets>

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 (see Figure ???).

<Figure 3-18: pullout parking>

All or part of pullout parking areas, queuing lanes or dedicated on-street parking lanes can be designed using permeable paving. 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 ???: 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 ???).

<Figure 3-19: traffic calming>

<Figure 3-20: traffic calming pic>

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:

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- 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.
- 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 ???: Amending Construction Site Soils and Section ???: Bioretention Areas for details).

<Figure 3-21: shared driveway>

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 3-22: shared driveway for large lots>

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 bio-retention 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 ???: Permeable Paving for details).

3.2.2 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 con-veyance 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.

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 (see Figure ??? and Fairhaven Heights case study).

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.

<Figure 3-23 conventional vs LID lot layout>

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).
- Minimize setbacks. Examples of minimum setbacks include:
  - 25-foot front yard.
  - 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 (see Figure ???).
- 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.

<Figure 3-24: zero lot line configration>

<Figure 3-25: small lot using LID practices>

Good site assessment is critical where development is proximate to or may directly impact sensitive areas. Equally important is creative site design (informed by the site assessment) that strategically protects native soil, vegetation and hydrology to the maximum extent possible. The following case study provides a good example of that design and assessment process with a site plan that accommodates scheduled growth and protects sensitive areas.

Project case study: Fairhaven Heights

<Figure 3-26: Fairhaven Heights graphics>

Low impact development practices applied at Fairhaven Heights

Site Assessment and Planning

- Detailed site analysis characterizing soils, vegetation, hydrology, topography, as well as community context.
- Clustering.

- Diverse use of housing type to reduce the development envelope and building height while creating an aesthetic, desirable neighborhood.
- Use of open space.
- Retained vegetation and soils.

Stormwater Management

- Reduction of impervious surfaces.
- Use of amended top soil.
- Bioretention.
- Permeable pavement.

Project background

This 82 acre infill site, located in northern Puget Sound had been logged several times and was quarried for gravel, but now contains second and third growth vegetation and wetlands. Under early planning regulations the site was slated to accommodate a significant amount of growth at over 1,460 residential units. Changes in the 1990s reduced site entitlement to 739 units, which represented 3-5% of the city's projected housing needs to 2022.

The site is well-situated to accept growth. It is mostly surrounded by development and is within an urban boundary. Single family homes border the west, south and north-east sides of the site and multifamily housing is located to the north. The site is less than a half mile from two schools and an existing bus route that passes within a couple hundred feet of its western border could be extended to the property.

Physically restricting future development, however, are the site's critical areas. There are several wetlands that bisect the site into two restricting connections between the halves of future development. Also, there are a few areas of critical slopes towards the north end of the property.

Site analysis

Topography, soils, stormwater, micro-climate, flora and fauna are all an interconnected part of an ecosystem. The site analysis focused on gaining a thorough understanding of ecosystem functions and how proposed development would be compatible with those functions.

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Understanding site hydrology was critical for protecting the site's wetlands. Water quantity, quality and temperature contributed to the health of on-site habitat and offsite systems. Site studies, including nearly 50 pits and borings, probed into soils, water infiltration rates and fluctuations through the seasons and examined how the wetlands might be interconnected both above and below grade. The site drains to two major watersheds, but contains many small watersheds each requiring detailed analysis and measurement. It was the goal of the team that existing wetland hydrology be maintained post-development.

The interdisciplinary team of experts, synthesized this information into analysis diagrams, as a series of overlays that would guide the planning. Based on this information, an approximate development boundary was established that would encompass the flattest site areas and the former gravel quarry; avoid critical slopes, the significant wetlands and their required buffers; and maintain large stands of vegetation. Several smaller isolated lower quality wetlands that were created through the site quarrying, could be filled within regulations. Mitigation for these smaller wetlands would include enhancement and restoration of damaged areas within the higher quality wetlands and their buffers. Further, wetland buffers would be enhanced beyond minimum requirements, where necessary to maintain their functions.

Site planning and layout

In order to minimize the impact of the development, the smallest, most compact site development footprint was planned through creative site planning. Proposed uses are limited to about half the site, leaving 40 acres as preserved natural area and enhanced wetland buffers. This was accomplished through a marriage of modest tweaks to the building program and building type, efficient land planning that worked in conjunction with the site's features and topography and low impact development strategies, all of which maintained the allowed 739 residential units.

In previous site plan proposals, single family detached homes were less than 20% of the building program but occupied nearly two-thirds of the proposed land area. There were a small amount of town homes and the majority (537 units) were placed in multifamily buildings with nearly two-thirds of the residences in 8-10 story buildings. By adding more town homes to the program, and reducing the amount of single family detached homes, Weber Thompson was able to save an additional 20 acres of land area from development. At the same time, by proposing more low-rise multifamily structures, with grade related entrances, the development

would have the feel and scale of town homes, provide more variety of unit types to the multi-family housing program, and likely attract a wider range of residents.

In order to meet 739 units, one might suspect that building height had to increase as a result of reducing the land area; in fact, the converse is true. The plan allowed more area for multi-family structures and in turn, the overall height of buildings could be reduced. More than half the proposed site's homes are in 2-3 story structures, and only 100 units, or 13% are in one five floor structures, making it likely that little or none of the development would be visible beyond the preserved trees. As the previous plan had 62% of its units in 8-10 story buildings, the visibility of the project to the surrounding neighbors was a big concern of the opposition. Another land saving tactic was in the handling of parking. Nearly all structures used the topography to have tuck-under parking, thereby freeing up more land for other purposes. While this is a more expensive way of handling parking, savings were made in other ways. Fewer roads, and less infrastructure and re-grading would reduce site development construction costs, while reduced building height allowed for a less expensive construction type.

The compactness of the plan had compounding environmental benefits as well. It reduced the amount of land disturbed for construction and allowed very large contiguous swaths of vegetation, soils and habitat to be preserved. It also reduced the amount of roads, parking and related impervious surfaces, creating less storm water runoff. At the same time, the plan provides a generous amount of planned green spaces, centrally located parks and community centers with possible daycare, access to trails and transit that combined with the ample access to natural areas provides exceptional livability in a compact, pedestrian, socially-focused community.

The native topography of the site informed where the roads were to be located and the shape of each neighborhood. In order to avoid extensive re-grading, the proposed roads follow the line of the existing topography working their way gradually up and around hills. The site's entrance road posed a particular challenge. Wetlands and topography combined with design restrictions on the main access road resulted in one access point that was feasible, and would require skirting between the site's two major wetlands to connect the development. It was proposed that this road be raised over the wetland at key portions to allow water and wildlife to flow underneath. To combat this lack of vehicle inter-connectivity between the two sides, many trail connections are planned that would make it easy to walk within the neighborhood and

connect to future transit link on the main road.

In conjunction with the civil engineer, wetland biologist and landscape architects, the site plan employs low impact storm water strategies that are modeled to maintain pre-development hydrology. A proposed linear rain garden or bio-swale lines every street. Pervious pavement in alleys and on parking strips infiltrates storm water where it falls. Runoff is also directed to a series of rain gardens in neighborhood green spaces, including a large infiltration area over the former gravel pit, now turned central park. All these features serve to slow, clean, cool and infiltrate the runoff before it is dispersed to the wetlands. At the low point of the site near the entrance, some runoff is held back from an overflow vault for a water feature. There is only one small conventional storm water pond located near the single family homes.

Planning and Architecture: Weber Thompson
Civil Engineer: Ronald T. Jepson and Associates
Geotech, Hydrology: GeoEngineers, Inc.
Landscape Architect: The Watershed Company
Traffic: The Transpo Group

End of case study

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.

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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).

<Figure 3-27: conventional large lot vs rural cluster>

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 ???: 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.

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- Place clusters on the site and use native vegetation to screen or buffer higher density clusters from adjacent rural land uses.

3.2.3 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 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 ??? Vegetated Roofs and Section ??? Roof Rainwater Collection Systems for design guidelines).
- Use low impact foundations (see Section ???: 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 ???: Vegetation Protection, Reforestation, and Maintenance, and Chapter ???: Clearing and Grading).

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3.3 Commercial

3.3.1 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.

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 reducing TIA below a maximum allowed is required 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).

<should we add more discussion on landscape requirements and integrating bioretention into those requirements>

Project case study: Wilson Motors, Bellingham, WA

<Figure 3-28: Wilson Motors graphics>

Project background

Wilson Motors has been a locally owned Bellingham business for almost three decades. Over the years they out grew their old facility and in their search for a new location found a 6.26 acre parcel on the northern bank of Whatcom Creek. The site was the location of an auto recycling yard which had been in operation for decades.

When the development process and remediation of the brownfield site began, talks with the City of Bellingham and the design team focused on the potential impacts to Whatcom Creek, which is on the Washington State Department of Ecology's 303(d) list of Impaired Waters of

the State. Because of this, stormwater quality was critical, along with stormwater quantity. During the shoreline permitting process stormwater characteristics including temperature, pH, water quantity, and water quality were the primary concern for the development.

Pervious concrete provides several pollutant removal mechanisms inherent to the paving structure. These mechanisms include: stormwater volume reduction (through infiltration), reduced spray and vehicle wash off, biological degradation, filtration, adsorption, and volatilization. Through these mechanisms, the typical pollutants removed include hydrocarbons (oil, grease, and gasoline), polycyclic aromatic hydrocarbons (PAH's), metals (lead, copper, zinc, cadmium, and chromium), sediment, nutrients, and bacteria. The high solar reflectance index of Portland cement concrete significantly decreases the heat island effect that is normally produced by darker, less reflective surfaces. This benefit was also favorable to help provide for cooler water temperatures in the salmon habitat of Whatcom Creek. For these reasons, as well as environmental stewardship, pervious concrete was chosen as a pavement surface for more than two acres of the site.

Site design

During the design process, alternatives were considered. When evaluating the site with conventional stormwater design practices (i.e. impervious asphalt cement (AC), catch basins, conveyance pipes, cartridge filters, vaults, etc.), the estimated costs for the conventional design were $465,000 *in excess* of the design incorporating pervious concrete. The significant cost savings, combined with its long-term lifecycle value, made pervious concrete pavement an easy choice for the owner.

In the specifications for the project, it was stated that the installer must be certified through the National Ready Mixed Concrete Association's (NRMCA) Pervious Concrete Contractor Certification Program, which ensured that the installer was experienced and knowledgeable in the field. During the pour, additional concrete workers participated to gain experience working with pervious concrete.

The LID site design also included approximately two acres of porous asphalt in the low traffic areas. Pervious concrete was selected for the high traffic and truck lane areas because of its durability and structural integrity. Parking areas were constructed with a 6" thick section and the truck-heavy use travel lane was completed with an 8" thick section of pervious concrete.

The pervious concrete mix used within the truck lane also included an epoxy additive and fiber to increase the strength and lifespan of the pavement. Stormwater detention is provided in the 40 percent void space found with the aggregate base.

The result

The project's completion in September of 2008, with its demonstrated economic and environmental benefits, has caught the attention of municipalities, engineers, state officials, as well as those interested in the implementation of Low Impact Development (LID). Because of the onsite stormwater management achieved through the use of pervious concrete, the owner is eligible for additional cost savings with a 20 percent reduction in monthly stormwater fees.

Civil Engineer: 2020 Engineering

End of case study

3.4 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). 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. 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.

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Chapter 4: Vegetation and Soil Protection, Reforestation and Maintenance

In this chapter

Mature native vegetation and soil are necessary to maintain watershed hydrology, stable stream channels, wetland **hydro-periods** 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 (see Table ???) (AHBL, 2002).

Table ???: 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 Western Washington Hydrologic Model.

	Detention storage reduced (ft^3)	**Detention storage required (ft^3)**
Conventional development	0	**270,070**
Low impact development design		
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' pervious pavement road	-29,988	
Total reduction	-226,500	**43,500**

Retaining native soil and vegetation protection areas is a primary objective for low impact development in order to: reduced total impervious surface coverage; provide infiltration areas for overland flows generated in adjacent developed portions of the project; and 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.

Objectives for on-site native vegetation coverage:

- Rural and large lot development: 65 percent minimum.
- Medium density (4-6 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 ???: Site Planning and Layout section).
- Riparian Management Areas can be included as a part of the native vegetation retention area and are the highest priority for native vegetation retention and protection.

The 65% forest retention objective is a watershed level target based on best available science for maintaining watershed hydrologic functions (cite). Not all projects can achieve 65% protection at the project site. However, projects attaining 40, 50 or 60 percent native vegetation protection and using a full compliment 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 Soil and Vegetation Protection

Native vegetation and soil protection areas in 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, and 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 the 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 (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).

<figure 4-1: low live crown ratio tree photo>

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).

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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 facilities 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 Vegetation and soil protection during 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 2-3 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 6-8 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 the increase in **soil bulk density**. In response to soil compaction tree root penetration declines, root respiration and associated uptake of nutrients and minerals decline, **mycorrhizal** activity is reduced, and susceptibility to root disease increases (Matheny and Clark, 1998).

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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:

- Develop a **soil management plan** (showing areas to be protected and restoration methods for disturbed areas) before land clearing starts (see "Developing a soil management plan" in section ???, Amending Construction Site Soils).
- 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 three feet beyond the existing tree canopy along the outer edge of the tree stand <check this recommendation>. Fencing should provide a strong physical and visual barrier of high strength plastic or metal and be a minimum of 3-4 feet high (see Ecology 2004 SMMWW BMP C103 and C104). Silt fencing, a compost berm or compost sock 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:
    - 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**. Assessing the extent of the root zone to protect can be factored in several ways.

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 another. 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 breast height (DBH ~ 4.5 ft). Factors that influence the specific distance calculated include the tree's tolerance to disturbance, age and vigor (Matheny and Clark, 1998). See Figures ??? and ???.

- 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.
- Prohibit the stockpiling or disposal of excavated or construction materials in the vegetation retention areas to prevent contaminants from damaging vegetation and soils.
- 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% 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.
- 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.
- 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.
- Prevent wounds to tree trunks and limbs during the construction phase.
- 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.
- 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

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construction activities.

- Where construction operations unavoidably require temporary access over tree root zones or other soil protection areas, provide protection as follows:
  - *For foot access or similar light surface impacts*, apply a 6 inch layer of **arborist wood chip mulch** and water regularly to maintain moisture, control erosion, and protect surface roots.
  - *For any vehicle or equipment access*, apply a minimum 1" steel plate or 4" thick timber planking over 2-3" of arborist wood chip mulch, or a minimum ¾" plywood over 6-8 inches of AWCM, to protect roots and root zone soil from disturbance or compaction. Protect tree trunks and above-ground root flare with solid barriers such as plywood boxes.

<figure 4-2: tree and root section graphic>

<figure 4-3: tree root protection zone>

<figure 4-3: tree protection fencing and signage>

4.2 Re-establishment of native vegetation

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 ???: 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 when 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 posses an imminent safety threat as determined by a qualified arborist or urban forester.

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. 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 use for replacement purposes.

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 planting 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 15-20 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 water during the establishment period.
- For larger tree stock coniferous and broadleaf evergreen material should be a minimum of three feet in height and deciduous trees should have a minimum caliper size of one inch (Kantz, 2002).

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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 ???: Street Trees and Appendix ???: Bioretention Area Plants).

4.2.4 Reference Documents for Planting

Vegetation restoration/planting methods should conform to published standards. The following guidance documents are provided as 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 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 are stormwater management facilities. Clearly written management plans and protection mechanisms are

necessary for maintaining the benefits of these areas for the long term. Some of the 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 incorporated in all of 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% survival of all planted vegetation. If during the three-year period survival of planted vegetation falls below 80%, additional vegetation should be installed as necessary to achieve the required survival percentage. Additionally, the likely cause of the high rate of plant mortality should be determined (often poor soils and compaction) and corrective actions taken as needed to ensure plant survival. If it is determined that the original plant choices are not well suited to site conditions, these plants should be replaced with plant species that are better suited to the site.

Maintenance of soil stormwater functions and plant health requires continuing surface inputs of organic matter to feed the soil ecosystem. In natural areas, leaving fallen leaves and woody material provides that input. In areas that have been disturbed or replanted (with native or landscape plantings), applying arborist wood chip mulch annually until the understory canopy closes (3-5 years) will feed the soil, reduce water stress, and prevent weed invasion. In areas converted to turf, blowing fall leaves into beds and using mulching mowers (leaving clippings on-site) and minimal fertilization with organic-based products will maintain soil health.

Ongoing protection of native vegetation areas also requires preventing impacts from adjacent developed areas. Best practices include developing an Integrated Pest Management Plan that avoids use of herbicides, fungicides and insecticides on turf or landscaped areas, treating road or parking runoff with bioretention swales or other methods before it flows into natural areas, and preventing compaction (by foot or equipment) of turf and landscape bed areas that may be colonized by adjacent trees' roots.

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 the vegetation

retention areas may be required to limit encroachment.

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Chapter 5: Precision Site Preparation and Construction

In this Chapter

Protecting native soil and vegetation, minimizing soil compaction and retaining hydrologic function during the site preparation and construction phases presents some 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 as interlow or shallow groundwater flow. 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. On project sites with native outwash soils and vegetation, where surface and interflow are negligible, the increase in overland flow can be greater than native till conditions 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 were significantly reduced at suspended solids levels of 50-80 mg/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 are 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. Prevention as a primary protection strategy minimizes the extent of grading, retains vegetation cover, and is the most cost-efficient and effective method for controlling sediment yield (Corish, 1995).

5.1 Precision Site Preparation

Several factors including topography, hydrology, zoning density and plat design, financial disbursements, bond release, 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. **Precision site preparation** refers to a process where mass clearing and grading (that increases the probability of high sediment loads released from the property, excessive soil compaction and sediment management expense) is replaced with more targeted clearing and grading and sequencing that protects native soils and vegetation, minimizes exposure soil and reduces soil compaction.

Proper installation and maintenance of erosion and sediment **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 2012 *Stormwater Management Manual for Western Washington* Volume 1 Chapter 2: Minimum Requirements for New Development and Redevelopment snd Volume II chapter 4.

New compost-based erosion and sediment control BMPs (compost blankets, berms, and socks) are effective and have the added value of bringing compost onsite that can later be used to meet the Department of Ecology's post-construction soil amendment requirements (see section ???, Amending Construction Site Soils). These compost BMPs are described in the Ecology manual referenced above, with more detailed specifications available in the US EPA's *National Menu of stormwater BMPs* are being developed at http://cfpub.epa.gov/npdes/stormwater/menuofbmps/index.cfm. A short description and examples are shown in "Erosion Control with Compost," available at http://www.buildingsoil.org/tools/Erosion_Control.pdf

5.2 Techniques to Minimize Site Disturbance

Planning and implementation techniques to minimizing site disturbance fall into four categories: 1) site design; 2) construction planning (e.g. site preparation, homebuilding and utility connection); 3) training; and 4) equipment.

5.2.1 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 ???: Site Planning and Layout).

- Develop a Soil Management Plan during design that maps both soil protection areas and areas to be disturbed, and describes measures to be taken either for protection or for restoration of functional topsoil conditions (minimum 12 inches deep) over the entire site (see section ???, Amending Construction Site Soils for guidance on developing a Soil Management Plan).
- Retain natural topographic features that slow and store storm flows.
- Limit overall project cut and fill through efficient road design, lot layout and drainage and utility siting.
- 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 ??? Minimal Excavation Foundation 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. If permeable pavement is used, protect subgrade from sedimentation and compaction (see section ???: Construction of LID Facilities for details).

5.2.2 Coordinate planning and activity 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. 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. Re-establish TESC around homebuilding activities. Maintain an approved plan set with contact for project TESC manager or specialist on site.
- 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 3-4 feet high (see Ecology 2001 SMMWW BMP C103 and C104). Silt fencing or a compost berm is necessary in addition to, or incorporated with, the barrier for erosion control.

- To reduce soil compaction, erosion and sediment impacts establish efficient construction access roads, cover with aggregate base material immediately after grading, and keep all equipment traffic on those road bases to the greatest extent possible.
- Stockpile materials in areas designated for clearing and grading (avoid areas within the development envelope that are designated for bioretention or other infiltration areas).
- Stockpile and reuse excavated topsoil to amend disturbed areas where native soil characteristics merit (see section ???: Amending Construction Site Soils for details).
- Small stockpiles of soil should be covered and larger piles seeded for erosion control during wet months and in wind prone areas.
- Contact the local Conservation District or native plant salvage program for salvaging and reusing native plants from cleared areas.
- Inspection (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. If controls are not adequately protecting designated areas, adjust existing or implement additional protection measures.
    - Conduct a final inspection to verify that re-vegetated areas are stabilized and that stormwater management systems are in place and functioning properly.

5.2.3 Adequate training of 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 property with equipment operators and project foremen regularly to clarify construction boundaries, limits of disturbance and construction activities. Particular attention must be given to subgrade preparation for permeable pavement and bioretention installations and techniques to avoid subgrade compaction (see section ???: Permeable

pavement design, section ???: Permeable pavement construction and section:???: Bio-retention construction for details).

- Require erosion and sediment control training for operators.

5.2.4 Proper equipment

Research in the agricultural setting indicates that ground contact pressure generally determines the potential for compaction in the upper 6-8 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 (70-90 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 or excavators 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)

5.3 Inspection of LID Facilities

5.3.1 Amended construction site soils

Verification of soil protection or restoration over the entire site falls into four visits (Stenn, *Building Soil: Guidelines and Resources for Implementing Soil Depth and Quality BMP T5.13 in WDOE Stormwater Management Manual for Western Washington*, 2003 and Seattle Department of Planning and Development, CAM 531 Post Construction Soil Management, 2009):

Pre-construction review

- Verify soil management plan (SMP) is in place that identifies soil and vegetation protection zones on all plans, and describes quantities of compost amendment, stockpiled or imported topsoil, and mulch to be used to restore all construction-disturbed soil areas at end of project.

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Visits during construction

- Verify that protection areas have been fenced and not impacted.
- Verify SMP has been communicated to all contractors.
- Verify that equipment is kept to road base wherever possible, and TESC is maintained.

Pre-planting visit (after soil amendment)

- Verify that protection areas have not been impacted.
- Inspect delivery tickets for compost, topsoil, and mulch to verify they match quantities on SMP.
- Probe with shovel or bar to verify soil in all disturbed areas is uncompacted to at least 12" depth (shovel enters 12 inches with inspector's weight).
- Dig several holes to visually verify brown color at least 8" deep, indicating that compost or compost-amended topsoil has been incorporated at least to that depth.

Post-construction visit

- Verify that amended or restored topsoils have not been compacted by equipment traffic.
- Verify mulch placed over landscape beds after planting.

5.3.2 Bioretention

Inspection and verification criteria and timing can be organized into five site visits. Also included below is a critical first step for reviewing and confirming the inspection and verification process as part of an LID pre-construction review (Seattle Public Utilities, Construction Inspection Checklist for Stormwater Code Compliance, 2010 and Hinman, LID Technical Workshop Series for Puget Sound, 2011).

Pre-construction review

- Set guidelines, expectations and timing for inspections.
- Discuss construction sequencing and field change process.
- Review checklists.
- Include developer, builder, utilities, plan and critical areas reviewers, inspectors in pre-construction review.

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- Determine training needs for review, inspection and construction personnel. For example, the landscapers may need to be briefed on the location and care of permeable pavement installations to prevent BSM placement on and clogging of the pavement.
- Clearly identify lay-down and staging areas on plans and mark in field.
- Confirm where all stormwater management requirements are located. For example, within an LID project plan set and specifications there may be stormwater requirements within the landscaping guidelines.

Visit one (pre-BSM placement)

- Confirm that native/existing soils are comparable to design specs.
- TESC correctly installed and working properly to prevent runoff to the bioretention areas from within project and from adjacent properties. Adjacent permeable pavement and other infiltration areas are protected.
- Downstream catch-basins are protected.
- Bioretention areas are clearly marked on site and barriers are adequate to prevent equipment from entering the bioretention area.
- Rough grading and bioretention dimensions are to plans.
- Verify side slopes and other dimensions are per specifications.
- If appropriate, curb-cuts openings are blocked to prevent construction stormwater from entering the bioretention areas.
- Under-drain(s) and overflow are at proper elevations and locations.
- Subgrade soil scarified to minimum of 2 inches.
- Protective measures are in place if BSM will be installed later in the construction process (e.g. plastic sheeting, mulch or a minimum of 6 inches of soil as a barrier to sedimentation). If soil is placed as a protective layer, cover the under-drain with filter fabric to prevent sedimentation.
- Implement any field changes (the field change process should have been confirmed during pre-construction meetings).

Visit two (pre-mulch or planting)

- TESC correctly installed and working properly to prevent runoff to the bioretention areas from within project and from adjacent properties.

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- Verify that subgrade soil is free of construction runoff fines. If sediment has entered the bioretention area remove adequate subgrade soil to remove introduced fines (appropriate subgrade condition should be approved by responsible Engineer).
- If under-drain is installed, verify that the aggregate backfill material for the drain is free of fines. If present remove top 6 inches of backfill and replace with aggregate per design.
- Verify that BSM meets composition guidelines. If using the guidelines in section <???> : Bioretention soil media, pre-placement laboratory analysis for saturated hydraulic conductivity of the BSM is not required. Verification of the mineral aggregate gradation, compost guidelines and mix ratio in section <???> : Bioretention soil media should be provided to verify performance guidelines in that section. Collect sample for testing if required. If the BSM uses a different mineral aggregate gradation, compost guidelines and mix ratio than section <???> : Bioretention soil media, then the verification of the BSM composition and hydraulic conductivity should be provided through laboratory testing of the material to be used in the installation. Verification should be with a grain size analysis of the mineral aggregate, compost quality analysis and verification of aggregate to compost ratios.
- Verify that excavated cell subgrade does not have standing water or is not saturated and that BSM is not saturated when placed.

Visit three (pre-mulch and planting)

- TESC correctly installed and working properly to prevent runoff to the bioretention areas from within project and from adjacent properties.
- Verify that BSM is placed per specifications and meets depth and compaction requirements. If depth cannot be verified through other means, expose BSM profile to subgrade. A penetrometer can be used for compaction when properly calibrated and with appropriate training.
- Verify that mulch is placed if required immediately after placement and before planting (e.g. placement during summer months and fall planting) to prevent weed establishment.
- Verify that sediment has not entered the bioretention area. If present, the contractor should remove and replace the top layer of the BSM to a depth that removes all sediment (typically 3-6 inches or 7.5 to 15 cm). Adequate removal of sediment and infiltration capacity should be approved by responsible Engineer.
- Verify that the finished BSM elevation is below sidewalks, curbs, driveways and other pavement per plans (typically 1 inch of 2.5 cm).

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- Verify side slopes and other dimensions are per specifications.

Visit four (post-planting and mulch)

- Verify plant type and density per plans.
- Verify mulch type and depth (typically 2-3 inches)
- Verify that no sediment is accumulated on the mulch.
- Verify there is not excessive weed or invasive plant establishment (see Appendix ??? for various levels of service and weed management).

Visit five (post-construction and overall site inspection)

- Verify final grade.
- Verify that contributing area size is per plans and stabilized.
- Verify BSM not clogged/infiltration rate adequate. If infiltration tests are necessary, spot checks with a double ring infiltrometer are adequate.
- Verify that vegetation vigor and survival rate is per specifications.
- Schedule removal of TESC (TESC should remain in place at least three months following bioretention completion).
- Verify that the operation and maintenance plan is in place.

5.3.3 Permeable pavement

Inspection and verification timing and processes fall into four site visits. Also included below is a critical first step for reviewing and confirming the inspection and verification process as part of an LID pre-construction review (Seattle Public Utilities, Construction Inspection Checklist for Stormwater Code Compliance, 2010 and Hinman, LID Technical Workshop Series for Puget Sound, 2011).

Pre-construction review

- Set guidelines, expectations and timing for inspections.
- Discuss construction sequencing and field change process.
- Review checklists.
- Include developer, builder, utilities, plan and critical areas reviewers, inspectors in pre-construction review.

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- Determine training needs for review, inspection and construction personnel. For example, the landscapers may need to be briefed on the location and care of permeable pavement installations to prevent BSM placement on and clogging of the pavement.
- Clearly identify lay-down and staging areas on plans and mark in field.
- Confirm where all stormwater management requirements are located. For example, within an LID project plan set and specifications there may be stormwater requirements within the landscaping guidelines.

Visit one (subgrade preparation and geotextile and aggregate base placement)

- TESC correctly installed and working properly to prevent run-on to the permeable pavement areas from within project and from adjacent properties.
- Traffic control measures in place to protect permeable paving.
- Adjacent permeable pavement, bioretention or other infiltration areas protected from sediment, construction debris, material storage, and construction traffic.
- Downstream catch-basins are protected.
- Methods for treating over-compacted areas (e.g. dedicated travel ways for construction equipment) have been determined as construction is completed.
- Measures are in place to protect subgrade including travel ways clearly defined, protective cover (e.g. steel plates or aggregate base) where construction vehicles must access subgrade for utility or other construction activity.
- Final excavation performed with construction equipment operating on grade that is 1 foot (30 cm) above final grade.
- Final subgrade excavation completed during dry weather.
- Prior to placement of geotextile (if specified) and aggregate base, verify that subgrade soil is free of construction sediment. If present, the contractor should remove the top layer of the subgrade to a depth that removes all sediment (typically 3-6 inches or 7.5 to 15 cm) and replace with material per design. Adequate removal of sediment should be approved by responsible Engineer.
- Verify that final subgrade infiltration rate and/or compaction effort is within acceptable limits. Infiltration rate and compaction effort should be approved by responsible Engineer.
- Final elevation checks complete per construction drawings.

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Visit two (geotextile and aggregate base placement)

- If geotextile is specified, verify product for strength requirements and that installation (e.g. overlap) is per specifications.
- If subgrade check-dams are specified verify berm material, spacing, dimensions and method for keying to subgrade are per construction plans.
- If specified, confirm that under-drains are installed per drawings and drain to an approved discharge point.
- Verify that aggregate base are per specifications and choker and leveling course materials (if specified) are per specifications.
- Depth of aggregate layers are per specifications.
- Geotextile is wrapped over aggregate base and secured per specification to protect base from sediment.
- Adjacent areas are stabilized to protect aggregate base from sediment.

Visit three (pavement placement)

- TESC correctly installed and working properly to prevent run-on to the permeable pavement areas from within project and from adjacent properties.
- Traffic control in place to rout foot and vehicular traffic around pavement until pavement is fully cured/stabilized.
- Verify that materials for aggregate base and leveling or choker courses (if specified) and compaction of the aggregate are to specification.
- Verify pavement sources and materials submittals have been received and approved by Engineer.
- If required, verify that placement personnel certifications have been received and approved.
- If specified, verify that test section is completed and accepted per specification prior to placement of full installation.
- For full installation, verify that pavement materials are placed per specifications and accepted test section (see section ???: Permeable Pavement for guidelines).
- Geotextile (if specified) is wrapped over pavement and secured per specification to protect pavement from sediment.
- Adjacent areas are stabilized to protect pavement from sediment.

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- Remove any sediment and debris deposited on pavement and demonstrate infiltration capability per specification.
- Protection measures and traffic control removed.

Visit four (post-construction and overall site inspection)

- Verify final grade.
- Overall site is stabilized to prevent construction sediment from entering permeable pavement area.
- Schedule removal of TESC and verify that the operation and maintenance plan is in place.

5.4 Construction sequencing of LID Facilities

Proper construction sequencing and correctly implementing specific techniques for building LID facilities are critical for project success. LID facilities are often part of, or adjacent to, the road ROW and building sites and require special attention to the construction process for preventing sedimentation and compaction.

The following section focuses on bioretention within the ROW and permeable pavement. Both of these practices are associated with, and impacted by, several other construction activities and require coordinated planning, sequencing and inspection. In contrast, green roofs, rain water collection and reuse and LID foundations are within the building envelop and are impacted by relatively fewer activities.

Specific sequencing and construction techniques will be determined by individual site conditions and constraints; however, the below guidelines provide a framework and major considerations for the construction process. The overall process for LID sequencing and construction are:

- Consider and plan the construction sequence to prevent compaction and sedimentation to LID facilities with the project team (permitting jurisdiction, owner, developer, construction manager and foreman).
- During the construction planning phase, identify the specific (and perhaps unique) construction processes necessary to prevent compaction and sedimentation. This and the previous bullet are the most important steps for successful implementation.
- Provide clear and robust signs to identify limits of clearing and grading, and explain the use

and management of the facilities.

- Provide robust construction barriers to prevent entrance and compaction of bioretention areas and where possible permeable pavement.
- Plan to meet and walk property with equipment operators regularly to clarify construction boundaries, limits of disturbance and construction activities. Particular attention must be given to subgrade preparation for permeable pavement and bioretention installations and techniques to avoid subgrade compaction (see section ???: Permeable Pavement design, section ???: Permeable Pavement Construction and section ???: Bioretention for details).

5.4.1 Bioretention

Minimizing sedimentation and removing sediment from bioretention areas when project is complete are necessary for a proper functioning system. However, deep compaction in bioretention areas is very difficult, if not possible, to mitigate and must be prevented (see section ???: Proper Equipment for compaction depths). The following provides typical construction scenarios and outlines compaction and sedimentation management strategies.

Residential: Site flat or sloping away from bioretention facility:

- Develop a performance bond that defines proper functioning condition and testing to demonstrate performance when construction is complete.
- If bioretention area can be protected from compaction, complete bioretention area with roads, utilities, and other storm infrastructure before completing homes.
- Clearly delineate building site entrance.
- Install robust construction barriers and signage (e.g. chain-link fencing) to prevent entrance and compaction with sediment and erosion control (e.g. sediment fence with compost sock).
- Meet with homebuilder and construction foreman to identify bioretention areas and discuss their function as infiltration facilities.

<figure 5-1: Meadow on the Hylebos bioretention area>

Residential: Site sloping to bioretention facility in dense development (8 du/acre or greater):

This presents a significantly more difficult construction scenario requiring careful planning, personnel management and sequencing. As with the above scenario, develop a performance

bond that defines proper functioning condition and testing to demonstrate performance when construction is complete. There are two primary decision pathways:

1. Divert flows around facility and treat during construction. This will require a parallel storm system or temporary conveyance to treatment/storage area(s)

<figure 5-2: Highpoint construction with bioretention>

2. Partially complete and allow storm flows through facility. *This method should only be used if there is no other alternative.*

Without under-drain

- Delineate or partially grade to define facility.
- Install robust construction barriers (e.g. chain-link fencing) to prevent entrance and compaction with sediment and erosion control (e.g. sediment fence with compost sock).
- Keep construction traffic off area (mitigating deep compaction may not be possible).
- Stabilize upslope construction area as best as possible by reducing flow distances and capturing sediment on slope (e.g. silt fence or berms) or deep mulch (e.g. hog fuel).
- If flows allowed through facility, leave temporary grade at least 6 inches above final grade (protects final subgrade from sedimentation). Facility can be further protected by lining with plastic (stormwater is conveyed to storage/treatment area) or mulch (water is allowed to infiltrate, but sediment captured in mulch).
- Additional sediment control can be used such as a temporary forebay to localize sedimentation.
- Once construction is complete and upslope area stabilized remove liner or mulch and excavate to final grade (sediment captured in 6" of soil profile is removed at final excavation). Final subgrade condition should be approved by the project engineer

With under-drain

- Place under-drain and aggregate filter and bedding layer while maintaining a temporary grade at least 6 inches above final grade in bioretention area surrounding excavation.
- Place protective covering (plastic or filter fabric) over under-drain aggregate filter and bedding layer and cover with a protective layer of sandy aggregate.
- Follow guidelines in construction scenario above without under-drain.

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Agreements

Partial excavation and completion of facility after homes are finished and landscaping stabilized requires clear agreement among developer, homebuilder and jurisdiction.

5.4.2 Permeable Pavement

Various strategies are described below to protect permeable pavement installations during construction. Other techniques or combinations of the below techniques are possible. Additional measures may be necessary for adequate protection depending on the project setting. For example, tire washing stations for construction equipment or separate haul roads may be appropriate as stand-alone strategies or incorporated with other techniques.

Roads and sidewalks (where roads are not used for construction access)

- Install robust construction barriers (e.g. chain-link fencing) to prevent entrance and compaction with sediment and erosion control (e.g. sediment fence with compost sock).
- Meet with homebuilder and construction foreman to identify permeable pavement areas, discuss their function as infiltration facilities and confirm methods to protect pavement from sediment and structural damage .
- Determine threshold for designating pavement as clogged, and methods and responsible party for cleaning pavements if clogged.
- Protect subgrade and install base and pavement. See section ???: Subgrade for techniques to minimize subgrade compaction and section ???:Types of permeable pavement for installation techniques of specific pavement types.
- Cover with plastic (optional).
- Cover with filter fabric and secure.
- Close and protect area.
- Maintain good TESC until site is stabilized.

<5-3: Highpoint construction with wrapped sidewalk>

Roads (permeable concrete or asphalt used for construction access)

Option 1

- Install robust construction barriers (e.g. chain-link fencing) to prevent entrance and compaction with sediment and erosion control (e.g. sediment fence with compost sock).

- Meet with homebuilder and construction foreman to identify permeable pavement areas, discuss their function as infiltration facilities and confirm methods to protect pavement from sediment and structural damage.
- Protect subgrade and Install open graded asphalt treated base (ATB). See section ???: Subgrade for techniques to minimize subgrade compaction.
- Cover and secure protective fabric over open graded ATB and use for construction access.
- Maintain good TESC until site is stabilized.
- Complete construction, remove protective fabric, clean where necessary, and complete wearing course over ATB. See section ???: Types of permeable pavement for installation techniques of specific pavement types.
- The project engineer should inspect site to confirm that the ATB is clean and infiltrating adequately.

<figure 5-4: Oregon residential project with porous asphalt>

Option 2

- Install robust construction barriers (e.g. chain-link fencing) to prevent entrance and compaction with sediment and erosion control (e.g. sediment fence with compost sock).
- Meet with homebuilder and construction foreman to identify permeable pavement areas, discuss their function as infiltration facilities and confirm methods to protect pavement from sediment and structural damage.
- Protect subgrade and install base and choker course if necessary. A choker course will be necessary to create an adequate surface for vehicles and protect the geotextile from puncture if the base aggregate is large (e.g. 2-3 inch or 25-75 mm). See section ???: Subgrade for techniques to minimize subgrade compaction and section ???:Types of permeable pavement for installation techniques of specific pavement types.
- Cover and secure protective geotextile fabric.
- Maintain good TESC until site is stabilized.
- Remove the protective base aggregate and geotextile and complete paver installation per specifications.
- The project engineer should inspect the site to confirm that the aggregate base is clean and infiltrating adequately.

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<figure 5-5: construction example>

Roads (permeable pavers are used for construction access)

Option 1

- Install robust construction barriers (e.g. chain-link fencing) to prevent entrance and compaction with sediment and erosion control (e.g. sediment fence with compost sock).
- Meet with homebuilder and construction foreman to identify permeable pavement areas, discuss their function as infiltration facilities and confirm methods to protect pavement from sediment and structural damage.
- Protect subgrade and install sub–base and base. See section ???: Subgrade for techniques to minimize subgrade compaction and section ???:Types of permeable pavement for installation techniques of specific pavement types.
- Cover and secure protective geotextile fabric and 2 inches (50 mm) of base aggregate over the fabric.
- Maintain good TESC until site is stabilized.
- Remove the protective base aggregate and geotextile and complete paver installation per specifications.
- The project engineer should inspect the site to confirm that the aggregate base is clean and infiltrating adequately.

Option 2

- Install robust construction barriers (e.g. chain-link fencing) to prevent entrance and compaction with sediment and erosion control (e.g. sediment fence with compost sock).
- Meet with homebuilder and construction foreman to identify permeable pavement areas, discuss their function as infiltration facilities and confirm methods to protect pavement from sediment and structural damage.
- Protect subgrade and complete paver installation. See section ???: Subgrade for techniques to minimize subgrade compaction and section ???:Types of permeable pavement for installation techniques of specific pavement types.
- Cover and secure protective geotextile fabric over pavers and cover fabric with 2 inches No. 8 stone.
- Protect installation as best as possible particularly from tight radius turns (e.g. strategically placed steel plates or plywood).

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- Maintain good TESC until site is stabilized.
- After construction is complete and area is stabilized, remove protective stone and geotextile fabric.
- Project engineer should inspect site to confirm that the paver cells or joints are clean and infiltrating adequately.

Option 3

- Install robust construction barriers (e.g. chain-link fencing) to prevent entrance and compaction with sediment and erosion control (e.g. sediment fence with compost sock).
- Meet with homebuilder and construction foreman to identify permeable pavement areas, discuss their function as infiltration facilities and confirm methods to protect pavement from sediment and structural damage.
- Protect subgrade, complete paver installation and allow construction traffic to use finished paver surface. See section ???: Subgrade for techniques to minimize subgrade compaction and section ???:Types of permeable pavement for installation techniques of specific pavement types.
- Protect installation from construction traffic damage (e.g. strategically placed steel plates or plywood where construction vehicles are making tight radius turns).
- Maintain good TESC until site is stabilized.
- Complete construction and stabilize area.
- Wet and vacuum a test portion of the pavement surface with a machine capable of removing 1 inch (25 mm) of the stone from paver joints to remove sediment with associated aggregate in voids. Inspect test area to ensure all sediment is removed (if necessary adjust vacuum until there are no visible traces of sediment).
- Project engineer should inspect site to confirm that the paver cells or joints are clean and infiltrating adequately.

Agreements

Partial excavation and completion of pavement after homes are finished and landscaping stabilized requires clear agreement among developer, homebuilder and jurisdiction.

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Chapter 6: Integrated Management Practices

In this chapter

Guidelines for:

- Bioretention
- Amending construction site soils
- Permeable pavement
- Urban trees
- 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 for erosion and sediment control and conventional stormwater control structures) because the controls are integrated throughout the project. Through good site analysis IMP's are landscape amenities that take advantage of site topography, existing soils and vegetation and location in relation to impervious surfaces to provide stormwater volume reduction, flow attenuation, water quality treatment, and ultimately better approximate native hydrologic patterns.

6.1 Bioretention Areas

The bioretention concept for managing stormwater 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, soil microbes, and the mineral aggregate and organic matter in soils to transform, 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 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.

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- Facilities designed to more closely mimic natural forested conditions, where healthy soil structure and vegetation promote the infiltration, storage, filtration, 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. For example, bioretention can be used as a stand-alone practice on an individual lot; however, best performance is often achieved when integrated with other LID practices.

The terms bioretention and rain garden are sometimes used interchangeably. However, for Washington State the term bioretention is used to describe an engineered facility sized for specific water quality treatment and flow control objectives that includes designed soil mixes and perhaps under-drains and control structures. The term rain garden is used to describe a non-engineered landscape depression to capture stormwater from adjacent areas with less restrictive design criteria for the soil mix (can be compost amended native soil) and usually without under-drains or other control structures. Both are applications of the same LID technique and can be highly effective for flow control and water quality treatment.

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. Side slopes are typically gentle; however, side slopes may be steep or vertical in urban areas with space limitations. Ponding depths are typically 6 to 12 inches (15 to 30.5 cm).
- *Bioretention swales*: Incorporate the same design features as bioretention cells; however, bioretention swales are designed as part of a system that can convey stormwater when maximum ponding depth is exceeded
- *Bioretention planter boxes*: Designed soil mix and a variety of plant material including trees, shrubs, grasses, and/or other herbaceous plants within a vertical walled container usually constructed from formed concrete, but could include other materials. The planter may be completely impervious and include a bottom (this design must include an under-drain) or have an open bottom that allows infiltration to the subgrade. These designs are often used in ultra-urban settings. Planter-box designs also include patented or pro-

prietary systems (usually using high flow media and placed subsurface along roads or in parking lots) for water quality treatment.

<Figure 6-1-1: bioretention section with primary design elements>

<Figure 6-1-2: bioretention planter section with major design characteristics>

The following section outlines various applications and general design guidelines, as well as specifications, for individual bioretention components. This section draws information from numerous sources including a growing body of international research; however, many of the specifications and guidelines are from extensive work and experience developed by the City of Seattle.

6.1.1 Applications

While the original applications focused primarily on stormwater pollutant removal, bioretention can be highly effective for flow control as well. Where the surrounding native soils have adequate infiltration rates bioretention can be used as a primary or supplemental retention system. 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, an orifice or other control structure is necessary for designs with under-drains to provide significant flow control benefits.

Applications with or without under-drains vary extensively and can be applied in new development, redevelopment and retrofits. Bioretention areas are most often designed as a multifunctional landscape amenity that provides water quality treatment, stormwater volume reduction and flow attenuation. Typical applications include:

- Individual lots for managing rooftop, driveway, and other on-lot impervious surface.
- 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 (often linear bioretention swales and cells). These facilities are sometimes designed to have traffic calming functions as well.
- Common landscaped areas in apartment complexes or other multifamily housing designs.

- Planters on building roofs, patios, and as part of streetscapes.

Examples 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 but are not limited to:

- Bioretention cells or rain gardens integrated into gardens on individual lots.

<Figure 6-1-3: Rain garden>

- Bioretention cells or swales in landscaped parking lot islands or along roadways can be used to meet landscaping requirements and manage traffic flow, as well as manage stormwater. These can be used with curb or curbless inlet designs.

<Figure 6-1-4: Bioretention in parking lot islands or along roadways>

- Bioretention swales (individual bioretention cells connected by a conveyance system) alongside roadways. This bioretention configuration is also called in-line bioretention.

<Figure 6-1-5: Bioretention swales>

- Bioretention swales can be used for higher gradient settings with appropriate gradient controls such as check dams, gravel mulch and catch basins to reduce flow velocity and manage erosion and sediment transport.

<Figure 6-1-6: High gradient bioretention swale>

- Bioretention planters are often used in highly urban settings as stormwater management retrofits next to buildings or within streetscapes. Bioretention planters are generally not recommended in new construction or less dense settings where larger scale bioretention areas can be incorporated for increased flow control capability.

<Figure 6-1-7: Bioretention planter>

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- 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 under-drain system. Tree box filters are generally not recommended in new construction or less dense settings where larger scale bioretention areas can be incorporated for increased flow control capability (see section ???: Urban Trees for more detail).

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 bioretention soil mix (BSM) and soils underlying and surrounding bioretention facilities are the principal design elements for determining infiltration capacity, sizing, and associated conveyance structures. The BSM placed in the cell or swale is typically composed of a highly permeable sandy mineral aggregate mixed with compost and will often have a higher infiltration rate than the surrounding subgrade; however, in some cases (such as outwash soils) the subgrade infiltration rate may be higher. See Section <???>: Bioretention Components for details.
- *Site topography:* Based on geotechnical concerns, infiltration on slopes greater than 10 percent should only be considered with caution. The site assessment should clearly define any landslide and erosion critical areas and coastal bluffs and appropriate setbacks provided by the local jurisdiction. Thorough geotechnical analysis should be included when considering infiltration within or near slope setbacks. Depending on adjacent infrastructure (e.g. basements and subsurface utilities) and subgrade geology, geotechnical analysis may also be necessary on relatively low gradients. An effective flow control and water quality treatment technique for slopes is sloped biodetention (see section <???> for details).
- *Depth to hydraulic restriction layer:* separation to a hydraulic restriction layer (rock, compacted soil layer or water table) is an important design consideration for infiltration and flow control performance. Contamination of groundwater is an important factor when infiltrating stormwater; however, when determining depth to the water table the primary concern in the SWMMWW is infiltration capacity (as influenced by ground water mounding) and associated flow control performance. When properly designed and constructed the BSM will provide very good water quality treatment before infiltrated stormwater reaches the sub-

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grade and then groundwater (see section <???> for recommended BSM depth and section <???> for water quality treatment performance). The following are recommended minimum separations to groundwater:

- 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, landscape and other pervious surface. 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 smaller contributing areas in relation to bioretention area.

- 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, landscape and other pervious surface.
- *Utility conflicts*: Consult local jurisdiction requirements for horizontal and vertical separation required for publically owned utilities, such as water, sewer, and stormwater pipes. Consult the appropriate franchise utility owners for separation requirements from their utilities, which may include communications and/or gas. See Figure <???> for an example design detail illustrating vertical and horizontal separation requirements for roadway bioretention. When the separation requirements cannot be met, designs should include appropriate mitigation measures, such as impermeable liners over the utility, sleeving utilities, fixing known leaky joints or cracked conduits, and/or adding an under-drain to the bioretention areas to minimize the amount of infiltrated stormwater that could enter the utility.

<Figure 6-1-8: utility setback section>

- *Setbacks:* Consult local jurisdiction guidelines for appropriate bioretention area setbacks from wellheads, on-site sewage systems, basements, foundations, utilities, slopes and property lines.

- *Expected pollutant loading:* Bioretention can provide very good water quality treatment for heavy pollutant loads associated with industrial or commercial sites. In these settings an impermeable liner between the BSM and the subgrade and an under-drain may be required due to soil and groundwater contamination concerns. See sections <???>: Bioretention components and <???>: Performance for recommended designs by pollutant type.
- *Transportation safety:* The design configuration and selected plant types should provide adequate sight distances, clear zones, and appropriate setbacks for roadway applications in accordance with the local jurisdiction requirements.
- *Ponding depth and surface water draw-down:* Plant and soil health, flow control needs, water quality treatment performance, location in the development, and mosquito breeding cycles will determine draw-down timing. For example, front yards and entrances to residential or commercial developments may require more rapid surface dewatering than necessary for plant and soil health due to aesthetic needs. See Section <???>: 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 or provide elevated or bermed pathways in areas where foot traffic is inevitable (see section <???>: Bioretention components for details) and provide barriers, such as wheel stops, to restrict vehicle access in parking lot applications.
- *Visual buffering:* Bioretention areas can be used to buffer structures from roads, enhance privacy among residences, and for an aesthetic site feature.
- *Site growing characteristics and plant selection:* Appropriate plants should be selected for sun exposure, soil moisture, and adjacent plant communities. Native species or hardy cultivars are recommended and can flourish in the properly designed and placed BSM with no nutrient or pesticide inputs and 2-3 years irrigation for establishment. Manual invasive species control may be necessary. Pesticides or herbicides should never e applied in bioretention areas
- *Maintenance:* see section <???>: Maintenance and Appendix 4 for details.

6.1.2.1 Determining subgrade and bioretention soil media design infiltration rates

Determining infiltration rates of the soils underlying the bioretention areas and the BSM is necessary for sizing facilities, routing, checking for compliance with the maximum drawdown time, and determining flow reduction and water quality treatment benefits when using the

Western Washington Hydrologic Model (WWHM) or MGS Flood. See Figure <???> for a graphic representation of the process to determine infiltration rates.
This section describes methods for determining infiltration rates and design procedures specific to bioretention areas. For information on overall site assessment see Chapter ???: Site Assessment.

Determining the flow control and water quality treatment benefits of bioretention areas without under-drains requires knowing:

- The short-term (initial/measured) **saturated hydraulic conductivity** (Ksat) and then determining if correction factors are applied to determine the long-term (design) infiltration rate of the site soils underlying the bioretention areas (see below for determining initial and design infiltration rates).
- The estimated long-term BSM rate (short-termed or initial Ksat with appropriate correction factor applied).

Determining the flow control and water quality treatment benefits of bioretention areas with under-drains requires knowing:

- The estimated long-term BSM rate (short-termed or initial Ksat with appropriate correction factor applied).
- Orifice or control structure design.

See Chapter <???> for more detail on flow control modeling for bioretention areas.

1. Subgrade soils underlying the bioretention areas

A preliminary site assessment is necessary for designing LID projects with bioretention areas and other distributed stormwater management practices integrated into the project layout. Preliminary site assessment includes surface and subsurface feature characterizations to determine infiltration capability of the site, initial design infiltration rates and potential bioretention area locations. For more information on initial site assessment see Chapter 2: Site Assessment and Section 2.1: Soil and subsurface characterization.

The methods below are used to determine the short-term (initial) saturated hydraulic conductivity rate for subgrade soil profile (existing) soils beneath the bioretention areas. The initial or measured saturated hydraulic conductivity with no correction factor may be used as

the design infiltration rate if the qualified professional engineer deems the infiltration testing described below (and perhaps additional tests) are conducted in locations and at adequate frequency capable of producing a soil profile characterization that fully represents the infiltration capability where the bioretention areas are located. For example, if the small-scale PITs are performed for all bioretention areas and the site soils are adequately homogeneous.

If deemed necessary by a qualified professional engineer, a correction factor may be applied to the measured saturated hydraulic conductivity to determine the long-term (design) infiltration rate. Whether or not a correction factor is used and the specific number used will depend on heterogeneity of the site soils and number of infiltration tests in relation to the number of bioretention areas (see section ??? for more details on correction factors). The overlying BSM provides excellent protection for the underlying native soil from sedimentation; accordingly, the underlying soil does not require a correction factor for influent control and clogging over time.

If a single bioretention facility serves a drainage area exceeding 1 acre, a groundwater mounding analysis should be done in accordance with section ??? of the SMMWW.

The initial Ksat can be determined using:

A. In-situ small-scale pilot infiltration test (PIT); or
B. A correlation to grain size distribution from soil samples if the site has soils that are not consolidated by glacial advance. The latter method uses the ASTM soil size distribution test procedure (ASTM D422), which considers the full range of soil particle sizes, to develop soil size distribution curves.

See Section 2.1 Soil and subsurface characterization for test procedure details.

If feasible, small-scale PITs are recommended for each bioretention site. Long, narrow bioretention facilities, such as a bioretention swale following the road right-of-way, should have a test location every 50 feet. However, if the site subsurface characterization, including soil borings across the development site, indicates consistent soil characteristics and adequate depths to seasonal high groundwater conditions, the number of test locations may be reduced. Observations through a wet season can identify a seasonal groundwater restriction.

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Correction factors for subgrade soils underlying bioretention areas

The correction factor for in-situ, small-scale pilot infiltration test is determined by the number of tests in relation to the number of bioretention areas and site variability. Correction factors range from 0.33 to 1 (no correction).

Tests should be located and be at adequate frequency capable of producing a soil profile characterization that fully represents the infiltration capability where the bioretention areas are located. If used, the correction factor depends on the level of uncertainty that variable subsurface conditions justify. If a pilot infiltration test is conducted for all bioretention areas or the range of uncertainty is low (for example, conditions are known to be uniform through previous exploration and site geological factors) one pilot infiltration test may be adequate to justify no correction factor (see Table ???: Correction factors for in-situ Ksat measurements to estimate long-term (design) infiltration rates).

If the level of uncertainty is high, a correction factor near the low end of the range may be appropriate. Two example scenarios where low correction factors may apply include:

- Site conditions are highly variable due to a deposit of ancient landslide debris, or buried stream channels. In these cases, even with many explorations and several pilot infiltration tests, the level of uncertainty may still be high.
- Conditions are variability, but few explorations and only one pilot infiltration test is conducted. That is, the number of explorations and tests conducted do not match the degree of site variability anticipated.

A correction factor for siltation and bio-buildup is not necessary for bioretention area subgrades. Correction factors are applied to the BSM to account for the influence of siltation (see section below on determining infiltration rates for the BSM).

Table ???: Correction factors for in-situ Ksat measurements to estimate long-term (design) infiltration rates

Site Analysis Issue	Correction Factor
Site variability and number of locations tested	CF = 0.33 to 1
Degree of influent control to prevent siltation and bio-buildup	No correction factor required

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2. Bioretention soil media (BSM)

The following provides recommended tests and guidelines for determining infiltration rates of the bioretention soil media. However, if you choose to provide a media that meets all of the specifications for mineral aggregate, compost material, and the mix in section ???: Bioretention soil media, you do not have to perform any tests to establish the infiltration rate. You can assume 6 inches per hour and a correction factor of 2 or 4 depending upon the drainage area as described below. If an alternative BSM is used, the media must meet the minimum criteria of: CEC > 5 meq/100 gms of dry soil; pH in the range of 5.5 – 7; total organic content of 5 to 8 percent; and infiltration rates described in section ???: Infiltration rates. Depending on the size of contributing area use one of the following two guidelines.

A. 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, landscape, and other pervious surface:
   - Use ASTM D 2434 Standard Test Method for Permeability of granular Soils (Constant Head) with a compaction rate of 85 percent using ASTM D1557 Test Method for Laboratory Compaction Characteristics of Soil Using Modified Effort.
   - Use 2 as the infiltration reduction (correction) factor.

B. If the contributing area of the bioretention cell or swale is equal to or exceeds any of the following thresholds: 5,000 square feet of pollution-generating impervious surface; or 10,000 square feet of impervious surface; or ¾ acre of lawn, landscape, and other pervious surface:
   - Use ASTM D 2434 Standard Test Method for Permeability of granular Soils (Constant Head) with a compaction rate of 85 percent using ASTM D1557 Test Method for Laboratory Compaction Characteristics of Soil Using Modified Effort.
   - Use 4 as the infiltration reduction (correction) factor.

Enter the subgrade and BSM infiltration rates in WWHM or MGS Flood to determine the flow reduction and water quality treatment benefits of the bioretention areas.

<figure 6.1.10 from LID manual…flow diagram for infiltration rate testing and determination>

ASTM D 2434 Standard Test Method for Permeability of Granular Soils provides standardized guidelines for determining hydraulic conductivity of mineral aggregate (granular) soils. Bioretention soil mixes contain significant amounts of organic material and specific procedures

within geotechnical labs can vary. Appendix 3: Laboratory Procedures for Determining Bioretention Soil Mix Saturated Hydraulic Conductivity provides guidelines to standardize procedures and reduce inter-laboratory variability when testing BSM's with mineral and organic material content.

6.1.2.2 Bioretention components

The following provides a description and suggested guidelines and 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 <???> for various bioretention design examples.

Flow entrance and Presettling

Flow entrance design will depend on topography, flow velocities and volume entering the pretreatment and bioretention area, adjacent land use, and site constraints. Flows entering a rain garden should be less than 1.0 ft/second to minimize erosion potential. Five primary types of flow entrances can be used for bioretention cells:

- *Dispersed, low velocity flow across a landscape area:* Landscape areas and vegetated buffer strips slow incoming flows and provide an initial settling of particulates and are the preferred method of delivering flows to the bioretention 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 or sheet flow across pavement or gravel and past wheel stops for parking areas.*
- *Curb cuts for roadside, driveway or parking lot areas:* Curb cuts should include a rock pad or other erosion protection material in the channel entrance to dissipate energy. Avoid the use of angular rock or quarry spalls and instead use round (river) rock if needed. Removing sediment from angular rock is difficult. 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). Curb cuts used for bioretention areas in high use parking lots or roadways require special attention due to high coarse particulates and trash accumulation in the flow entrance and associated bypass of flows. The following are methods recommended for areas where heavy trash and coarse particulates are anticipated:
    - Curb cut width <need recommendation on this>

- At a minimum the flow entrance should drop 2 to 3 inches from gutter line into the bioretention area and provide an area for settling and periodic removal of debris. However, consider a small forebay at the flow entrance to capture more of the debris and sediment load from these areas.
- Anticipate relatively more frequent inspection and maintenance for areas with large impervious areas, high traffic loads and larger debris loads associated with these areas.
- Avoid piped flow entrance in this setting.

<Figure 6-1-9: curb cut inlet in high use area>

<Figure 6-1-10: Portland curb cut details>

- *Pipe flow entrance:* Piped entrances should include rock or other erosion protection material in the channel entrance to dissipate energy and disperse flow.
- *Catch basin:* In some locations where road sanding or higher than usual sediment inputs are anticipated, catch basins can be used to settle sediment and release water to the bioretention area through a grate for filtering coarse material.
- *Trench drains:* can be used to cross sidewalks or driveways where a deeper pipe conveyance creates elevation problems. Trench drains tend to clog and may require additional maintenance.

<Figure 6-1-11: catch basin inlet>

<Figure 6-1-12: 3 trench drain inlets and details>

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).

Bottom area and side slopes

Bioretention areas are highly adaptable and can fit various settings such as rural and urban roadsides, ultra urban streetscapes and parking lots by adjusting bottom area and side slope configuration. Recommended maximum and minimum dimensions include:

- Maximum planted side slope if total cell depth is greater than 3 feet: 3H:1V. If steeper side slopes are necessary rockeries, concrete walls or soil wraps may be effective design options. Local jurisdictions may require bike and/or pedestrian safety features, such as railings or curbs with curb cuts, when steep side slopes are adjacent to sidewalks, walkways, or bike lanes.
- Minimum bottom width for bioretention swales: 2 feet (to prevent channelization).

<Figure 6-1-13: bioretention rockery walls>

Bioretention areas should have a minimum shoulder of 12 inches (30.5 cm) between the road edge and beginning of the bioretention side slope where flush curbs are used. Compaction effort for the shoulder should 90 percent proctor.

<Figure 6-1-14: bioretention area with flush curb and shoulder>

Ponding area

Ponding depth recommendations:

- Maximum ponding depth: 12 inches (30.5 cm).
- Surface pool drawdown time: 24 hours

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). 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). For bioretention areas with under-drains, elevating the drain to create a temporary saturated zone beneath the drain is advised to promote denitrification (conversion of nitrate to nitrogen gas) and prolong moist soil conditions for plant survival during dry periods (see section <???>: Under-drains for details).

Surface overflow

Surface overflow can be provided by vertical stand pipes that are connected to under-drain

systems, by horizontal drainage pipes or armored overflow channels installed at the designed maximum ponding elevations. Overflow conveyance structures are necessary for all bioretention facilities to safely convey flows that exceed the capacity of the facility and to protect downstream natural resources and property.

<Figure 6-1-15: bioretention section with stand pipe and elevation drop to bioretention area>

<Figure 6-1-16: rock lined or stand pipe overflow>

The minimum freeboard from the invert of the overflow stand pipe, horizontal drainage pipe or earthen channel should be 6 inches unless otherwise specified by the local jurisdiction's design standards.

Bioretention soil media

Primary for the design and successful application of bioretention are the soil media and plants that, working together, provide flow control and a highly effective filter media for many stormwater pollutants. Soil mixes for bioretention areas need to balance three primary design objectives to provide optimum performance:

- Provide high enough infiltration rates to meet desired surface water drawdown and system dewatering.
- Provide infiltration rates that are not too high in order to optimize pollutant removal capability.
- Provide a growth media that supports long-term plant and soil health (Hinman, 2009).

Bioretention soil media (BSM) recommendations often have a topsoil component that generally does not have a grain size distribution specification and is highly variable depending on the source. As a result, the BSM can have higher than desired fines which may result in lower than desired infiltration rates.

The percent fines (aggregate passing the 200 sieve) in a BSM is important for proper system performance and requires particular attention. Presence of some fine material improves water retention, nutrient exchange and, as a result, the growing characteristics of soils. Smaller aggregate also increase receptor sites for adsorbing pollutants. In contrast, fine material strongly controls hydraulic conductivity and a small increase as a percentage of total

aggregate can reduce hydraulic conductivity below rates needed for proper system draw-down (Hinman, 2009).

Overall gradation is important for BSM performance as well. The soil mix will likely infiltrate too rapidly if the aggregate component is a uniform particle size. Specifically, a **uniformly graded**, fine-grained material will have relatively low **hydraulic conductivity** (K). A uniformly graded, coarse-grained material will have a relatively high K. However, a **well-graded** material that appears coarse-grained can have relatively lower K (Robertson, 2009). For more information on bioretention performance and supporting data for BSM recommendations see section <???>.

The following provides guidelines for Department of Ecology approved BSM. If the BSM is verified to meet the mineral aggregate gradation and compost guidelines below then no laboratory infiltration testing is required. If a different aggregate gradation and compost guideline is used laboratory infiltration tests (ASTM methods given below) are required to verify that the BSM will meet infiltration requirements.

Infiltration rates

- When using the approved BSM guidelines provided below enter 6 inches per hour in WWHM or MGSFlood.
- If using a different BSM guideline, laboratory Ksat testing is required. The Ksat determination should be no less than 1 inch per hour after a correction factor of 2 or 4 is applied (see section 6.1.2.1 Determining subgrade and bioretention soil media design infiltration rates) and a maximum of 12 inches per hour (no correction factors applied).

Mineral aggregate

Percent fines

- A range of 2 to 4 percent passing the 200 sieve is ideal and fines should not be above 5 percent for a proper functioning specification. <ASTM test>

Aggregate gradation

According to ASTM D 2487-98 (Classification of Soils for Engineering Purposes (Unified Soil Classification System)), well-graded sand should have the following gradation coefficients:

- Coefficient of Uniformity ($C_u = D_{60}/D_{10}$) equal to or greater than 4 and

- Coefficient of Curve ($Cc = (D_{30})^2/D_{60} \times D_{10}$) greater than or equal to 1 and less than or equal to 3.

Table <???> provides a gradation guideline for the mineral aggregate component of a BSM specification in western Washington (Hinman, Robertson, 2007). The sand gradation below is often provided by vendors, as a well-graded utility or screened sand. With compost, this blend provides enough fines for adequate water retention, hydraulic conductivity within the recommended range (see below), pollutant removal capability, and plant growth characteristics for meeting design guidelines and objectives.

Table <???>: Guideline for BSM gradation

Sieve Size	Percent Passing
3/8”	100
#4	95-100
#10	75-90
#40	25-40
#100	4-10
#200	2-5

Compost to aggregate ratio and organic matter content

- Compost to aggregate ratio: 60 percent mineral aggregate, 40 percent compost.
- Organic matter content: 4-8 percent by weight.

Existing soils

- Where existing soils meet the above aggregate gradation, those soils may be amended rather than importing mineral aggregate.

For small projects that do not trigger treatment requirements, the native soil may be amended according to guidance in the Rain Garden Handbook for Western Washington Homeowners. The minimum design infiltration rate of the amended soil should be 0.25 inches per hour after using an infiltration reduction correction factor of 2. <Need more discussion on this>

BSM recommendations with a topsoil component (e.g. sandy loam) contain some percentage of organic matter. When topsoil is a component of a BSM, 30-35 percent compost is typically used to attain a desired percent organic matter by weight. The BSM guideline for western

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Washington uses sand only which has very little or no organic material. Accordingly, the volumetric ratio to attain 4-8 percent organic material is 40 percent compost and 60 percent screened or utility sand. Soil components must be uniformly mixed.
<sidebar: determining OM content of soil mixes, pg 82 LID Manual>

Compost

Compost is the other primary component of a Bioretention Soil Mix. Compost qualities often determine the success or failure of bioretention soil mixes, in terms of infiltration and plant growth. See the Appendix ??? for two compost specifications: 1) for general soil amendment; and 2) for bioretention soils.

General compost standards for amending construction site soils (see Chapter ??? Amending Construction Site Soils for details) include:

- Meets the definition of "composted materials" in WAC 173-350, section 220 (including contaminant levels and other standards), available online at http://www.ecy.wa.gov/programs/swfa/compost/
- Must have an organic matter content of 35-65%.
- Must have a carbon to nitrogen ratio below 25:1 (the C:N ratio may be as high as 35:1 for plantings composed entirely of plants native to the Puget Sound Lowlands region).

For bioretention soil mixes, the above standards apply plus these additional standards to ensure that the compost will support healthy plant growth and root matrix development, contribute to biofiltration of pollutants, and not restrict infiltration when used in the higher proportions typical of bioretention soils:

- Produced at a composting facility permitted by the WA Department of Ecology. A current list of permitted facilities is available at http://www.ecy.wa.gov/programs/swfa/compost/
- Stable (low oxygen use and CO_2 generation) and mature (capable of supporting plant growth) by tests shown below. This is critical to plant success in a bioretention soil mixes.
- Moisture content range: no visible free water or dust produced when handling the material.
- Tested in accordance with the U.S. Composting Council "Testing Methods for the Examination of Compost and Composting" (TMECC), as established in the Composting Council's "Seal of Testing Assurance" (STA) program. Most Washington compost facilities now use these tests.

- Screened to the size gradations for Fine Compost under TMECC test method 02.02-B (gradations are shown in the specification in Appendix)
- pH between 6.0 and 8.5 (TMECC 04.11-A)
- Manufactured inert content less that 1% by weight (TMECC 03.08-A)
- Minimum organic matter content of 40% (TMECC 05.07-A).
- Soluble salt content less than 4.0 mmhos/cm (TMECC 04.10-A).
- Maturity greater than 80% (TMECC 05.05-A "Germination and Vigor").
- Stability of 7 or below (TMECC 05.08-B "Carbon Dioxide Evolution Rate").
- Carbon to nitrogen ratio (TMECC 04.01 "Total Carbon" and 04.02D "Total Kjeldahl Nitrogen") of less than 25:1. The C:N ratio may be up to 35:1 for plantings composed entirely of Puget Sound Lowland native species and up to 40:1 for coarse compost to be used as a surface mulch (not in a soil mix).

More information on verifying compost quality can be found in the Compost for Bioretention Soil Mixes specification in the Appendix ???. More information on using compost, compost benefits, a list of soil laboratories, and more can be found in *Building Soil: Guidelines and Resources for Implementing WDOE Soil Quality and Depth BMP T5.13 in WDOE Stormwater Manual for Western Washington* (Stenn, 2003) available online at www.soilsforsalmon.org or www.buildingsoil.org

Cation exchange capacity

- Cation Exchange Capacity (CEC) must be ≥ 5 milliequivalents/100 g dry soil.

CEC is a measure of how many positively charged elements or cations (e.g. magnesium (Mg^{+2}), calcium (Ca^{+2}) and potassium (K^{+1})) soil can retain. Clay and organic material are the primary soil constituents providing receptor sites for cations and to a large degree determine CEC. One of the parameters for determining site suitability for stormwater infiltration treatment systems is CEC. Site Suitability Criteria #6 in the Stormwater Management Manual for Western Washington requires that soil CEC must be ≥ 5 milliequivalents/100 g dry soil (Ecology, 2005). Bioretention soil mixes easily meet and exceed the Site Suitability Criteria #6 requirement.

pH

- pH 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).

BSM depth

- Typical BSM depth is 12 to 24 inches.
- For enhanced treatment and using the BSM guidelines in this manual as a Department of Ecology approved media, depth should be a minimum of 18 inches.
- A minimum depth of 24 inches should be selected for improved phosphorus and nitrogen (TKN and ammonia) removal where under-drains are used.

Deeper BSM profiles (> 24 inches) may 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.

Infiltration rates and water quality treatment considerations

Bioretention soil media provide the necessary characteristics for enhanced treatment. To meet Department of Ecology's current criteria for enhanced treatment (SSC-6 "Soil Physical and Chemical Suitability for Treatment") the maximum initial infiltration rate should be 2.4 inches per hour, the soil depth at least 18 inches, and the CEC at least 5 meq/100 grams of dry soil (Ecology, 2005). However, this maximum infiltration rate guideline was established for water quality treatment in existing or native soils and not for bioretention soil media designed for water quality treatment.

Bioretention soil media have high organic matter content and cation exchange capacities exceeding the above criteria. Additionally, recent water quality treatment research for bioretention soils suggest that metal capture remains very good at higher infiltration rates. Hsieh and Davis (2005) found excellent removal of oil and grease and lead (Pb) in similar bioretention soil mixes with significantly different infiltration rates (differences in infiltration a result of using different types of sand in the mix). At 6.61 in/hr, 22.44 in/hr and 9.45 in/hr mass

removal for oil and grease was >96 percent and Pb >98 percent for all infiltration rates. In the same analysis, percent mass removal for TSS, oil and grease and Pb was >96, >96 and >97 percent respectively. At 127.56 in/hr. Davis et.al. (2003) found relatively small differences in, but still very good, removal capabilities for total metals in bioretention soil mixes with different infiltration rates. At 0.79 in/hr copper (Cu), Pb and zinc (Zn) removal was 99, 97 and 95 percent respectively. At 3.19 in/hr percent mass removal for Cu, Pb and Zn was 87, 95 and 85 percent respectively.

The evaluations above vary from Washington Department of Ecology guidelines for enhanced treatment (i.e. influent concentrations are generally higher and total instead of dissolved metals are examined). However, this and other research suggest that removal of metals and hydrocarbons may remain high at infiltration rates well above 2.4 in/hr in bioretention systems. Nitrate and ortho-phosphate retention and removal is likely influenced by plants, organic matter and soil structure, as well as soil oxygen levels, soil water content, and hydraulic residence time. Accordingly, infiltration rate may play an important role for nitrate and phosphate management in bioretention systems, and more research is needed to develop defensible infiltration rate guidelines for nutrient management.

Phosphorus management recommendations

These recommendations are applicable and important <u>only</u> for bioretention areas that have under-drains and direct release to fresh water or eventually drain to water bodies with TDMLs for nutrients or are specifically designated as phosphorus sensitive by the local jurisdiction. Phosphorus (P) levels in bioretention areas are generally not a concern with groundwater unless there is groundwater transport of P through soils with low P sorption capability and close proximity to surface freshwater. Note that additional research is needed on P management in bioretention; however, current research indicates the following:

- *Mature stable compost*: reduces leaching of bio-available P.
- *Healthy plant community*: provides direct P uptake, but more importantly promotes establishment of healthy soil microbial community likely capable of rapid P uptake.
- *Aerobic conditions*: reduce the reversal of P sorption and precipitation reactions.
- *Increase BSM column depth*: increasing BSM to 24 or 36 inches may provide greater contact time with aluminum, iron and calcium components and sorption in the soil.

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- *Relatively neutral pH*: for western Washington, the BSM pH should be between 5.5 and 7.0 which is an acceptable range to minimize reversal of P sorption reactions and allow for sorption and precipitation using aluminum hydroxide.
- *Add metal oxides*: iron, aluminum and calcium are metals that can be added to adsorb or precipitate P. Aluminum is the most applicable for bioretention systems with appropriate adsorption reaction time, relative stability and pH range for reaction (Lucas 2009). Water treatment residuals (WTRs), used for settling suspended material in drinking water intakes, is a waste product and source for aluminum and iron hydroxides. More research is needed in this area, but current trials indicate that WTRs can be added at a rate of 10% by volume to the BSM for sorption of P. WTRs are fine textured and, if incorporated into the BSM, laboratory analysis is required to verify appropriate hydraulic conductivity (see section ???: Determining subgrade and bioretention soil media design infiltration rates). If using WTRs at a rate of 10% by volume, add shredded bark at 15% by volume to compensate for the fine texture of the WTRs (e.g. 60% sand, 15% compost, 15% shredded bark, 10 WTRs)..
- *Available P:* the molar ratio of ammonia oxalate extracted P in relation to ammonia oxalate extracted Fe.and Al in the BSM should be < 0.25.
- *Robust sandy gravel filter bed for under-drain*: provides a good filter for fine particulates and additional binding sites for P (see section <???> for more details on under-drains.

Nitrogen management recommendations

These recommendations are applicable and important <u>only</u> for bioretention areas that have under-drains and direct release to marine water. Nitrogen levels in bioretention areas are generally not a concern with groundwater unless there is groundwater transport of N in close proximity to marine water. Note that additional research is needed on N management in bioretention; however, current research indicates the following:

- *Mature stable compost*: reduces leaching of bio-available NO_3-N.
- *Healthy plant community*: provides direct NO_3-N uptake, but more importantly promotes establishment of healthy soil microbial community likely capable of rapid NO_3-N uptake.
- *Increase BSM column depth*: increasing BSM to 24 or 36 inches may provide greater contact time with small anaerobic pockets within the soil structure and denitrification in the soil column.
- *Elevated under-drain*: research suggests that nitrogen capture and retention in bioretention areas varies from good retention to export of nitrate. Where nitrate is a concern, various

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under-drain designs can be used to create a fluctuating anaerobic/aerobic zone below the drain pipe (Figure ???). **Denitrification** within the anaerobic zone is facilitated by microbes using forms of nitrogen (NO_2 and NO_3) instead of oxygen for respiration. A suitable carbon source provides a nutrition source for the microbes, enables anaerobic respiration, and can enhance the denitrification process (Kim, Seagren and Davis, 2003). Dissolved and particulate organic carbon that migrates from the BSM to the aggregate filter and bedding layer likely provides adequate carbon source for microbes.

Biosolids and manure composts can be higher in bio-available phosphorus than compost derived from yard or plant waste. Accordingly, biosolids or manure compost in bioretention areas are not recommended in order to reduce the possibility of exporting bio-available phosphorus and nitrogen in effluent.

Under-drain (optional)

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 above the bottom of the bioretention facility (subgrade) can be used in the WWHM or MGSFlood for flow control benefit (see Chapter <???> for bioretention area flow control credits). Under-drain systems should only be installed 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 below the minimum rate allowed by the local jurisdiction or that are not adequate to meet maximum pool and soil column drawdown time
- In an area that does not provide the minimum depth to the seasonal high groundwater table.

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

Under-drain pipe

Under-drains should be slotted, thick-walled plastic pipe. The slot opening should be smaller

than the smallest aggregate gradation for the gravel filter bed (see under-drain filter bed below) to prevent migration of material into the drain and clogging. This configuration also allows for pressurized water cleaning and root cutting if necessary (personal communication, Tracy Tackett, 2004). Under-drain pipe recommendation:

- Minimum pipe diameter: 4 inches (pipe diameter will depend on hydraulic capacity required, 4 to 8 inches is common).
- 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.
- Under-drains should be sloped at a minimum of 0.5 percent unless otherwise specified by an engineer (Low Impact Development Center, 2004).

<Figure 6-1-17: slotted drain detail>

Perforated PVC or flexible slotted HDPE pipe cannot be cleaned with pressurized water or root cutting equipment, are less durable and are not recommended. 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, Tracy Tackett, 2004).

Under-drain aggregate filter and bedding layer

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

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- Guideline for under-drain aggregate filter and bedding layers with heavy walled slotted pipe (see under-drain pipe guideline above):

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

The above gradation is a Type 26 mineral aggregate (gravel backfill for drains, City of Seattle).

- Place under-drain on a bed of the Type 26 aggregate with 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.

Drain position

Research suggests that nitrogen capture and retention in bioretention areas varies from good retention to export of nitrate. Where nitrate is a concern, various under-drain designs can be used to create a fluctuating anaerobic/aerobic zone below the drain pipe (Figure ???). **Denitrification** within the anaerobic zone is facilitated by microbes using forms of nitrogen (NO_2 and NO_3) instead of oxygen for respiration (Kim, Seagren and Davis, 2003). Dissolved and particulate organic carbon that migrates from the BSM to the aggregate filter and bedding layer likely provides adequate carbon source for microbes.

Orifice and other flow control structures

Under-drains also rapidly convey water out of the bioretention area and decrease detention time and flow retention. Properly designed and installed bioretention have shown very good flow control performance on soils with low infiltration rates (Hinman, 2009). Accordingly, when under-drains are used, orifices or other control structures are recommended to improve flow control. Access for adding or adjusting orifice configurations and other control structures is also recommended for adaptive management and optimum performance (see figures ??? for under-drain configuration and a proprietary two stage control structure). The minimum orifice diameter should be 0.25 inches to minimize clogging and maintenance requirements.

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<Figure 6-1-18: upturned under-drain>

<Figure 6-1-19: ILM/WSU flow control structure>

Check dams and wiers

Check dams are necessary for reducing flow velocity and potential erosion, as well as increasing detention time and infiltration capability on sloped sites. Typical materials include concrete, wood, rock, compacted dense soil covered with vegetation, and vegetated hedge rows. Design depends on flow control goals, local regulations for structures within road right-of-ways and aesthetics. Optimum spacing is determined by flow control benefit (modeling) in relation to cost consideration. Some typical check dam designs are included in Figure ???.

<figure 6-1-20: check dam berms, concrete weirs and wood>

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 infiltration to subgrade soils and are used for groundwater protection when bioretention facilities are installed to filter storm flows from pollutant hotspots or on sidewalls of bioretention areas to restrict lateral flows to roadbeds or other sensitive infrastructure. Where geomembrane liners are used to line the entire facility under-drain systems are necessary. The liner should have a minimum thickness of 30 mils and be ultraviolet (UV) resistant.

<figure 6-1-21: Portland bioretention planter section with liner>

Plants

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 root structures, root exudates and contribution of organic matter that aids in the development of soil structure and infiltration capacity. See Appendix <???> 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.
- *Sun exposure:* existing sun exposure and anticipated exposure when bioretention plants mature is a primary plant selection consideration.
- *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).
- *Expected pollutant loadings:* Plants should tolerate typical pollutants and loadings from the surrounding land uses.
- *Adjacent plant communities and potential invasive species control:* consider planting hearty, fast growing species when adjacent to invasive species, as well as anticipate maintenance needs to prevent loss of plants to encroachment of invasives.
- *Habitat:* native plants and hardy cultivars attract various insects and birds and plant palettes can be selected to encourage specific species.
- *Site distances and setbacks for roadway applications.*
- *Expected use:* in higher density settings where foot traffic across bioretention areas is anticipated elevated pathways with appropriate vegetation or other pervious material that can tolerate pedestrian use can be used <see figure ???>. Pipes through elevated berms for pathways across bioretention areas can be used to allow flows from one cell to another.

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- *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.

<Figure 6-1-22: Highpoint swales with elevated foot path and aesthetic vegetation>

Note that the BSM provides and excellent growth media and plants will often attain or surpass maximum growth dimensions. Accordingly, planting layouts should consider maximum dimensions for selected plants when assessing site distances and adjacent uses.

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 (see figures ???). 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 small 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 ??? for a sample planting plan.

<Figure 6-1-23: section and plan view of planting plan>

Native and hardy cultivar 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. To increase survival rates and ensure quality of plant material, the following guidelines are suggested:

- 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). Typically small herbaceous material and grasses are supplied as plugs or 4 inch pots and small trees and shrubs are generally supplied in pots of 3 gallons or less.
- Plant maturity and placement: Bioretention areas provide excellent soil and growing conditions; accordingly, plants will likely reach maximum height and width. Planting plans should anticipate these dimensions for site distances, adjacent infrastructure and planting densities.
- 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. Properly selected mulch material reduces weed establishment (particularly during plant establishment period), regulates soil temperatures and moisture, and adds organic matter to soil. When used, mulch should be:

- Coarse compost in the bottom of the facilities (compost is less likely to float during cell inundation).
- Shredded or chipped hardwood or softwood on side slopes above ponding elevation and rim area. Arborist mulch is mostly woody trimmings from trees and shrubs and is a good source of mulch material. Wood chip operations are a good source for mulch material that has more control of size distribution and consistency.
- 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).

<Figure 6-1-24: bioretention area mulch>

If planting bioretention areas is delayed (e.g. BSM placed in summer and plants are not installed until fall) mulch should be placed immediately to prevent weed establishment.
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 high heavy metal loading is not anticipated (Prince George's County, 2002). Mulch is recommended in conjunction with the groundcover until groundcover is established.

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 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).

In bioretention areas where higher flow velocities are anticipated an aggregate mulch may be used to dissipate flow energy and protect underlying BSM. Aggregate mulch varies in size and type, but 1 to 11/2 inch gravel (rounded) decorative rock is typical.

<Figure 6-1-25: aggregate mulch>

6.1.2.3 Installation

Prior to construction, meet with contractor, construction management and inspection staff to review critical design elements and confirm specification requirements, proper construction procedures, construction sequencing and inspection timing.

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 never be allowed during wet or saturated conditions (compaction can reach depths of 2-3 feet during wet conditions and mitigation is likely not possible). 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, beneath the surface of the BSM, can be vertical if soil stability is adequate. Exposed sidewalls of the completed bioretention area with BSM in place should be no steeper than 3H:1V (see section ??? above). The sidewalls and bottom should be tilled or scarified to minimum depth of 6 inches before placement of BSM. 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

Placement

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

bioretention facility.

Compact the BSM to a relative compaction of 85 percent of modified maximum dry density (ASTM D 1557). Compaction can be achieved by boot packing (simply walking over all areas of each lift) and then apply 0.2 inches (0.5 cm) of water per 1 inch (2.5 cm) of BSM depth. Water for settling should be applied by spraying or sprinkling.

Verification

If using the guidelines in section <???> : Bioretention soil media, pre-placement laboratory analysis for saturated hydraulic conductivity of the BSM is not required. Verification of the mineral aggregate gradation, compost guidelines and mix ratio in section <???> : Bioretention soil media should be provided to verify performance guidelines in that section.

If the BSM uses a different mineral aggregate gradation, compost guidelines and mix ratio than section <???> : Bioretention soil media, then the verification of the BSM composition (2-5 percent passing the #200 sieve, 5-8% OM content, CEC $\geq$ 5 MEQ/100 grams dry soil, pH in the range of 5.5 – 7) and hydraulic conductivity (initial rate less than 12 inches per hour and a long-term rate more than 1 inch per hour) should be provided through laboratory testing of the material to be used in the installation.

BSM infiltration rates are determined per ASTM Designation D 2434 (Standard Test Method for Permeability of Granular Soils) at 85 percent compaction per ASTM Designation D 1557 (Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort). Determine the organic matter content before and after permeability test using ASTM D2974 (Standard Test Method for Moisture, Ash, and Organic Matter of Peat and Other Organic Soils). Appendix ???: Recommended Procedures for ASTM D 2434 When Measuring Hydraulic Conductivity for Bioretention Soil Mixes provides guidelines to standardize procedures and reduce inter-laboratory variability when testing BSM's with mineral and organic material content.

If testing infiltration rates is necessary for post-construction verification use Pilot Infiltration Test method or a double ring infiltrometer test. If using the PIT method do not excavate BSM (conduct test at level of finished BSM elevation), use a maximum of 6 inch ponding depth and conduct test before plants are installed. If using the double ring infiltrometer measurements should be taken at enough locations within the bioretention area to provide a representative

infiltration rate (e.g. 2-3 locations per 50 feet).

Filter fabrics

Do not use filter fabrics between the subgrade and the BSM. The gradation between existing soils and BSM is not great enough to allow significant migration of fines into the BSM. Additionally, filter fabrics may clog with downward migration of fines from the BSM.

Temporary Erosion and Sediment Control (TESC)

Controlling erosion and sediment are most difficult during clearing, grading, and construction; accordingly, minimizing site disturbance to the greatest extent practicable is the most effective sediment management. During construction:

- Bioretention areas should not be used as sediment control facilities and all drainage should be directed away from bioretention areas 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). If introduction of construction runoff cannot be avoided see below for guidelines.
- Construction on bioretention facilities should not begin until all contributing drainage areas are stabilized according to erosion and sediment control BMPs and to the satisfaction of the engineer.
- If the design includes curb and gutter, the curb cuts and inlets should be blocked until BSM and mulch have been placed and planting completed (when possible), and dispersion pads are in place.

<Figure 6-1-26: good TESC>

Every effort during design, construction sequencing and construction should be made to prevent sediment from entering bioretention areas. However, bioretention areas are often distributed throughout the project area and can present unique challenges during construction. See section ???: Construction sequencing of LID Facilities for guidelines if no other options exist and runoff during construction must be directed through the bioretention areas.

Erosion and sediment control practices must be inspected and maintained on a regular basis.

6.1.2.4 Maintenance

Bioretention areas require periodic plant, soil, and mulch layer maintenance to ensure optimum infiltration, storage, and pollutant removal capabilities. Providing more frequent and well-timed maintenance (e.g weeding prior to seed dispersal) during the first three years will ensure greater success and reduce future maintenance of bioretention areas. For a detailed maintenance plan including levels of service and associated type and timing of activities see Appendix 4 . 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.
- *Sediment removal:* follow the maintenance plan schedule for visual inspection and remove sediment if the volume of the ponding area has been compromised.
- *Plant material:* Depending on aesthetic requirements, pedestrian obstruction or site distances, 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 and adequately shade and capture the site from weed establishment.
- *Weeding*: 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. The weeding schedule should become less frequent if the appropriate plant species and

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planting density are used and the selected plants grow to capture the site and exclude undesirable weeds.

- *Nutrients 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 areas are located in areas where phosphorous and nitrogen levels may be elevated and these should not be limiting nutrients. If in question, have soil analyzed for fertility.
- *Mulch:* Replace mulch annually in bioretention araeas where heavy metal deposition is high (e.g., contributing areas that include gas stations, ports and roads with high traffic loads). In residential settings or other areas where metal or other pollutant loads are not anticipated to be high, replace or add mulch as needed (likely 3-5 years) to maintain a 2 to 3 inch depth.
- *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.

6.1.2.5 Performance

Flow control processes in bioretention

While the original applications focused on water quality treatment, bioretention can be highly effective for stormwater volume reduction and flow attenuation. Where the surrounding native soils have adequate infiltration rates, bioretention can be used as a retention facility. Under-drain systems can be installed in facilities where existing soils have low infiltration rates; however, uncontrolled drains rapidly convey water out of the bioretention area and decrease detention time and flow retention. Properly designed and installed bioretention have shown very good flow control performance on soils with low infiltration rates (Hinman, 2009). Accordingly, when under-drains are used, orifices or other control structures are recommended to improve flow control. Access for adding or adjusting orifice configurations and other control structures is also recommended for adaptive management and optimum performance.

Flow control processes in bioretention areas include:

- *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 on soils with lower infiltration rates in the Puget Sound region.
- *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.
- *Transpiration* is the movement of water from the roots, through the plant supporting structure and out the stomata in leaves. Transpiration is minimal in the winter months when plants are relatively dormant; however, some transpiration may occur in bioretention areas in winter. No research is available estimating the transpiration component of evapotranspiration in the winter for bioretention areas.

Flow control performance

In the City of Seattle, Seattle Public Utilities (SPU) 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. 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).

In a subsequent SPU study four blocks of 110th Street Cascade bioretention system (high gradient with no under-drains) was evaluated for flow control. The surface (mulch) layer is gravel to prevent erosion with compost amended soil beneath. The subgrade is composed of till-like soils. The portion of the system that was monitored manages runoff from a contributing area that is approximately 7.3 ha (43% impervious, 57% lawns). Over three full wet seasons the bioretention areas retained 48% of flow measured at the inlet. When estimated flow inputs between inlet and outlet of the monitored section plus flow measured at the inlet were considered together, 74% of the total stormwater volume entering the system was retained (Chapman and Horner, 2010).

In a study of a 3.35-hectare (8.27-acres), 35-home residential LID pilot project in southern Puget Sound, that incorporates LID stormwater management practices, total precipitation volume retained and measured at the final outfall was 96 percent during the 2007-2008 wet season. At the same project, surface and sub-surface flows were monitored for a sub-basin including seven homes and four bioretention areas 0.32 hectares (0.8 acres). During the 2007-2008 wet season 99 percent the total precipitation volume was retained was and the sub-basin met the DOE standard for pre-development forested condition. Soils at the project were characterized as silt loam overlying cemented till with measured infiltration rates of 0.0 to 6.35 cm/hr (Hinman, 2009).

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.
- *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.

Pollutant removal efficiency in bioretention areas

Metals

Laboratory and field research indicates that bioretention areas have excellent capability to capture 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 <???> summarizes percentages of pollutants removed from pilot-scale laboratory studies performed at University of Maryland.

Table <???> 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)
Also see Appendix <???> for summaries of bioretention swale and bioretention cell research. Table <???> provides data summarizing research on other typical stormwater BMPs for comparison.

Subsequent studies confirm the metal capture capability of bioretention. Sun and Davis applied dissolved metals in synthetic storms to columns with grasses. Overall metal capture in the columns was good for both low and high loading regimes: Zn (l) 94%, (h) 97%; Cu (l) 88%, (h) 93%; Pb (l) 95%, (h) 97%; Cd (l) >95%, (h) >98%. Type of grass species did not significantly affect metal capture; however, the concentration of metals in the plant material did vary among grass species. Mass distribution of metals was 88-97% in soil media, 0.5-3.3% accumulated in plants and 2.0-11.6% in effluent.

Godecke et. al. (2009) examined the effect of wetting and drying and the presence of a saturated zone (with and without a carbon source) on the capture and accumulation of heavy metals in columns with plants. Soil cores were taken at various depths. Soil media was comprised of sandy loam (top layer), fine sand (filter layer), coarse sand (transition layer), and

fine gravel (drainage layer). Good metal capture was observed during wet periods with or without saturated zone and carbon source: Cu with = 95.2% ± 5.7, without 88 ± 3; Pb with and without = 99.2 ± 0.9; Zn with and without = 97.4 ± 1.7; Cd with and without = > 89.6; TSS with = 97.5 ± 2, without = 98.3 ± 1.3. Cu capture did improve with saturated zone <why>. No effect of drying detected in columns with saturated zones and carbon source. Most metal capture at top of filter and concentrations were generally below detection limits below 200 mm. Even with long drying periods and no saturated or carbon source filters performed well (% capture: Cu 70%, Zn and Pb = 90%).

Li and Davis (2008) analyzed soil profile samples collected at a bioretention cell constructed in 2001 with a 0.77 ha parking lot contributing area. Samples were analyzed for heavy metal concentrations. The cell was approximately 4.5 years old when sampled. Accumulation of Zn and Pb was mostly at surface of the bioretention cell. Below 10 cm concentrations were at background levels. Accumulation of Cu in surface layers was less prevalent and there was more association of Cu with lower media layers. The association of Cu with soil particles was weaker than Zn and Pb, and Cu tended to associate with OM that can be discharged with dissolve OM in bioretention effluent. Fractions of soluable-exchangable metal (indicator for leaching or bioavailability) was Zn>Cu>Pb. The analysis found low fractions of soluable-exchangable metals indicating metals were tightly bound to street dirt particles or media.

Table <???> 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)

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Finally, Hinman (2009) found metals below detection limits in the effluent of a 3.35-hectare (8.27-acre), 35-home residential LID pilot project in southern Puget Sound with bioretention as the primarily stormwater management practice. Dissolved lead, copper and Zinc were <0.002 µg/ L, <0.02 µg/L, <0.05 µg/L respectively at the **point of compliance**. Influent to bioretention areas was highly distributed and characterizing influent concentrations was not feasible. Only two storms were analyzed.

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

At the University of New Hampshire Stormwater Center, stormwater flows are distributed equally to various stormwater management practices from a nine 9 acre parking lot to compare the pollutant removal efficiency and flow control of each practice. Bioretention removal efficiency was 99% for total petroleum hydrocarbons-diesel.

Chapman and Horner, 2010 examined surface flow from roadside bioretention swales in Seattle and found 96% reduction from influent to effluent for total petroleum hydrocarbons.

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As part of a larger BMP performance monitoring program, Hathaway et. al. (2009) collected inflow and effluent grab samples for 12 stormwater BMPs. BMPs included two dry detention basins, one pond, two stormwater wetlands, one bioretention area, and three proprietary devices. Fecal coliform (FC) and E. coli were evaluated. The best performing BMPs for bacteria concentration reduction were bioretention and one of the wetlands, with the following results: fecal coliform: wetland = 0.98%, bioretention = 0.89%; E. coli: wetland = 0.96%; bioretention
= 0.92%.

Rusciano and Obrupta (2007) examined total suspended sediment (TSS) and fecal coliform (FC) capture in bioretention soil media. Columns were filled with planting substrate (equal parts sphagnum peat, triple shredded mulch and clean sand), 30.4 cm clean sand, filter fabric, and pea gravel from top to bottom. Manure was mixed to concentrations typical in stormwater and applied to columns at the rate of 77 mL/min. over a period of nine months (17 simulated storm events). Soil analysis at various depths was conducted after dosing. Mean reduction of TSS = 91.5% (range from 81.0 to 99.4%) and FC = 95.9% (range from 54.0 to 99.8%). Influent concentrations for FC increased percent removal, but also effluent concentrations. FC colony forming Units were observed in the post-dosing soil analysis from the depth 0-5.1 cm only.

<add Battelle study>

Thermal attenuation

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).

<add Hunt study>

Phosphorus

While metal, hydrocarbon, TSS, bacteria and possibly organics capture in bioretention areas is very good to excellent, nutrient management presents particular challenges. The BSM contains compost and therefore, a bank of nutrients. Nitrate-nitrogen (NO_3-N) and phosphate (PO_4) are bio-available forms of nitrogen and phosphorus and are of particular concern for eutrophication of fresh and marine receiving waters.

Geochemical cycling

Phosphorus (P) cycling in soils and through bioretention systems is complex. The majority of particulate P is phosphorus that is adsorbed onto clay fractions containing iron and aluminum oxides and/or precipitated with iron and/or calcium (Lucas, 2009). Adsorption reactions on media surfaces are relatively fast compared to calcium phosphate precipitation (a relatively irreversible reaction) and deposition of P within aluminum and iron oxide mineral structures (more reversible reaction) (Zang et. Al., 2008). The reversibility of these reactions depends primarily on dissolved PO_4 concentrations, redox status and pH (Lucas, 2009). For example, in anoxic conditions iron reduction (ferric to ferrous species) will release PO_4 from precipitates (Lucas, 2009).

Lucas and Greenway (2008) observed very good PO_4 capture by adding iron and aluminum oxides in the form of water treatment residuals (WTRs) to their bioretention soil mix. The iron and aluminum oxides provide adsorption sites for PO_4 ; however, these reactions may be reversible at lower pH and redox potentials. Davis et al., 2001 found P removal in bioretention soils increases with depth of facility. Increased contact time and sorption of P onto aluminum, iron, and clay minerals in the soil is the likely mechanism of removal.

Phosphorus availability is one of several parameters to determine the risk of phosphorus transport from agricultural land to fresh water systems. The sum of this analysis results in a P- index and includes rain fall, irrigation, erosion potential (i.e. slope, hydraulic conductivity, soil and crop management), and fertilizer application (Elrashidi, 2001). In properly designed bioretention systems, erosion, nutrient application and irrigation should not be of concern, especially once plants and soil structure are established. Accordingly, P availability is likely the single most important assessment from the P-index to indicate potential P transport from bioretention areas. Excessive levels of available P (>100 to 250mg/kg) suggest that bio-available phosphorus can exceed plant need or uptake and contribute to the pool of water soluble P that may be present in surface flow or soil water effluent (Stevens, 2008). Additional work is needed to correlate these agricultural tests in bioretention systems and to test available P when a bioretention soil mix is placed and then after the soil is planted and soil structure is improving.

Biological cycling

While the geochemical cycling of P is important for determining P availability, bacteria and

fungi are capable of rapid uptake and immobilizing of P and nitrogen (N). Of course plants require and take up N and P for growth; however, plants also provide a primary source of energy (carbohydrates) through root exudates and decomposition that support soil microbial activity. Lucas and Greenway (2008) observed significantly higher P capture due to microbial immobilization in planted compared to unplanted **mesocosms**.

<Tabel: Lucas Greeway 2008 P results>

Organic and inorganic P can be leached from compost amended soils and while some of the P load leached from compost is in a less readily available form, the negatively charged organic matter can displace considerable amounts of PO_4 available in the media (Lucas, 2009; Pitt and Clark, 2009).

Phosphorus management recommendations

These recommendations are applicable and important only for bioretention areas that have under-drains and direct release to fresh water or eventually drain to water bodies with TDMLs for nutrients or are specifically designated as phosphorus sensitive by the local jurisdiction. Phosphorus levels in bioretention areas are generally not a concern with groundwater unless there is groundwater transport of P through soils with low P sorption capability and close proximity to surface freshwater. Note that additional research is needed on P management in bioretention; however, current research indicates the following:

- *Mature stable compost*: reduces leaching of bio-available P.
- *Healthy plant community*: provides direct P uptake, but more importantly promotes establishment of healthy soil microbial community likely capable of rapid P uptake.
- *Aerobic conditions*: reduce the reversal of P sorption and precipitation reactions.
- *Increase BSM column depth*: increasing BSM to 24 or 36 inches may provide greater contact time with aluminum, iron and calcium components and sorption in the soil.
- *Relatively neutral pH*: for western Washington, the BSM pH should be between 5.5 and 7.0 which is an acceptable range to minimize reversal of P sorption reactions and allow for sorption and precipitation using aluminum hydroxide.
- *Add metal oxides*: iron, aluminum and calcium are metals that can be added to adsorb or precipitate P. Aluminum is the most applicable for bioretention systems with appropriate adsorption reaction time, relative stability and pH range for reaction (Lucas 2009). Water treatment residuals (WTRs), used for settling suspended material in drinking water intakes,

is a waste product and source for aluminum and iron hydroxides. More research is needed in this area, but current trials indicate that WTRs can be added at a rate of <10%> by volume to the BSM for sorption of P. WTRs are fine textured and, if incorporated into the BSM, laboratory analysis is required to verify appropriate hydraulic conductivity (see section ???: Determining subgrade and bioretention soil media design infiltration rates).

- *Available P:* the molar ratio of ammonia oxalate extracted P in relation to ammonia oxalate extracted Fe and Al in the BSM should be < 0.25.
- *Robust sandy gravel filter bed for under-drain*: provides a good filter for fine particulates and additional binding sites for P (see section <???> for more details on under-drains.

Nitrogen

Nitrate removal is highly variable in bioretention, but generally poor and at times NO_3-N production and export has been observed (Kim et al., 2003).

Geochemical cycling

Production or export of NO_3-N is likely a result of organic and ammonia nitrogen that is converted to nitrate NO_3-N between storms (presumably through the **ammonification** and **nitrification** process). NO_3-N is then washed from the facility during subsequent storm events (Kim et al., 2003).

In laboratory columns Kim et al. (2003) observed improved reduction of NO_3-N concentrations by creating an anaerobic zone with a suitable carbon source (e.g. wood chips mixed in the gravel) acting as an electron donor or energy source for denitrifying bacteria. The fluctuating aerobic, anaerobic zone promotes denitrification (transformation of NO_3-N to nitrogen gas) and improve nitrate removal. Davis (2001) also showed improved nitrate removal by simply increasing the BSM depth to 24 or 36 inches. However, Hunt et.al. (2006) did not observe improved nitrate removal in bioretention field sites comparing bioretention cells with and without saturated zones at the bottom of the facilities. Also, the Davis study showing improved NO_3-N with increased BSM depth may have been a result of small saturated zones within the soil matrix and additional NO_3-N contact time though the soil column. Soil water and oxygen level characteristics are highly dependent on soil texture, soil structure and plants; accordingly, soil depth and NO_3-N removal requires additional analysis.

Biological cycling

In a large study with 125 columns and treatments including various plants, soil media blends, filter depth and area, and pollutant inflow concentrations, and hydraulic load Bratieres et.al (2008) found vegetation selection important for nutrient management (Carex appressa and Meleleuca ericifolia performed best). Additional findings in this study include: bioretention built to studies optimal specification can reliably capture 70% of nitrogen and 85% phosphorus; all columns effectively removed TSS (95%); increasing filter depth increased **NOx** effluent concentration, but performance improved as plants matured in deeper columns; filter media depth showed no effect on TP or phosphate capture.

Lucas and Greenway (2008) examined retention of P and N in 240 L mesocosms with various soil mixes. Half were vegetated with shrubs and grasses and half barren. Total phosphorus retention in the vegetated loam was 91% compared to 73% in the barren loam and TN retention was 81% in the vegetated loam compared to 41% in the barren loam. TP retention was 86-88% in the sand treatments and TN retention was 64% in the vegetated sand compared to 30% in the barren sand. The TP and TN retention significantly exceeds uptake rates for plants suggesting that there are additional processes involved for nutrient retention and transformation in the soil.

<Tabel: Lucas Greeway 2008 N results>

Nitrogen management recommendations

These recommendations are applicable and important only for bioretention areas that have under-drains and direct release to marine water or fresh water with TMDLs for nutrients. Nitrogen levels in bioretention areas are generally not a concern with groundwater unless there is groundwater transport of N in close proximity to marine water. Note that additional research is needed on N management in bioretention; however, current research indicates the following:

- *Mature stable compost*: reduces leaching of bio-available NO_3-N.
- *Healthy plant community*: provides direct NO_3-N uptake and promotes establishment of healthy soil microbial community likely capable of rapid NO_3-N uptake.
- *Increase BSM column depth*: increasing BSM to 24 or 36 inches may provide greater contact time with small anaerobic pockets within the soil structure and denitrification in the soil column.

- *Elevated under-drain*: elevate the under-drain from the bottom of the bioretention facility and located within a gravel blanket to create a fluctuating anaerobic/aerobic zone below the drain pipe. With a suitable carbon source acting as an electron donor (energy source for bacteria), the anaerobic zone can promote denitrification and improve nitrate removal. The BSM above the aggregate anaerobic zone will likely provide an adequate carbon source for bacteria and adding wood chips or other carbon source is not recommended.

For additional studies and details on research cited above see Bioretention Research in Appendix <???>.

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6.2 Amending Construction Site Soils

Native soils are highly complex systems that provide essential environmental benefits including: physical filtration, chemical transformation and biological uptake 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. The micro-and macro-pores created by the enhanced structure 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 typically 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.

Current landscape practices often do not require adequate preparation of turf and planting bed areas in order to regain the hydrologic and plant growth 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 flows just below the surface of the ground 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).

The following section focuses on soil amendment guidelines for general landscape and vegetation protection areas to meet the provisions of BMP T5.13 “Post Construction Soil Quality and Depth” in Ecology’s Stormwater Management Manual for Western Washington. For specific application of soils in bioretention facilities see Section ???: Bioretention. Soil protection and restoration must also be coordinated with the TESC and Grading plans in the Stormwater Pollution Prevention Plan (SWPPP) for the site, and by minimizing/balancing cut and fill during subsoil grading to reduce impacts and transportation costs (see Chapter ???: Precision Site Preparation, Grading and Inspection of LID Facilities).

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:

- Improved soil structure and porosity and reduced bulk density (US Composting Council, 2005).
- Increased infiltration (US Composting Council, 2005).
- Increased moisture holding capacity (US Composting Council, 2005).
- Increased cation exchange capacity, pollutant adsorption and filtration (US Composting Council, 2005)
- Buffers soil pH (US Composting Council, 2005).
- 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 ??? for soil specifications

in bioretention areas and Section???: Urban Trees for soil requirements in tree planting areas). Application rates and techniques for incorporating amendments will vary with the use and plant requirements of the area. For example, amendment depths will be less in tree root protection zones than in new turf and planting beds, and turf areas typically are amended at a lower rate than planting beds. (see Section ???: Design for details).

6.2.2 Design and implementation

Much of the information supplied here is a summary of *Building Soil: Guidelines and Resources for Implementing Soil Depth and Quality BMP T5.13 in WDOE Stormwater Management Manual for Western Washington* (Stenn, 2003). An update of this guidance is available at: http://www.soilsforsalmon.org. For more detail on specifications, verification, and inspection procedures, and additional resources consult the above cited manual.

6.2.2.1 Developing a soil management plan

Protecting or enhancing construction site soil requires planning for proper construction sequencing to reduce construction impacts and to delineate soil and vegetation protection areas, soil enhancement areas, access roads, and locations for material storage. These areas should be clearly delineated on site or grading plan and communicated to the contractors. At a minimum the soil management plan (SMP) should include 1) a site plan drawing and 2) a soil, compost and mulch worksheet showing:

- Soil, vegetation and tree protection zones (show clearing limits and/or soil stockpile areas if applicable).
- Soils that will be disturbed during construction and will be improved and revegetated.
- Soils disturbed by previous development and will be improved and revegetated,
- Locations for laydown and storage areas, construction vehicle access and haul roads, temporary utilities and construction trailers (all of the above should be located outside protection areas). These areas will need to be restored breaking up compaction and amending the soil at end of construction.
- Describe how protection areas and soil enhancement areas will be protected from compaction.
- Describe the treatment details for each area scheduled for soil enhancement (disturbed soil areas) and calculate the quantities of compost and/or compost-amended topsoil and mulch that will be used to meet the provisions of BMP T5.13.

The SMP should also show intended locations of permanent infiltration facilities (pervious pavement, bioretention etc.) and be coordinated with the TESC/SWPPP to prevent unintended erosion or sedimentation of infiltration areas. Check with the permitting jurisdiction for SMP requirements within the permit and construction process.

To determine the treatment details for disturbed soils that will be amended, the five following steps should be completed:

1. Review site grading and landscape plans.
2. Visit site to determine soil conditions prior to construction.
3. Select amendment options.
4. Identify compost or topsoil for amendment and mulch.
5. Calculate compost, topsoil and mulch volumes.

More information on each step can be found in the above-mentioned *Building Soil: Guidelines for Implementing BMP T5.13*, available at www.soilsforsalmon.org or www.buildingsoil.org .

<Figure 6-2-1: graphic of plan and form for SMP (David McDonald will create/provide)>

Characteristics of soils to promote infiltration and healthy vegetation

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

- A target organic matter content of 10 percent (8-10% range) by dry weight for all planting beds and other landscaped areas except turf. Organic Matter (OM) content is measured in soil laboratories using dried sample by the “loss-on-ignition test. *Acceptable test methods for determining organic matter include the most current version of ASTM D2974 “Test Methods for Moisture, Ash, and Organic Matter of Peat and Other Organic Soils,” and TMECC 05.07A ”Loss-On-Ignition Organic Matter Method”. Organic matter tests are not needed when using the Pre-approved Amendment Rates shown below.
- A target organic matter content* of 5% (3-5%range) in turf areas. An exception is sand-based turf sports fields, which require specialized soil mixes with typically lower organic content but a similar depth of free-draining sandy soil.
- pH between 6.0 and 8.0 or a pH appropriate for installed plants.

- A minimum organic-amended depth of 8 inches (except in tree root protection areas—see next page).
- Subsoils below topsoil applications should be scarified to a depth of at least 4 inches and some topsoil material incorporated to prevent stratification, for a finished un-compacted soil depth of 12 inches. See tilling recommendations below for specific application methods.
- Planting beds should be mulched after planting with 2 to 3 inches (maximum) of organic material such as arborist wood chips.

Pre-approved amendment rates

The simplest way to calculate soil and amendment needs is to use these pre-approved rates:

- Planting Beds: 10% organic matter (8-10% OM range) using 3 inches of compost incorporated to an 8-inch depth, or a topsoil mix containing 35-40% compost by volume.
- Turf Areas: 5% OM (3-5% range) using 1.75 inches of compost incorporated to an 8-inch depth, or a topsoil mix containing 20-25% compost by volume.

Calculating custom amendment rates to meet organic matter requirements

The target organic matter content may be achieved by using the pre-approved amendment rates outlined above or by calculating a custom amendment rate for the existing site soil conditions. The pre-approved rates simplify planning and implementation; however, the organic matter content of the disturbed on-site topsoils may be relatively good and not require as much 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, and moisture content. 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 *Building Soil: Guidelines and Resources for Implementing Soil Depth and Quality BMP T.5.13 in WDOE Stormwater Management Manual for Western Washington* (Stenn, 2003) for additional information on testing and custom-calculation procedures, available at www.soilsforsalmon.org . A spreadsheet that performs these calculations is available on that website at www.soilsforsalmon.org/excel/Compost_Calculator.xls and

another easy to use calculator is available at
http://your.kingcounty.gov/solidwaste/compost_calculator.htm.
Custom compost application rates are calculated using the following equation:

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

Where:
CR = compost application rate (inches)
D = finished depth of incorporated compost (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 turf or landscape area)*
CBD = compost bulk density *(lb/cubic yard dry weight)*
COM% = compost organic matter (%)

Methods to achieve recommended soil characteristics
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. More than one method can be used on different portions of the same site. Slope, accessibility, stockpile area available, cost, and intended plant material may be part of the decision on which option to use where.

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. If these areas are protected from all impacts throughout construction they do not have to be amended or restored. See Chapter ???: Site Planning, Chapter ???: Vegetation Protection, Reforestation and Maintenance and Chapter ???: Site Preparation and Construction for conservation techniques.
2. **Amend existing disturbed topsoil or subsoil.**
   Till compost into soil to an 8-inch depth, fully mixing the organic matter into that zone. If soil has been compacted by construction traffic, scarify the subsoil 4 inches below that 8-inch organic zone to achieve a 12-inch depth of uncompacted soil. Do not scarify soil within

the drip-line of existing trees to be retained. Within 3 feet of the tree drip-line (or Critical Root Zone as determined by an arborist), amendment should be incorporated no deeper than 3 to 4 inches to reduce damage to roots.

- *Planting Beds (target 10 percent organic content):* Place and till 3 inches (or custom calculated amount) of compost into the upper 8 inches of soil. Rake beds smooth, remove rocks larger than 2 inches in diameter. Mulch beds after planting with 2-3 inches of organic mulch such as arborist wood chips.
- *Turf Areas (target 5 percent organic content):* Place and till 1.75 inches (or custom calculated amount) of compost into the upper 8 inches of soil. 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 in diameter.

<Figure 6.2.2: properly amended soil section>

3. **Stockpile topsoil from cleared areas, amend if necessary, and replace prior to planting.**

   Stockpile and cover soil with 3 inches of wood chips, weed barrier or other breathable material that sheds moisture yet allows air transmission in approved location prior to grading. Test the stockpiled material for organic matter content to determine whether additional compost must be tilled into the stockpiled soil to meet the required OM targets (see “Calculating custom amendment rates” earlier in this section). 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. 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.

   - *Planting Beds (target 10 percent organic content):* Place and till 3 inches of compost (or custom calculated amount depending on stockpiled soil’s tested organic content) into upper 8 inches of soil. Rake beds to smooth, remove rocks larger than 2 inches in diameter. Mulch beds after planting with 2-3 inches of organic mulch or stockpiled duff.
   - *Turf Areas (target 5 percent organic content):* Place and till 1.75 inches (or custom calculated amount) of compost into the upper 8 inches of soil. Water or roll compact soil to 85 percent of maximum. Rake to level, and remove surface woody debris and rocks larger than 1-inch in diameter.

4. **Import topsoil with required organic matter content standards.**
   Scarify or till subgrade in two directions to at least a 4-inch depth before placing 8 inches of imported topsoil. The entire surface should be disturbed by scarification. 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.
   - *Planting Beds (target 10 percent organic content):* Use imported topsoil mix containing 8-10 percent organic matter (typically around 35-40 percent compost by volume in the soil mix). The mineral portion must be sand or sandy loam as defined by the USDA soil classification system and should have less than 20 percent pass through a #200 sieve and 100 percent should pass through a ¾-inch screen (WORC, 2003). 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, and remove surface rocks over 2 inches in diameter. Mulch beds after planting with 2-3 inches of organic mulch.
   - *Turf Areas (target 5 percent organic content):* Use imported topsoil mix containing 3-5 percent organic matter (typically around 20-25 percent compost by volume in the soil mix). Soil portion must be sand or sandy loam as defined by the USDA soil classification system and should have less than 20 percent pass through a #200 sieve and 100 percent should pass through a ¾-inch screen (WORC, 2003). 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).

6.2.2.2 Verifying soil quality and depth

The following steps are provided to help inspectors verify guidelines summarized in this section and provided in *Building Soil: Guidelines and Resources for Implementing Soil Depth and Quality BMP T5.13 in WDOE Stormwater Management Manual for Western Washington* (Stenn, 2003). These steps may be completed at multiple visits as a project progresses or in one final project approval inspection, depending on local practices.

Step1: Compare site conditions with the approved Soil Management Plan (SMP).

- The SMP approved with the site permit describes soil treatments approved for each area. Make sure site conditions match these details in the SMP:

- Site location and permit holder.
- Turf and planting areas match approved drawings.
- Areas to remain as undisturbed native soil and vegetation have been fenced off during construction to prevent soil compaction or damage to plants.

Step 2: Inspect delivery tickets for compost, topsoil and mulches.

- The permitee must provide original delivery tickets for all soil and mulch products. Compare delivery tickets with the SMP to match the following information:
  - Delivery location.
  - Total quantities for each soil product and mulch.
  - Product descriptions and sources. If materials other than those listed in the SMP were delivered, laboratory test results must be provided to confirm that they are equivalent to approved products.

Step 3: Verify depth of amended soil and scarification.

- Use a shovel to dig at least one test hole per acre for turf and one per acre for planting beds to verify eight inch topsoil depth (below mulch layer), incorporation of amendments, and four inches of uncompacted subsoil (see Figure 6.2.3).
- The top eight inches of soil should be easy to dig using a garden spade driven solely by the inspectors weight. The soil should be darker than the unamended soil below, and particles of added organic matter are likely to be visible. Clay soil that been saturated and then dried may require jumping on the shovel step to penetrate, but the soil should yield easily when moist. Soil that requires vigorous chipping with the shovel to penetrate probably does not meet the specification.
- The next four-inch depth of soil should be loose enough to penetrate with the shovel. It may be rocky and the loosened depth may vary due to the pattern of scarifying equipment , but some sections of subsoil in a one foot square hole should be loose four inches deep into the subsoil (that is, to a total 12 inch depth from the soil surface).

Step 4: Check soil depth in several spots.

- Use a simple “rod penetrometer” (see Figure 6.2.3) to confirm that the soil is uncompacted twelve inches deep at ten locations per acre – with a minimum of ten on smaller sites. To locate test spots, imagine a line dividing the site (or each acre) in half lengthwise, then divide each half into five nearly equal sections. Conduct tests near the middle of each

section. Additional test locations are encouraged. The rod penetrometer should enter the soil twelve inches deep, driven solely by the inspector's weight. Irregular scarification or rocks in the lower layer may require probing a few spots at each location to reach the full depth.

Step 5: Check mulch depth.

- Use a shovel to scrape away and reveal surface mulch thickness. A two inch layer of organic material (mulch) such as composted sawdust, wood chips, or ground bark should be distinguished from the underlying soil on all planting beds.

Final step: Record results on "Field Verification Form" or similar document.

See *Building Soil: Guidelines for Implementing BMP T5.13* cited above and available at www.soilsforsalmon.org or www.buildingsoil.org for additional verification details.

<Figure 6.2.3: Verifying soil depth and quality >

6.2.2.2 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.

Determining compost quality

Compost quality can be determined by examining the material and quantitative 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.

Compost suppliers should supply documentation that their compost meets of one or both of the following two standards:

- 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. A current list of permitted composting facilities in Washington meeting these standards is available at http://www.ecy.wa.gov/programs/swfa/compost/.
- Material may also meet the US Composting Council’s “Seal of Testing Assurance” (STA) program, which includes regular testing for maturity, stability, and other standards described below that help ensure optimal plant growth. Many Washington compost facilities are part of this USCC STA quality assurance program.

Testing standards for compost quality (typically available from compost suppliers) include:

- Organic matter content between 35 and 65 percent as determined by loss of ignition test method (ASTM D 2974 or TMECC 05.07A).
- pH between 6.0 and 8.5.
- Carbon:nitrogen ratio between 15:1 and 25:1 for both turf areas and planting beds (however a C:N ratio of 30:1 to 35:1 is preferred for plantings composed entirely of Puget Sound lowland native species).
- Maximum electrical conductivity of 5 mmhos/cm or 5 deci-Siemen/meter (dS/m).
- 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 by dry weight.
- Metals should not be in excess of limits in the following table from Washington State’s compost facility testing requirements in WAC 173-350-220:

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

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Nickel	≤ 210 ppm
Selenium	≤ 18 ppm
Zinc	≤ 1400 ppm

Determining final grade with amended soils

Two factors affect final grade when tilling or ripping and amending or placing amended soils:

- "Fluff factor" from tilling up compacted subsoils.
- Settling factor as compost amended soils settle in place.

These two factors tend to cancel each other, resulting in a typical combined settling factor of 10-15% volume in compost-amended soils. This means an 8-inch amended soil should be initially placed to a level around 1-1.5 inches higher than the intended final grade to allow for settling. The best way to settle soil in place is to thoroughly wet each lift as applied or amend the soil a month before final landscaping. Mechanical compaction should not be used.

These factors vary widely by soil type, initial compacted conditions and compost type, so creating a test plot during the project may be the best way to establish fluff and settling factors. Practically, it's best to place or amend and allow soil to settle (or settle by watering), and then plan for a final addition of up to 1-2 inches of amended soil to meet final grades where critical (such as adjacent to sidewalks and curbs). Another strategy is to design final grades to be slightly mounded to allow for later settling in place. Note: if mounding for later settlement, erosion and sediment controls should be considered to prevent runoff and sediment to adjacent impervious or pervious surfaces and infiltration areas.

Turf areas and drainage

Compost-amended soil (20-25% compost by volume) provides improved turf lawn growth, rooting depth, drought resistance, and reduced fertilizer and pesticide demands while also promoting detention, infiltration, and biofiltration of stormwater (McDonald 1999). As previously noted, sports fields with sand-based turf requires specialized soil mixes with less organic and sandy texture to promote free drainage. Lawns on poorly drained sites can become spongy. On those sites a sandy soil mix with 15-20% compost by volume provide a firmer surface. A drainage route or subsurface collection system is often recommended for high-traffic turf applications in poorly draining soils.

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6.2.2.3 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.

6.2.3 Construction sequencing for protecting construction site soils

Soil protection and restoration begins with the initial site survey and continues throughout the project. Following these steps at each phase will save time and money, and result in a higher-value final landscape on site as well as better stormwater performance (adapted from When to Amend: Construction Sequencing for Soil Protection and Restoration, McDonald 2008, available at www.buildingsoil.org/tools/When_to_Amend.pdf).

Design phase

- Survey site soils and vegetation to determine where good quality existing soil and vegetation may be candidate areas for protection.
- Identify vegetation and soil protection areas, and verify they work with the site access and development program.
- Identify areas to be graded, and most cost-effective stockpiling, amendment, or topsoil import options. Calculate compost amendment, topsoil, and mulch quantities needed for each area.
- Record the above information on a Soil Management Plan.
- Review construction schedule, identifying how the soil protection and restoration practices will be incorporated at each phase.
- Involve entire design team in reviewing the Soil Management Plan, and communicating it to construction managers and contractors.

Land clearing and grading phase

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- Fence all vegetation and soil protection areas prior to first disturbance, and communicate those areas and the Soil Management Plan to clearing and grading operators. Root zones of trees that may extend into the grading zone should be either protected or cut rather than ripped during grading.
- Land-clearing debris can often be chipped on-site and reused immediately as erosion-control cover, or stockpiled for reuse as mulch at end of project.
- Stockpile topsoil to be reused with a breathable cover such as wood chips or landscape fabric.
- If amended topsoils will be placed at end of project, grade 8-12 inches below finish grade to allow for placing the topsoil.

Construction phase

- Ensure erosion and sediment control BMPs are in place before and revised after grading to protect construction activities. Compost based BMPs (2-inch compost “blankets” for surfaces, and compost berms or socks for perimeter controls) give a two-for-one benefit because the compost can be reused as soil amendment at the end of the project.
- Lay out roads and driveways immediately after grading and place rock bases for them as soon as possible. Then keep as much construction traffic as possible on the road base, and off open soils. This will improve erosion compliance, reduce soil compaction, and increase site safety by keeping rolling equipment on a firm base.
- Maintain vegetation and soil protection area barriers and temporary tree root zone protection BMPs throughout construction and ensure that all contractors understand their importance.

End of construction, soil prep before planting

- Ensure vegetation and soil protection barriers stay up until end of project.
- Disturbed or graded soil areas that have received vehicle traffic will need to be de-compacted to a minimum 12-inch depth. This can be done with a cat-mounted ripper, or with bucket-mounted ripping teeth.
- Amend all disturbed areas with compost at least 8 inches deep by tilling, ripping, or mixing with bucket loader. Alternatively place compost-amended stockpiled topsoil, or import a compost-amended topsoil. It is good practice to scarify or mix soil/compost several inches into the underlying subsoil to enhance infiltration and root penetration. Compost from

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erosion BMPs (compost blankets, berms, or socks) can be reused at this point if immediately followed by planting and mulching so there is no lapse in TESC.

- Amended topsoils can be placed as soon as building exterior work is complete, if contractors understand that vehicles must stay on road and driveway pads. Compost, soil blends provide good ongoing erosion protection.
- Avoid tilling through tree roots – instead use shallow amendment and mulching.
- Final prep for turf areas will include raking rocks, rolling, and possibly placing 1-2 inches of sandy loam topsoil before seeding or sodding.
- Plan for amended soil to settle, by placing amended soil slightly higher than desired final grade, or retain or import a smaller amount of amended topsoil to meet final grades adjacent to hardscape such as sidewalks.
- Keep compost, topsoil, and mulch delivery tickets so inspector can verify that quantities and products used match those calculated in the Soil Management Plan at start of project.

After planting and end of project phase

- Remove protection area barriers. Evaluate trees for stress and need for remediation such as pruning, root-feeding, mulching etc. – plan to have an arborist on-site.
- Mulch all planting beds where soil has been amended and re-planted with 2-3 inches of arborist wood chip mulch.
- Protect amended/restored soils from equipment-caused compaction, using steel plates or other BMPs if equipment access is unavoidable across amended soils.
- Communicate a landscape management plan to property owners that includes: onsite reuse of organics (mulch leaves, mulch-mow grass clippings) to maintain soil health; avoiding pesticide use; and minimal organic-based fertilization.

6.2.4 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 and settling soil to stabilize site as soon as possible.

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- Landscape management plans should continually renew organic levels through mulch-mowing (grasscycling) on turf areas and allowing leaf-fall to remain on beds and/or replenishing mulch layers every 1-2 years.
- Minimize or eliminate use of pesticides and fertilizers. Landscape management personnel should be trained to minimize chemical inputs, use non-toxic alternatives, and manage the landscape areas to minimize erosion, recognize soil and plant health problems, and optimize water storage and soil permeability.

6.2.5 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) cleared, graded and compacted test plots with silt loam soil to simulate construction site conditions and then applied combinations of deep tillage (single shank ripper behind bulldozer lowered into soil 90 cm (35 inches)) and chisel plow (four shanks behind a tractor lowered 30 cm (12 inches) into soil). Compost was tilled into selected plow treatments and simulated storms applied to the plots. The deep-tilled only plots increased runoff volume compared to the control (no grading or compaction), and the combined chisel plow and deep-tilled treatment with no compost 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 less runoff volume than 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).

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6.3 Permeable Pavement

Pavement for vehicular and pedestrian travel occupies roughly twice the space of buildings. While essential for the movement of people, goods and services, vehicular pavement generates significant levels of heavy metals and most all hydrocarbon pollutants in stormwater (Ferguson, 2005). The concentration of pollutants (most specifically metals and hydrocarbons) in vehicular pavement surface flow, in general, increases with traffic intensity (Ferguson, 2005 and Colandini et al., 1995). Figure <???> shows metal concentrations in trapped particles recovered from porous asphalt parking lots and freeways in Europe.

Both pedestrian and vehicular pavements also contribute to increased peak flow, flow durations and associated physical habitat degradation of streams and wetlands. Optimum management of stormwater quality and quantity from paved surfaces is, therefore, critical for improving fresh and marine water conditions in Puget Sound.

<Figure 6-3-1: concentration of metals in recovered sediments from porous asphalt>

Permeable paving surfaces are an important integrated management practice within the LID approach and can be designed to accommodate pedestrian, bicycle and auto traffic while allowing infiltration, treatment and storage of stormwater. The general categories of permeable paving systems include:

- *Porous hot or warm-mix asphalt pavement* is a flexible pavement similar to standard asphalt that uses a bituminous binder to adhere aggregate together. However, the fine material (sand and finer) is reduced or eliminated and, as a result, voids form between the aggregate in the pavement surface and allow water to infiltrate.
- *Pervious Portland cement concrete* is a rigid pavement similar to conventional concrete that uses a cementitious material to bind aggregate together. However, the fine aggregate (sand) component is reduced or eliminated in the gradation and, as a result, voids form between the aggregate in the pavement surface and allow water to infiltrate.
- *Permeable interlocking concrete pavements (PICP) and aggregate pavers*. PICPs are solid, precast, manufactured modular units. The solid pavers are (impervious) high-strength Portland cement concrete manufactured with specialized production equipment. Pavements constructed with these units create joints that are filled with permeable aggregates and installed on an open-graded aggregate bedding course. Ag-

gregate pavers (sometime called pervious pavers) include modular precast paving units made with similar sized aggregates bound together with Portland cement concrete with high-strength epoxy or other adhesives. Like PICP, the joints or openings in the units are filled with open-graded aggregate and placed on an open-graded aggregate bedding course. The paving units are intended for pedestrian use only.

- *Grid systems* include those made of concrete or plastic. Concrete units are precast in a manufacturing facility, packaged and shipped to the site for installation. Plastic grids typically are delivered to the site in rolls or sections. The openings in both grid types are filled with topsoil and grass or permeable aggregate. Plastic grid sections connect together and are pinned into a dense-graded base, or are eventually held in place by the grass root structure. Both systems can be installed on an open-graded aggregate base as well as a dense-graded aggregate base.

Nomenclature for permeable paving systems varies among designers, installers and geographic regions. For this manual, permeable pavement is used to describe the general category of pavements that are designed to allow infiltration through the pavement section. The following terms are used throughout this manual and represent the major categories of permeable pavements that carry vehicular, as well as pedestrian traffic: pervious concrete, porous asphalt, permeable interlocking concrete pavements, and concrete and plastic grid pavements.

6.3.1 Applications

Typical applications for permeable paving include industrial and commercial parking lots, sidewalks, pedestrian and bike trails, driveways, residential access and collector roads, and emergency and facility maintenance roads. Grid pavers are not intended for streets but are often used for emergency access lanes and intermittently used (overflow) parking areas. All other types of permeable paving can withstand loads from the number of trucks associated with residential collector roads. Specialized engineering expertise is required for designs for heavy loads.

Thoroughfares, highways and other roads that combine high vehicle loads and high speed traffic are generally not considered appropriate for permeable pavements. However, porous asphalt has proven structurally sound and remained permeable in a few arterial and highway

applications (Hossain et al, 1992) and pervious concrete and permeable interlocking concrete paverment have been successfully used in industrial settings with low speeds and high vehicle loads.

The only porous surface designed and commonly applied for high-speed use is an asphalt open-graded friction course or OGFC. This is applied as a thin overlay on impervious asphalt pavement to reduce road noise and hydroplaning. OGFC has some shown some benefits in reducing highway pollutants. However, it will not be covered in this document since this surface has a limited ability to detain and treat stormwater as well as having a short design life.

<Figure 6-3-2: Sultan subdivision >

<Figure 6-3-3: Commercial pavers>

Table ???. Typical permeable pavement applications

Application	Residential walk/patio	Residential driveway	Commercial pedestrian plaza	Emergency access lane or overflow parking lot	Parking lot or travel lanes	Residential street or collector	High speed highway (>35mph)
Porous Asphalt	Yes	Yes	Yes	Yes	Yes	Yes	Limited to-date
Pervious Concrete	Yes	Yes	Yes	Yes	Yes	Yes	No
PICP	Yes	Yes	Yes	Yes	Yes	Yes	No
Grid Pavements	Yes	Yes	Yes	Yes	No	No	No

Permeable paving systems have been designed with aggregate storage to function as infiltration facilities with low subgrade infiltration rates (as low as 0.008 cm/hour or 0.003 inch/hour) in the Puget Sound region. When water is not introduced from adjacent areas, these systems have a lower ratio of contribution to infiltration area (i.e.1 to 1) than conventional infiltration pond facilities and are less likely to have excessive hydraulic loading. Using the 0.003 inch/hour soil infiltration rate as an example, a 24 hour storm and a 48 hour drain time (typical outflow design) yields over 0.2 in. of infiltrated water. This suggests that even on poorly draining soils, permeable pavements have a role in reducing runoff volumes and pollutants.

<sidebar: 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 ???: Performance for additional information).>

Permeable pavement should not be used or require additional engineering analysis and design considerations where:

- Excessive sediment is deposited on the surface (e.g. construction and landscaping material yards).
- Steep erosion prone areas are upslope of the permeable surface and will likely deliver sediment and clog pavement on a regular basis and where maintenance is not conducted regularly.
- Concentrated pollutant spills are possible such as gas stations, truck stops and industrial chemical storage sites and where infiltration will result in transport of pollutants to deeper soil or groundwater.
- Seasonally high groundwater can create prolonged saturated conditions at the ground surface and within 6 inches (15 cm) from the bottom of the pavement.
- Fill soils, when saturated, cannot be adequately stabilized.
- Sites receive regular, heavy applications of sand (such as weekly) for maintaining traction during winter.
- Steeps slopes where water within the aggregate base layer or at the subgrade surface cannot be controlled by detention structures (e.g. check dams) and may cause erosion and structural failure, or where surface runoff velocities may preclude adequate infiltration at the pavement surface. Note that permeable pavement has been used successfully on slopes up to 10 percent with subsurface detention structures (personal communication Chris Webb, 2005) and at 8 percent slopes without subsurface detention (personal communication Robin Kirschbaum, 2011).

Slope restrictions result primarily from flow control concerns and to a lesser degree structural limitations of the permeable paving. Gradient increases surface and subsurface flow velocities and reduces infiltration capability and storage capacity of the pavement system. Detention structures placed on the subgrade and below the pavement can be used to detain subsurface flow and increase infiltration and maximum slope recommendation (see section

??? for detention structure details). In general, detention structures should be considered for permeable pavement on slopes ≥ 3%. See Chapter ??? for the flow control reduction associated with permeable paving and subgrade detention structures. All permeable pavement surfaces should have a minimum slope of 0.5 to 1 percent to allow for surface overflow in extreme rainfall. General recommendations for maximum permeable pavement slopes include:

- Porous asphalt: 5 percent.
- Pervious concrete: Maximum slope will be determined by physical setting, vehicle load and cost of subsurface detention structures.
- Permeable interlocking concrete pavement: 12 percent (Smith, 2011).
- Concrete and plastic grid systems: maximum slope recommendations vary by manufacturer and generally range from 6-12 percent (primarily a traction rather than infiltration or structural limitation). Contact the manufacturer or local supplier for specific product recommendations.

Permeable pavements covered in this manual

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 porous hot or warm-mix asphalt, pervious Portland cement concrete, permeable interlocking concrete paverment, and a plastic grid system.

Examples of permeable pavement systems

Permeable paving materials and applications designed for infiltrating stormwater have evolved over the past four decades in the U.S. and are now used in a wide variety of applications. The following provide examples of recent and older applications.

<Figure 6-3-4: Porous asphalt test section, highway 87 south of Phoenix, AZ.>

<Figure 6-3-5: Pervious concrete installation, material handling yard Olympia, WA.>

<Figure 6-3-6: Permeable interlocking concrete pavers, <contact Mutual for image>

<Figure 6-3-7: Plastic grid system (Gravelpave) Point Defiance Zoo Tacoma, WA.>

<Figure 6-3-8: Concrete grid system <contact Mutual for image>

6.3.2 Design and Construction

Mix design, handling and installation procedures for permeable paving systems are different from conventional pavement. For the successful application of any permeable paving system four basic guidelines must be followed:

Pull quote: For successful application of any permeable paving system four general guidelines must be followed:

- Conduct adequate site analysis and appropriate site application.
- Follow correct design specifications.
- Use qualified contractors or preferably certified contractors where certification program exists.
- Control erosion and sediment (during construction and throughout service life).

1. Adequate site analysis and appropriate site application

As with all LID IMPs, adequate site analysis and the selection of the proper practice and materials within the context of the physical setting and development needs are critical. Important considerations include: vehicle use; soil type and permeability; groundwater; topography and the potential for sediment inputs to the permeable pavement; surrounding vegetation; and maintenance needs.

2. Correct design specifications

There are many design needs common to most permeable pavements and some unique aspects to each system. Industry associations can assist with design and specification guidance. Common and system-specific design needs are provided in detail later in this manual. In brief, they include, proper site preparation, correct aggregate base, pavement surface mix design, geotextile separation layer (if included), and underdrain design (if included). All are essential for adequate infiltration, storage and release of storm flows, as well as structural integrity. Construction specifications should include contractors on the job site holding certificates from industry programs on installing their systems. The pervious concrete and permeable interlocking concrete pavement industry associations offer such education

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programs for contractors. Specifications should also include contractor experience with projects of similar size and scope.

3. Qualified manufacturers, installation contractors and suppliers

Material manufacturers must have experience with producing proper mix designs for pervious concrete or porous asphalt and make materials that comply to national standards. Permeable interlocking concrete pavement and other factory produced materials should conform to national product standards. Installation contractors must be adequately trained , have substantial and successful experience with the pavement product and adhere to material specifications for proprietary systems. Installation contractors should provide information showing successful application of permeable pavements for past projects and recommended certification, if available, for the specific type of permeable pavement. Suppliers must have experience with producing proper mix designs for pervious Portland cement concrete or porous hot-mix asphalt. Substituting inappropriate materials or installation techniques will likely result in structural or hydrologic performance problems or failures.

4. Sediment and erosion control (during construction and long-term)

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 subgrade, base material and permeable surface. Muddy construction equipment should not be allowed on the base material or pavement, sediment laden runoff should be directed to treatment areas (e.g. settling ponds and swales), and exposed soil should be mulched, planted and otherwise stabilized as soon as possible. Construction sequencing for proper installation and minimizing erosion and sediment inputs is critical for project success. Long-term operation and maintenance plans that consider the physical setting, timing and equipment needs should be developed during the design phase.

The above guidelines are mandatory for the installation of permeable paving systems. Poor quality installations are most often attributed to not following the above four guidelines and structural or flow management problems or failures are likely without qualified contractors and correct application of specifications.

6.3.2.1 Common components, design and construction criteria for permeable pavement

The following provides the purpose and guidelines for the common components of permeable

paving systems. Design details for specific permeable paving system components are included in Section <???>: Types of Permeable Paving.

Contributing area

Minimizing the amount of run-on from adjacent surfaces is preferred in order to maximize the long-term performance of the pavement system. Introducing stormwater discharge from other impervious surfaces may be acceptable with the careful consideration of the following minimum conditions: 1) sediment is not introduced to the pavement surface or subgrade; and 2) the additional flows do not exceed the long-term infiltration capability of the pavement surface or subgrade.

Subgrade

Careful attention to subgrade preparation during construction is required to balance the needs for structural support while maintaining infiltration capacity. For all permeable pavements, relative uniformity of subgrade conditions is necessary to prevent differential settling or other stress across the system.

In general, the requirement for subgrade strength beneath rigid pavement (pervious concrete) is less than for flexible pavements. The structural performance of flexible permeable pavement systems rely on the proper design and construction of the aggregate base to provide structural support on subgrades with less compaction and increased soil moisture.

On sites where the topsoil is removed and native sub-soil is exposed, no compaction may be needed for adequate structural support while the protection of the subgrade from compaction is necessary to retain infiltration capacity. For applications with heavy truck traffic, some soil subgrade compaction may be necessary for structural support. The effect of compaction on subgrade permeability will vary significantly depending on soil type. For example, the permeability of a coarser textured sand may be effected minimally while the permeability of finer textured soils will likely be significantly degraded for a given compaction effort. The effects of compaction on soil permeability can be assessed by conducting laboratory Proctor density tests on subgrade soils from a proposed permeable pavement site. The soils in test areas can be compacted to various density levels through field measurements and the resulting permeability measured using ASTM test methods. See section ???: Determining subgrade infiltration rates for more detail on test procedures.

Two predominant guidelines are currently used for subgrade compaction of permeable pavement systems: firm and unyielding (qualitative) and 90-92% proctor (quantitative). Consult with the permitting jurisdiction and qualified engineer for applicable guidelines. To properly prepare and maintain infiltration capacity and structural support on permeable pavement subgrades, use the following procedures:

- Soil conditions should be analyzed by a qualified engineer for infiltration capability at anticipated compaction and load bearing capacity given anticipated soil moisture conditions.
- During and after grading, the existing subgrade should not be compacted more than recommended compaction effort by excessive construction equipment traffic or material stockpiling. The following guidelines should be used to prevent excessive compaction and maintain infiltration capacity of the subgrade:
    - Final grading should be completed by machinery operating on a preliminary subgrade that is at least 12 inches (30 cm) higher than final grade or structures to distribute equipment load (e.g. steel plates or aggregate base material). Final excavation then proceeds as machinery is pulling back and traveling on preliminary grade as final grade is excavated.
    - To prevent compaction when installing the aggregate base, the following steps (back-dumping) should be followed: 1) the aggregate base is dumped onto the subgrade from the edge of the installation and aggregate is then pushed out onto the subgrade; 2) trucks then dump subsequent loads from on top of the aggregate base as the installation progresses.
    - Avoid subgrade preparation during wet periods (soil compaction increases significantly if soil is wet).
    - If machinery must access the final grade limit the access to a specific travel way that can be tilled before application of the base aggregate or place heavy steel plates on subgrade and limit traffic to the protective cover.
    - NOTE: allowing heavy machinery on permeable paving subgrades during wet or saturated conditions will result in deep compaction (often 3 feet or 1 meter) and cannot be compensated for by shallow tilling or ripping soil (Balousek (2003).
- If using the pavement system for retention in parking areas, excavate the subgrade level to allow even distribution of water through the aggregate base and maximize infiltration across entire parking area (Cahill, 2005).

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- Immediately before base aggregate and pavement placement, remove any accumulation of fine material (if present) from erosion with light equipment and scarify soil to a minimum depth of 6 inches to prevent sealing of the subgrade surface.

Sub-surface detention structures

As permeable pavement subgrade slopes increase storage and infiltration capacity decrease, and flow velocities increase. To increase infiltration, improve flow attenuation and reduce structural problems associated with subgrade erosion on slopes use the following detention structures placed on the subgrade and below the pavement surface:

- Periodic impermeable check dams with an overflow drain invert placed at the maximum ponding depth. The distance between berms will vary depending on slope, flow control goals and cost.
- Gravel trenches with overflow drain invert placed at the maximum ponding depth. The distance between trenches will vary depending on slope, flow control goals and cost.
- Excavate the subgrade with level steps. The step length will vary depending on slope, flow control goals and cost. Excavating level steps is most applicable for parking lot s where the pavement surface is also stepped. While the subgrade is excavated level, the pavement surface should maintain a minimal slope of 2%.

<Figure 6-3-9: subgrade berm and trench section.>

Storage reservoir/aggregate base

The open-graded aggregate base provides: 1) a stable base that distributes vehicular loads from the pavement to the subgrade; 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 into the underlying soil or collection in under-drains for conveyance (Washington State Department of Transportation [WSDOT], 2003).

Aggregate base material is often composed of larger aggregate (1.5-2.5 inches). Smaller stone (leveling or choker course) may be used between the larger stone and the pavement depending on pavement type, working surface required to place the pavement and base aggregate size. Typical void space in base layers range from 20%-40% (WSDOT, 2003 and Cahill, Adams and Marm, 2003). Depending on the target flow control standard, groundwater and underlying soil type, retention or detention requirements can be partially or entirely met in

the aggregate base. Aggregate base depths of 6-36 inches (15-90 cm) are common depending on pavement type, structural design and storage needs.

Flexible pavements (e.g. porous asphalt and permeable pavers) require properly designed aggregate base material for structural stability. Rigid pavements (pervious concrete) do not require an aggregate base for structural stability; however, a minimum depth of 6 inches is recommended for stormwater storage and providing a uniform surface for applying pervious concrete.

Increasing aggregate base depth for stormwater storage provides the additional benefit of increasing the strength of the overall pavement section by isolating underlying soil movement and imperfections that may otherwise be transmitted to the wearing course (Cahill et al., 2003). For more information on aggregate base material and structural support see section ???: Infiltration and subgrade structural support and section ???: Types of permeable pavement for aggregate base recommendations by specific pavement type.

Geotextile and geogrids (optional)

Geotextiles between the subgrade and aggregate base are not required or necessary for many soil types. However, for all permeable pavements, geotextile is recommended on the side slopes of the open graded base perimeter next to the soil subgrade if concrete curbs or impermeable liners are not provided that extend the full depth of the base/subbase. AASHTO M-288 (AASHTO 2010) provides guidance for selection of geotextiles specifically for separation and drainage applications.

Geotextiles and geogrids are generally recommended:

- As a filter layer to prevent clogging of infiltration surfaces.
- For soil types with poor structural stability to prevent downward movement of the aggregate base into the subgrade (geotextiles or geogrids).

Clogging of the subgrade soil under permeable pavement systems could occur by fines from surface stormwater flow moving downward through the pavement section or from fines associated with the base aggregate washing off the rock and moving downward to the subgrade surface. Clogging of the base aggregate by the upward migration of fines into the aggregate has also been proposed. Probability of clogging from surface flow should be

extremely small given current research that shows accumulation of fines ptedominantly in the upper few centimeters of permeable pavement sections. Movement of fines from the aggregate base rock is likely if the aggregate base specification for the pavement system allows for excessive fines. The third process (upward movement of fines into the base aggregate) requires capillary tension for water (and sediment) to move upward into the base material. Base aggregate for permeable paving systems are open graded (20%-40% voids are common) which minimizes the capillary tension necessary for upward movement of materials.

Currently, the rate and subsequent risk of soil subgrade clogging from fines is not well understood. While permeable pavement surfaces trap sediment prior to entering the base and soil subgrade, there is no research or forensic exploration of existing permeable pavement projects demonstrating the extent of fines accumulating on soil subgrades.

For applications on fine grained weak soil types, geotextile or geogrid may be necessary to minimize downward movement of base aggregate. Geotextiles provide tensile strength as the subgrade attempts to deform under load and the fabric is placed in tension thereby improving load bearing of the pavement section (Fergusen, 2005).

If geotextile is used between the subgrade and base aggregate:

- Use geotextile recommended by the manufacturer's specifications and recommendations of the geotechnical engineer for the given subgrade soil type and base aggregate.
- Extend the fabric up the sides of the excavation in all cases. This is especially important if the base is adjacent to conventional paving surfaces. The fabric can help prevent migration of fines from dense-graded base material and soil subgrade to the open graded base. Geotextile is not required on the sides if concrete curbs extend the full depth of the base/subbase.
- Overlap adjacent strips of fabric at least 24 inches. Leave enough fabric to completely wrap over small installations (e.g. sidewalks) or the edge of larger installation adequately to prevent sediment inputs from adjacent disturbed areas. Secure fabric outside of storage bed.
- Following placement of base aggregate and again after placement of the pavement, the filter fabric (if used) should be folded over placements and secured to protect installation

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from sediment inputs. Excess filter fabric should not be trimmed until site is fully stabilized (U.S. Army Corps of Engineers, 2003).

<Figure 6-3-10: Highpoint sidewalk wrapped with geotextile>

Under-Drains (optional)

One or more under-drain may be installed at the bottom of a permeable pavement system if the infiltration capacity of the subgrade soil is not adequate to: protect the pavement wearing course from prolonged saturation that reduce infiltration capability; protect specific subgrade soil types from excessive periods of saturation that may lead to structural weakness; and protect the pavement and subgrade from freeze-thaw cycles. Under-drains without and orifice or control structure will reduce infiltration to the subgrade and flow reduction that modeling will predict. See Chapter ??? for properly representing under-drains in WWHM or MGSFlood.

Under-drains should include an orifice. With an orifice, the permeable pavement installation will operate as an underground detention system. Recommendations for permeable pavement under-drains include:

- Under-drain flows should be conveyed to an approved discharge point.
- At a minimum, slotted or perforated, thick-walled plastic pipe with a minimum diameter of 4 inches should be used.
- An appropriate cover depth and pipe material should be used considering vehicle loads.
- To prevent clogging, the minimum orifice diameter should be 0.25 inches and maintenance activities should include regular inspection. Review local jurisdiction requirements for local minimum orifice diameter for below ground structures.

Elevated drains (optional overflow)

An overflow or elevated drain may be installed in the aggregate base of a permeable pavement system if the infiltration capacity of the subgrade soil is not adequate to protect the pavement wearing course from saturation. An elevated drain can also be used to create retention beneath the elevated drain invert if the subgrade analysis determines that the subgrade can provide adequate structural support given the duration of saturated conditions. Facility overflow can be provided by subsurface slotted drain pipe(s) or by lateral flow through the storage reservoir to a surface or subsurface conveyance. Flows must be routed to an approved discharge point.

<Figure 6-3-11: elevated drain pipes and subsurface agg conveyance from Ferguson pg 40>

Recommendations for elevated drain design include the following:

- The maximum elevation of the overflow invert from the subgrade should drain water in the base aggregate before reaching the bottom of the permeable pavement wearing course and prevent saturation of the pavement.
- If site constraints necessitate an overflow pipe in an area subject to traffic or other loading, cover depth and pipe material should be designed to accommodate those loads.
- The pipe diameter and spacing for slotted overflow pipes will depend on the hydraulic capacity required. For a sloped subgrade, at least one overflow pipe should be installed at the downslope end of facility.
- Observation and cleanout ports should be used to determine whether the overflow is dewatering properly and allows access for back flushing.
- Overflows shall be designed to convey excess flow to approved discharge point.

Flow entrance

When designed to take runoff from other catchment areas, permeable pavement areas must be protected from sedimentation which can cause clogging and diminished facility performance. Acceptable flow entrance methods include sheet flow to the permeable pavement surface or subsurface delivery to the storage reservoir via pipes (e.g., for roof drainage). Accepted pre-treatment for sediment removal (e.g. filter strip for surface flow and catch-basin for subsurface delivery) should be included for any runoff to permeable pavement systems.

Backup infiltration

Backup infiltration can be designed into any permeable pavement system. Typical backup systems include: aggregate areas along roads; parking lot medians and perimeters; and surface drains that are connected to the aggregate reservoir/base layer under the permeable pavement. The permeable pavement surface is then sloped gradually to the overflow or backup infiltration area (1-2% maximum slope recommended).

<Figure 6-3-12: Cahill section or picture of aggregate median>

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Wearing course or surface layer

The wearing course provides support (in conjunction with the aggregate base) for the designed traffic loads while maintaining adequate porosity for storm flow infiltration. 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 ???: 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 Performance section for research on infiltration rates over time). Permeable paving systems allow infiltration of storm flows; however, to prevent freeze-thaw damage and retain infiltration capability, the wearing course should not become saturated from excessive water volume stored in the aggregate base layer.

Water quality treatment

Currently, no water quality treatment credit through Ecology is associated with stormwater passing through a standard permeable pavement wearing course or the aggregate base. However, <basic or enhanced> treatment can be attained using one of the following design approaches:

- Infiltrate 91% of the annual stormwater runoff file into subgrade soils that have a **cation exchange capacity** of ≥ 5 milliequivalents/100 grams dry soil, minimum organic matter content of 5% and infiltrate at a rate between 2 to 12 inches per hour (short-term or measured rate).
- Design a treatment layer into the aggregate base that has the characteristics described above for subgrade soils.

Freeze-thaw considerations

Properly designed permeable paving installations have performed well in the Midwest and Northeast U.S. where freeze-thaw cycles are severe (Adams 2003 and Wei 1986). Research demonstrated the ability of bases under pervious concrete (Kevern 2009), porous asphalt (Backstrom 2000) and permeable interlocking concrete pavement (Attarian 2010) do not heave during the winter and do not require thickening the aggregate base.

Infiltration and subgrade structural support

Water, and particularly prolonged saturated conditions, can weaken most subgrade soils (Ferguson, 2005). For flexible permeable pavements, reduced compaction of the subgrade

and the introduction of water to the subgrade can be compensated for by proper structural and hydrologic design given the subgrade soil type and, importantly, by selecting proper aggregate base materials and increasing the aggregate base depth. A properly designed aggregate base distributes vehicle load and subgrade bearing area (see Figure ???). The primary method for strengthening rigid pervious concrete is to increase the thickness of the pavement.

<Figure 6-3-13: load distribution section pg 83 Ferguson>

Increasing the aggregate base depth in permeable pavement systems provides the added benefit of increasing stormwater storage capacity which can be particularly beneficial on subgrades with low permeability. Additionally, open graded stone may remain more stable in saturated conditions than densely graded road bases because the clean stone has less aggregate fines and, as a result, reduced pore pressures during saturated conditions (Smith, 2011). However, the same author also references several sources that indicate reduced structural capacity of open-graded bases compared to dense-graded bases under stresses from vehicular loads. Industry association literature should be referenced for base thicknesses for structural support.

The U.S. Departments of Air Force and Army manual (1992) examines the relationship among subgrade **California Bearing Ratio** (CBR), traffic load and required pavement thickness for flexible pavements in non-freezing conditions. For residential streets a total pavement thickness of 14 inches (35.5 cm) is required at CBR 5% (total pavement thickness includes base aggregate and pavement). A CBR of 5% represents a very poor structural subgrade, typically organic silts and organic silty clays and inorganic silts, micaceous or diatomaceous fine sands or silts, inorganic silts and elastic silts (Unified Soil Classification OL, MH). At a CBR of 10% a total pavement thickness of just over 8 inches (20 cm) is required. A Unified Soil Classification CL (also poor structural subgrades) is typical for a CBR of 10% (Fergusen, 2005). For all conditions, the pavement structure should be designed and documented for vehicular load and soil conditions.

<Figure 6-3-14: subgrade CBR and pavement thickness, Ferguson pg 85>

Determining subgrade infiltration rates

A preliminary site assessment is necessary for designing LID projects with permeable

pavement and other distributed stormwater management practices integrated into the project layout. Preliminary site assessment includes surface and subsurface feature characterizations to determine infiltration capability of the site, initial design infiltration rates and potential locations for permeable pavement. For more information on initial site assessment see Chapter 2: Site Assessment and section 2.1: Soil and subsurface characterization.

Determining the infiltration rate of the underlying soil profile is necessary to design the aggregate base depth for stormwater storage and drain system (optional), as well as equate flow reduction benefits when using the Western Washington Hydrologic Model or MGS Flood. For details on flow modeling guidance see Chapter ???. See Figure ??? for a graphic representation of the process to determine infiltration rates.

The following outline the types of required infiltration tests and test methodologies organized by the scale of permeable pavement installation for soil profiles below the aggregate base material.

<u>Small permeable paving installations</u> (patios, walkways and driveways) on private property that include storage volume using base material below the grade of the surrounding land are modeled as gravel infiltration trenches. Infiltration tests for small permeable pavement installations are:

- Required where water quality treatment or flow control thresholds are triggered; and
- Recommended for installations below these thresholds.
- Infiltration tests required or recommended for small permeable pavement installations are listed below under large installations and should be performed at the final subgrade elevation.

<u>Large permeable paving installations</u> (sidewalks, alleys, parking lots, roads) that include storage volume using base material below the grade of the surrounding land are modeled as a gravel infiltration trench. Infiltration tests (performed at the final subgrade elevation) are required for large permeable pavement installations.

The methods below are used to determine the short-term (initial) saturated hydraulic conductivity rate for subgrade soil profile (existing) soils under permeable pavement

installations. The initial or measured saturated hydraulic conductivity with no correction factor may be used as the design infiltration rate if the qualified professional engineer deems the infiltration testing described below (and perhaps additional tests) are: 1) conducted in locations and at adequate frequency capable of producing a soil profile characterization that fully represents the infiltration capability where the permeable pavement is located; and that 2) the aggregate base material is clean washed material with < 1% fines passing the 200 sieve.

If deemed necessary by a qualified professional engineer, a correction factor may be applied to the measured saturated hydraulic conductivity to determine the long-term (design) infiltration rate. Whether or not a correction factor is used and the specific number used will depend on heterogeneity of the site soils, the number of infiltration tests in relation to the size of the installation and the percent fines passing the 200 sieve of the aggregate base material (see section ??? for more details on correction factors). The overlying pavement provides excellent protection for the underlying native soil from sedimentation; accordingly, the underlying subgrade soil profile does not require a correction factor for sediment input from sources above the pavement.

The initial Ksat can be determined using:

A. In-situ small-scale pilot infiltration test (small-scale PIT);
B. in-situ large-scale PIT; or
C. A correlation to grain size distribution from soil samples if the site has soils that are not consolidated by glacial advance. Method C uses the ASTM soil size distribution test procedure (ASTM D422), which considers the full range of soil particle sizes, to develop soil size distribution curves.

See Section 2.1 Soil and subsurface characterization for test procedure details.

On commercial property parking lots and driveways the small-scale PITs should be performed for every 2,500 ft2 of permeable pavement, but not less than 1 test per site. On residential developments small-scale PITs should be performed every 150 feet of roadway; and at every proposed lot if the driveways are permeable pavement. Tests at more than one site could reveal the advantages of one location over another. However, if the site subsurface characterization, including soil borings across the development site, has consistent characteristics and depths to seasonal high groundwater conditions, the number of test

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locations may be reduced.

Correction factors for subgrade soils underlying permeable pavement installations

The correction factor for in-situ, small-scale pilot infiltration test is determined by the number of tests in relation to the size of the permeable pavement installation, site variability and the quality of the aggregate base material. Correction factors range from 0.33 to 1 (no correction).

Tests should be located and be at adequate frequency capable of producing a soil profile characterization that fully represents the infiltration capability where the permeable pavement is located. If used, the correction factor depends on the level of uncertainty that variable subsurface conditions justify. If enough pilot infiltration tests are conducted across the permeable pavement subgrade to provide an accurate characterization or the range of uncertainty is low (for example, conditions are known to be uniform through previous exploration and site geological factors) then no correction factor for site variability may be justified. Additionally, no correction factor may be necessary if the aggregate base is clean washed material with , 1% fines passing the 200 sieve. See Table ???: Correction factors for in-situ Ksat measurements to estimate long-term (design) infiltration rates.

Table ???: Correction factors for in-situ Ksat measurements to estimate long-term (design) infiltration rates

Site Analysis Issue	Correction Factor
Site variability and number of locations tested	CFy = 0.33 to 1
Quality of pavement base material aggregate	CFin = 0.9 to 1

Total correction factor (CFt) = CFy x CFin

If the level of uncertainty is high, a correction factor near the low end of the range may be appropriate. Two example scenarios where low correction factors may apply include:

- Site conditions are highly variable due to a deposit of ancient landslide debris, or buried stream channels. In these cases, even with many explorations and several pilot infiltration tests, the level of uncertainty may still be high.

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- Conditions are variability, but few explorations and only one pilot infiltration test is conducted. That is, the number of explorations and tests conducted do not match the degree of site variability anticipated.

Verifying subgrade infiltration rates

Pilot Infiltration Tests are appropriate methods for estimating field infiltration rates. Infiltration tests should be conducted at the subgrade surface and followed by excavation into soil profile below the subgrade surface where stormwater will infiltrate. Initial infiltration tests, excavated to the subgrade from existing grade, provide necessary information for permeable paving design.

Infiltration tests may also be necessary once the subgrade preparation is complete to verify that infiltration rates used for design have not been significantly reduced from compaction. PITs, and associated excavation beneath the PIT elevation, are not recommended at this stage in order to maintain the structural integrity of the subgrade. Rather, large-scale ring infiltrometer tests are recommended for accuracy and minimal subgrade disturbance (see Figure <???> WSU pervious concrete infiltration tests). The large ring infiltration test uses a concrete, metal or plastic ring (minimum diameter of 3 foot) that is placed on the subgrade surface and pressed into the ground with soil backfill packed around the outside of the ring. This test follows the same procedures for timing and measuring water depth as the small-scale PIT; however, there is no excavation below the subgrade surface at the completion of the test.

<Figure 6-3-15: Large ring infiltrometer test from AESI>

<Figure 6-3-16: from LID manual, determining infiltration rates>

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.

<sidebar: See Chapter ??? for flow modeling guidelines and permeable paving systems when using the WWHM>

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Accessibility

The permeable paving systems examined in this section can be designed to meet ADA requirements. Local, state and federal ADA requirements can vary and designers should check with the permitting jurisdiction for ADA related requirements.

The federal ADA design guidelines state that surfaces on accessible paths and travel routes should meet the following critieria:

- Firm, stable and slip resistant.
- Maximum openings that do not allow insertion of a ½ inch (13 mm) sphere.

For Washington State, 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. Porous asphalt and pervious concrete, while rougher than conventional paving, do not have abrupt changes in level when properly installed. Concrete pavers have small openings or joints and when properly installed and most concrete paver surfaces create smooth surfaces that meet ADA design guidelines. Consult with the paver supplier to confirm that their product meets ADA requirements. Plastic and concrete grid systems use a specific aggregate with a reinforcing grid that creates a firm and relatively smooth surface (see Design sections below).

Two qualifications for use of permeable paving and designing for ADA 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 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 ADA parking spaces and walkways may need to include pavers with smaller permeable joints or solid pavers. Individual project designs should be assessed by site characteristics and regulatory requirements of the jurisdiction.

6.3.2.2 Types of permeable paving

The following section provides design guidelines for porous asphalt, pervious concrete, a

permeable interlocking concrete pavement, and a plastic grid system. Each product has specific design requirements and each site has unique characteristics and development requirements. Accordingly, qualified engineers and allied design disciplines, as well as association and manufacturer specifications should be consulted for developing specific permeable paving systems.

1. Porous hot or warm-mix asphalt

Porous hot or warm-mix asphalt is similar to standard hot or warm-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 is commonly 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), auto storage at ports and highways (Hossain, Scofield and Meier, 1992). Properly installed and maintained porous asphalt should have a structural service life that is comparable or longer than conventional asphalt (personal communication Tom Cahill, 2003).

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

Early applications of porous asphalt were subject to fairly rapid decline of infiltration rates and surface **raveling**. The primary cause of these problems was inadequate binder strength and associated **drain-down** of the binder from higher to lower elevation in the pavement. As a result, the binder coating and cohesion between the surface aggregate is reduced and the aggregate dislodges from vehicle wear. The additional binder moving downward in the pavement then collects just below the asphalt surface as it thickens from entrained particles lodged in the pores and as temperatures decline from the surface. The additional binder forms a layer that clogs the porous asphalt pores and reduces infiltration. According to Kandhal at the Auburn University National Center for Asphalt Technology, “new mixes using polymer modifiers, high asphalt content, fibers and open aggregate gradations have solved problems of rapid raveling and loss of permeability” (Kandhal, 2002).

In addition to the guidelines specific to porous asphalt, see section <???> for guidelines on common permeable pavement components and Chapter ??? for flow modeling guidance.

<Figure 6-3-17: porous asphalt section>

Design and construction

Several porous asphalt mixes and design specifications have been developed for open graded friction courses (porous asphalt layer over conventional asphalt) and as wearing courses that are composed entirely of a porous asphalt mix. The open graded friction courses (OGFC) are designed primarily to reduce noise, 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 porous 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.

Applications include but are not limited to: parking lots, residential access and collector roads, light arterial roads, pedestrian and bike paths, and utility access.

Soil infiltration rate

- See Appendix 1 section 8 of the Municipal Stormwater Permit for minimum infiltration rates. Soils with lower infiltration rates may require under-drains or elevated drains to prevent prolonged saturated conditions within 6 inches (15 cm) of the bottom of the pavement (wearing course) section.
- Surface flows directed from adjacent areas to the pavement surface or subgrade can introduce excess sediment, increase clogging, result in excessive hydrologic loading, and should only be considered with particular attention to sediment control and infiltration capacity of the subgrade.

Subgrade

- See section ??? Common components and design criteria for permeable pavement systems for guidelines and construction techniques to reduce compaction.

Under-drain

- An under-drain or elevated drain can be used for installations with seasonally high groundwater or subgrade infiltration rates that create prolonged saturated conditions within 6 inches (15 cm) from the bottom of the pavement . An orifice can be used to improve detention. See section ??? for under-drain design details.
- On extremely poor soils with low strength and very low infiltration rates use an impermeable liner with under-drains.
- Installations should have an observation well (typically 6-inch or 15 cm perforated pipe) extended to the subgrade surface and installed at the furthest downslope area.

Aggregate base/storage bed material

- Minimum base depth for structural support should be 6 inches (15 cm) for pedestrian use and 12 inches (30 cm) for vehicular loading (Porous Asphalt Summit, 2009).
- 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 12-24 inches are common depending on storage needs.
- Aggregate: several aggregate gradations can be used for a porous asphalt base. For a successful installation the aggregate should: 1) have adequate voids for water storage (20-40% voids is typical); 2) be clean and have minimal fines (0-2% passing the 200 sieve maximum); and 3) be angular and have adequate fractured face to lock together and provide structural support (70% minimum and 90% preferred for fractured face). Two example aggregate guidelines are provided below:
  1. WSDOT Permeable Ballast (9-03.9(2) 3/4 to 2.5 inches) with a 1-2 inch deep choker course consisting of the same aggregate gradation that is use for the pavement or wearing course (see below).
  2. 3/4 to 1 1/2 –inch, clean coarse, crushed rock aggregate with 0-2% passing the 200 sieve. This gradation provides a uniform working surface and does not require a chocker course.

Aggregate base/storage bed installation

- Stabilize area and install erosion control to prevent runoff and sediment from entering storage bed.
- Geotextile fabric: optional.
  - See section ??? Common components and design criteria for permeable pavement systems for geotextile).

- Install base aggregate in maximum of 8-inch lifts and lightly compact each lift. Compact complete aggregate base with a minimum 10-ton vibratory roller. Use a 13,500 lbf plate compactor with a compaction indicator in places that can't be reached by roller compactor. Make two passes with the roller in vibratory mode and two passes in static mode until there is no visible movement of the aggregate. Moist aggregate will compact more thoroughly than dry aggregate. Do not crush the aggregate during compaction. Compacted aggregate subbase and base should not rut under aggregate delivery trucks or other construction equipment.
- Use back dumping method described in section ??? Common components and design criteria for permeable pavement systems.
- If used, install choker course evenly over surface of course aggregate base and compact.
- Behind asphalt delivery trucks and in front of asphalt installation, rake out ruts caused by delivery trucks to provide a uniform surface and pavement depth.

Pavement or wearing course materials

An example aggregate gradation and bituminous asphalt cement guideline that has been successfully used in the Puget Sound region are provided below. Material availability may vary regionally and mix design may vary for those materials. Note: Do not use OGFC specs, stability of OGFCs rely on their asphalt bases.

Thickness:

- o Porous asphalt has a slightly lower structural contribution than conventional asphalt. Follow NAPA literature on the structural contribution and recommended asphalt pavement thicknesses.
- o Parking lots: 2-4 inches typical.
- o Residential access roads and arterials: 4-6 inches typical.

- Aggregate gradation

U.S. Standard Sieve	Percent Passing
¾"	100
½"	90-100
3/8"	70-90
4	20-40
8	10-20
40	7-13
200	0-3

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- 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.

- Bituminous asphalt cement:
  - Content: 6.0-6.5% by weight of total (dry aggregate) mix. **Performance Grade (PG): 70-22**. Do not use an asphalt cement performance grade less than 70-22 for open graded, porous asphalt mixes.
  - **Drain-down**: 0.3 percent maximum according to ASTM D6390-05.
  - An **elastomeric polymer** can be added to the **bituminous asphalt cement** to reduce drain-down (note: PG 70-22 and stiffer PG grades usually contain and elastomeric polymer).
  - Fibers can be added and may prevent drain-down.
  - **Anti-stripping agent**: as water moves through the porous asphalt pavement, the asphalt emulsion contact with water increases compared to conventional impervious asphalt. Ant-stripping agent reduces the erosion of asphalt binder from the mineral aggregate and is, therefore, recommended for porous asphalt. A qualified products list of anti-stripping additives is available from Washington Department of Transportation under Standard Specification: 9-02.4. Use an approved test for anti-strip such as AASHTO T 283-07 Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage or the Hamburg test.

Total void space should be approximately 16 to 25 percent per ASTM D3203 (conventional asphalt is 2-3%) (NAPA, ???).

<Figure 6-3-18: WSU porous asphalt installation>

Pavement or wearing course installation

The porous asphalt pavement installations use the same equipment and similar procedures as conventional asphalt with three notable differences:

- <need temp range> At the Porous Asphalt Summit we decided on 260-280F for mixing and 240-260 F for lay down. John Grisham w/Miles Resource (formerly Woodworth and Company) suggested (uses) 307-318 F for mixing and 286-295 F for compaction (lay down), and a minimum air temperature of 45 F and rising. Add warm mix.

- The stiffer performance grade for the bituminous asphalt cement adheres more to delivery trucks and installation machinery; accordingly, additional time is required to clean equipment.
- Permeable pavement aggregate base and choker courses are relatively uniform gradations and low in fine material. As a result, equipment operating on the aggregate base will cause more rutting than on more densely graded base material for conventional pavement and will require more hand labor to smooth ruts and prevent areas where the pavement is either too thin or too thick.

General installation

- Install porous asphalt system toward the end of construction activities to minimize sediment problems. The subgrade can be excavated to within 6 inches (15 cm) of final subgrade elevation 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.
- 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).
- 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 due to low subgrade permeability, a positive overflow (elevated drain) can be installed.

Backup systems for protecting porous asphalt systems

- See section ??? Common components and design criteria of permeable pavement systems for backup or overflow guidelines and construction techniques.

For an example specification for permeable asphalt paving see Appendix ???.

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2. Portland cement pervious concrete

Material and installation specifications for pervious concrete in Washington were originally derived primarily from the field experience and testing of the Florida Concrete and Products Association. Over the past several years industry groups, designers, installers, and local jurisdictions in the Puget Sound region have gained considerable expertise in mix design and installation. Puget Sound is now considered one of the leading regions in the U.S. for the application of pervious concrete for stormwater management.

Pervious Portland cement concrete is similar to conventional concrete with no or reduced fine aggregate (sand). The mixture is a washed crushed or round coarse aggregate (typically 3/8 or 1/4 inch), hydraulic cement, admixtures (optional) and water. The combination of materials forms an agglomeration of course aggregate surrounded and connected by a thin layer of hardened cement paste at their points of contact. When hardened the pavement produces interconnected voids that conduct water to the underlying aggregate base and soil (ACI 522R-10, 2010). Pervious concrete can be used for various light to heavy duty applications supporting low to moderate speeds. Properly installed and maintained concrete should have a structural life comparable to conventional concrete.

Pervious concrete pavement is a rigid system and does not rely to the same degree as flexible pavement systems on the aggregate base for structural support. Designing the aggregate base will depend on several factors, including project specific stormwater flow control objectives (retention or detention storage), costs and regulatory restrictions. As with other permeable pavement systems, deeper aggregate base courses (e.g. 12-24 inches or 30-60 cm) can provide important benefits including significant reduction of above ground stormwater retention or detention needs and uniform and improved subgrade support (FCPA, n.d.). See Chapter ??? for more information on flow modeling guidance.

<Figure 6-3-19: permeable concrete photo>

<Figure 6-3-20: permeable concrete section>

In addition to the guidelines specific to pervious concrete, see section <???> for guidelines on common permeable pavement components.

Design and construction

The following provides design guidelines that apply broadly to pervious concrete pavements. Design of pavements should be performed by experienced engineers with geotechnical and traffic data for the particular site and follow standards of the industry specific to pervious concrete materials and methods. Over the past several years pervious concrete mixes that include proprietary additives have been developed with varying degrees of success. The following section examines standard concrete mix design characterized by washed course aggregate (e.g. 1/4 or 3/8 inch (6.3 or 9.5 mm)), hydraulic cement, admixtures (optional) and water with no proprietary ingredients.

ACI 522 is the current national standard for specification of pervious concrete pavement. This manual defers to the current version of ACI 522 for developing pervious concrete pavement specifications. Included below are specific sections of ACI 522 relevant to this design manual and additional guidelines for infiltration rates, subgrade preparation and aggregate base placement specific to this region and developed from national and local experience.

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

Soil infiltration rate:

- See Appendix 1 section 8 of the Municipal Stormwater Permit for minimum infiltration rates. Soils with lower infiltration rates may require under-drains or elevated drains to prevent prolonged saturated conditions within 6 inches (15 cm) of the bottom of the pavement (wearing course) section.
- Surface flows directed from adjacent areas to the pavement surface or subgrade can introduce excess sediment, increase clogging, result in excessive hydrologic loading, and should be considered with particular attention to sediment control and infiltration capacity of the subgrade.

Subgrade

- See section ??? Common components and design criteria for permeable pavement systems for guidelines and construction techniques to reduce compaction.

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Under-drain

- An under-drain or elevated drain can be used for installations with seasonally high groundwater or subgrade infiltration rates that create prolonged saturated conditions at the ground surface and within 6 inches from the bottom of the pavement . An orifice can be used to improve detention. See section ??? for under-drain design details.
- On extremely poor soils with low strength and very low infiltration rates use an impermeable liner with under-drains.
- Installations should have an observation well (typically 6-inch or 15 cm perforated pipe) extending to the subgrade surface and installed at the furthest downslope area.

Aggregate base/storage bed materials

- The minimum base depth should be 6 inches (15 cm) (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 6-18 inches (15-30 cm) are common when designing for retention or detention.
- The coarse aggregate layer varies depending on structural and stormwater management needs. Typical placements are crushed washed aggregate and include WSDOT Permeable Ballast (9-03.9(2) 3/4 to 2.5 inches (2 cm to 6 cm)). Do not use round rock where perimeter of the base aggregate is not confined (e.g. sidewalk placed above grade). Round rock will easily move or roll from the perimeter of the aggregate base creating weak voids with no structural support for the pavement.
- The concrete can be placed directly over the coarse aggregate or a leveling course (e. g. 1.5 inch to US sieve size number 8 (AASHTO No 57 crushed washed stone)) which may be placed over the larger stone for final grading to provide a more stable, uniform working surface and reduce variation in thickness.

Aggregate base/storage bed installation

- Stabilize area and install erosion control to prevent runoff and sediment from entering storage bed.
- Geotextile fabric (optional):
  - See section ??? Common components of permeable pavement systems and design criteria for geotextiles.
- Install coarse aggregate in maximum of 8-inch lifts and lightly compact each lift (U.S. Army Corps of Engineers, 2003). Use back dumping method described in section ??? Common

components and design criteria for permeable pavement systems to protect subgrade from compaction.

- If utilized, install a 1 to 2-inch (2.5 cm) leveling course (typically No. 57 AASHTO crushed, washed stone) evenly over surface of coarse aggregate base and lightly compact to stabilize.

Pavement materials

The following guidelines provide typical ranges of materials for pervious concrete. Proper mix design and the resulting performance of the finished product depends on the specific aggregate used and proper cement content and water-cement ratios determined by that aggregate. Consult the qualified concrete supplier and ACI 522.1 for final mix design.

- Pavement thickness:
  - Parking lots: 5-9 inches (125-230 mm) typical.
  - Roads: 6-12 inches (150-300 mm) typical.
- Unit weights: 120-135 pounds per cubic foot typical. Pervious concrete is approximately 70-80% of the unit weight of conventional concrete) (FCPA, n.d.).
- Void content: (15-35%) per ASTM 1688 (interconnectivity of voids and, therefore, infiltration rates are inadequate below 15%) (ACI 522).
- Water cement ratio: 0.26-0.45 provides the optimum aggregate coating and paste stability. Water content is a critical design element of pervious concrete. If too dry, cohesiveness and cement hydration efficiency may be reduced. If too wet, the cement paste may drain down and result in a weak upper structure and clog the lower portion of the pavement. (ACI 522, 2010).

<Figure 6-3-21: pervious concrete in hand from Natl Redi Mix site>

- Aggregate to cement ratio: 4:0-4.5:1 typical. Total cementitious material content for the development of compression strength and void structure. The optimum content is entirely dependent on aggregate size, void content and gradation ((ACI 522, 2010).
- Aggregate: gradations are typically either single-sized coarse aggregate or gradations between 3/4 and 3/8 inch (19 and 9.5 mm). Typical in the Puget Sound are 1/4 or 3/8 (6.3 or 9.5 mm) clean crushed or round aggregate. In general the 1/4-inch (6.3 mm) crushed or round produces a slightly smoother surface than coarser aggregate. Aggregate should

meet requirements of ASTM D448 and C33/C33M.. Aggregate moisture at mixing is important to produce adequate workability and prevents draining of paste (ACI 522, 2010).

- Portland cement: Type I or II conforming to ASTM C150/C150M, C595/C595M or C1157/C1157M. Supplementary cementitious materials such as fly ash, ground blast furnace slag and silica fume can be added to Portland cement. Testing material compatibility is strongly recommended (ACI 522, 2010).
- Admixtures: water reducing/retarding, viscosity modifiers and hydration stabilizers can be used to increase working time and improve the workability of the pervious concrete mix.
- Water: Use potable water.
- Fibers may add strength and permeability to the placed concrete, are recommended and can be used as an integral component of the concrete mix.

Pavement placement

- See testing section below for confirming correct mixture and proper installation.
- With the correct water content, the delivered mix should contain a cement paste that smoothly covers all the aggregate particles while at the same time the paste does not slide or drain off the particles. The past should stick the aggregate particles to each other.
- Pervious concrete mix should be placed within 60 minutes from when water is introduced to mix, and within 90 minutes when using an extended set control admixture (ACI 522) or an admixture recommended by the manufacturer.
- Adding water in the truck at the point of discharge of the concrete should be allowed to attain optimum mix consistency, workability, placement, and finish (ACI 522).
- Base aggregate should be wetted to reduce moisture loss and improve the curing process of pervious concrete.
- Concrete should be deposited as close to its final position as possible directly from the truck, using a conveyor belt or hand or powered carts (pervious concrete mixes are stiff and cannot be pumped).
- Several screed and compaction methods can be used including low frequency vibrating truss screeds, laser screeds and hand screed that levels the concrete at above form (typically 3/8 to ¾ inch or 9 to 19 mm). The surface is then cover with 6-mil plastic and a static drum roller is used for final compaction (roller should provide approximately 10 pounds per square inch vertical force). A method that is becoming more prevalent and that has advantages for quality of finish and speed are rotating Bunyan screeds or hydraulically powered screeding drums that provide proper compaction at the finished ele-

vation and a nearly-finished surface in one operation (see figure <???>). Hydraulically operated sreeding drums come in various lengths and diameters.

<Figure 6-3-22: Bunyan screed>

- 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 pervious than conventional concrete. Accordingly, control joints are optional. If used, spacing of joints should follow the rules for conventional concrete and should typically be spaced at maximum 15-20 foot (3-6.7 meter) intervals. Joint depth should be1/4 to 1/3 he depth of te pervious concrete pavement. Control joints can also facilitate a cleaner break point if sections become damaged or are removed for utility work.

Curing

Due to the porous, open structure, pervious concrete dries rapidly. If curing is not controlled the bond between the aggregate becomes weak and structural integrity will be seriously compromised. Curing is, therefore, a critical step in pervious concrete installation and the following steps should be carefully planned and implemented (ACI 522):

- Completely cover surface and edges with 6-mil plastic within 20 minutes of concrete discharge. The surface and edges should remain entirely covered for the entire curing time.
- Curing time: 7 days for plain pervious concrete and 10 days for mixtures that incorporate supplementary cementitious materials such as fly ash and slag (ACI 522, 2010)
- Secure all edges adequately so that the plastic cannot be dislodged during cure time. Lumber, reinforcing bars and concrete blocks can be used to secure the plastic continuously along the perimeter. If wooden forms are used, riser strips can be nailed back in place to secure plastic. Do not use dirt, sand or other granular material on the plastic because the sediment may wash or spill into the pores of the concrete during rainfall or removal of plastic (ACI 522, 2010).
- Curing time: 7 days minimum. No truck traffic should be allowed for 10 days (U.S. Army Corps of Engineers, 2003).

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Note that admixtures are now becoming available that reduce or eliminate the need to cover the pavement installation with plastic. Consult ACI 522, industry representatives and suppliers for recommendations.

Quality control, testing and verification

The following provides a summary of Quality Control in ACI 522. Quality control and testing procedures to verify proper placement include test panels, fresh and hardened density and average compacted thickness of the installation. Critically important is requiring adequate NRMCA certified placement personnel and contractor experience for the installation (see ACI 522 for more details). There are currently no generally accepted standardized methods to test compression or flexural strength of pervious concrete and tests used for conventional concrete are not applicable due to the high variability in strength within the porous structure of pervious concrete and should not be used for verification (ACI 522, 2010).

- The contractor should place test panels using mix proportions, materials, personnel, and equipment proposed for the project. Test the fresh and hardened density and thickness of the test panel(s). See the current version of ACI 522 for test procedures and tolerances. If the test panel is outside acceptable limits for one or more of the verification tests, the panel should be removed and replaced at the contractor's expense. If the test panel is accepted it may be incorporated into the completed installation.
- Obtain a minimum 28 L (1 ft3) sample for fresh density testing for each day of placement (see ACI 522 for test procedures and tolerances).
- Remove three cores per 450 m2 (5000 ft2) not less than seven days after placement to verify placement hardened density and thickness. See ACI 522 for test procedures and tolerances. If the tested portion of the installation is outside acceptable limits for one or more of the verification tests, the installation is subject to rejection and should be removed and replaced at the contractor's expense unless accepted by the owner.

Minimum infiltration rate for the pervious concrete pavement

The minimum infiltration rate for newly placed pervious concrete should be 200 in/hr. Use ASTM 1701 to test infiltration rates of the test panel and at locations representative of the pavement finished product at a maximum rate of 5,000 ft2 per test.

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Backup systems for protecting pervious concrete systems

- See section ??? Common components and design criteria of permeable pavement systems for backup or overflow guidelines and construction techniques.

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3. Permeable interlocking concrete pavement

Permeable interlocking concrete pavers (PICP) are designed with various shapes and thicknesses from high-density concrete to allow infiltration through a built-in pattern of openings or joints filled with aggregate. Pavers are typically 3 1/8 in (80 mm) thick for vehicular applications and pedestrian areas may use 2 3/8 in (60 mm) thick units (Smith, 2011). When compacted, the pavers interlock and transfer vertical loads to surrounding pavers by shear forces through aggregate in the joints (Pentec Environmental, 2000). 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 up to 40 years (Smith, 2011).

<Figure 6-3-23: 2 pavers close up photos>

Design and construction

The Interlocking Concrete Pavement Institute provides technical information on best practices for PICP design, specification, construction and maintenance. Manufacturers or suppliers of particular pavers should be consulted for materials and guidelines specific to that product. Experienced contractors with a certificate in the Interlocking Concrete Pavement Institute (ICPI) PICP Installer Program should perform installations. This requirement should be included in project specifications. The following provides design guidelines that apply broadly to permeable interlocking concrete pavers.

Application: Industrial and commercial parking lots, industrial sites that do not receive hazardous materials, utility access, low speed (<40 mph) residential access roads, driveways, patios, promenades, and walkways.

<Figure 6-3-24: paver application example photo>

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Soil infiltration rate:

- See Appendix 1 section 8 of the Municipal Stormwater Permit for minimum infiltration rates. Soils with lower infiltration rates may require under-drains or elevated drains to prevent prolonged saturated soil conditions at or near the ground surface within the pavement section (Smith, 2011).
- Surface flows directed from adjacent areas to the pavement subgrade or surface can introduce excess sediment, increase clogging, result in excessive hydrologic loading, and should be considered with particular attention to sediment control and infiltration capacity of the subgrade.

Subgrade

- Soils should be analyzed by a qualified professional for infiltration rates and load bearing, given anticipated soil moisture conditions.
- The ICPI recommends a minimum CBR of 4% (96-hour soak per ASTM D 1883 or AASHTO T 193) to qualify for use under vehicular traffic applications (Smith, 2011).
- See section ??? Common components and design criteria for permeable pavement systems for guidelines and construction techniques to reduce compaction.

Aggregate base/storage bed materials

- Minimum subbase thickness depends on vehicle loads, soil type, stormwater storage requirements, and freeze thaw conditions. Typical subbase depths range from 6 to 24 in. and base depths are consistently held at 4 in. ICPI recommends base/subbase thicknesses for pavements up to a lifetime of 1 million 18,000 lb equivalent single axle loads or ESALs. For example, at lifetime ESALs of 500,000 with a CBR of 5%, the subbase (ASTM No. 2 stone) should be 18 in. and the base (ASTM No. 57 stone) thickness should be 4 in. Increased aggregate subbase thicknesses can be applied for increased stormwater volume storage. See Interlocking Concrete Pavement Institute guidelines for details on base thickness and design (Smith 2011).
- Minimum sub-base depth for pedestrian and bike applications should be 6 inches (Burak, 2007).
- See figure <???> for aggregate sub-base, base, bedding course and paver materials.
- The sub-base and base aggregate should be hard, durable, crushed stone with 90 percent fractured faces, a **Los Angeles (LA) Abrasion** of < 40 (per ASTM C131 and C535) and a design CBR of 80 percent (Smith, 2007)

<figure 6-3-25: paver section (use Smith, 2011 pg 15)>

Aggregate base/storage bed installation

- Stabilize area and install erosion control or diversion to prevent runoff and sediment from entering aggregate sub-base, base and pavers. Prevent sediment from contaminating aggregate base material if stored onsite.
- If using the base course for retention in parking areas, excavate subgrade level to allow even distribution of water and maximize infiltration across entire parking area.
- Geotextile fabric (optional):
  - Geotextiles are recommended on the sides of excavations where a full-depth concrete curb is not used to prevent erosion of adjacent soil into the aggregate base. The fabric should extend at least 1 foot (0.3 m) onto the subgrade bottom. A minimum overlap of 1 foot (0.3 m) is recommended for well-drained soils and 2 feet (0.6 m) for poor-draining soils (Smith, 2011).
  - The use of geotextiles on the bottom of the subgrade excavation is optional.
  - See section ??? Common components and design criteria for permeable pavement systems for recommended use and geotextile installation.
- Install No. 2 aggregate in 6-inch (150 mm) lifts. Use back dumping method described in section ??? Common components and design criteria for permeable pavement systems to protect subgrade from compaction. Compact with at least 4 passes of a 10-ton steel drum vibratory roller or a 13,500 lbf (60 kN) plate compactor. The first two passes should be with vibration and the final two passes should be static. Consolidation of the sub-base is improved if the aggregate is wet. Compaction is complete when there is no visible movement in the sub-base as the roller moves across the surface (Smith, 2011).
- The No. 57 aggregate base can be spread as one, 4-inch (100 mm) lift. Compact with at least 4 passes of a 10-ton steel drum vibratory roller or a 13,500 lbf (60 kN) plate compactor. The first two passes should be with vibration and the final two passes should be static. The No 57 stone should be installed moist to facilitate proper compaction.
- Adequate density and stability are developed when no visible movement is observed in the base as the roller moves across the surface (personal communication, Dave Smith ICPI). If field testing is required, a nuclear density gauge can be used on the No 57 base in back-scatter mode; however, this type of test is not effective/appropriate for the larger No 2 sub-base stone. A non-nuclear stiffness gauge can be used to assess aggregate base density as well (Smith, 2011).

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- Asphalt stabilizer can be used with the No. 57 and/or the No 2 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 2-2.5 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).

Bedding layer

- Install 2 inches (50 mm) of moist No. 8 aggregate for the leveling or choker course over compacted base. Screed and level No. 8 stone to within ± 3/8 inch over 10 feet (± 10 mm over 3 m) surface variation. The No. 8 aggregate should be moist to facilitate movement into the No 57 stone. Keep construction equipment and foot traffic off screed bedding layer to maintain uniform surface for pavers.

Under-drain

- Under-drain: three under-drain configurations are typical depending on stormwater management goals and infiltration capacity:
  - For installations with soil permeability that allows for adequate infiltration to meet stormwater management goals, install an elevated drain to protect installation from extreme events (see Figure ???).
  - An under-drain or elevated drain can be used for installations with seasonally high groundwater or subgrade infiltration rates that create prolonged saturated conditions at the ground surface and within 6 inches from the bottom of the pavement (see Figure ???). An orifice can be used to improve detention. See section ??? for under-drain design details.
  - On extremely poor soils with low strength or very low infiltration rates use an impermeable liner with under-drains (see Figure ???).
  - All installations should have an observation well (typically 6-inch perforated pipe) installed at the furthest downslope area. The well should be inserted into the subgrade 4-6 inches (100-150 mm) and kept 3 feet (1 m) from the side of the installation (Smith, 2011).

<figures 6-3-26 paver sections with under-drain configurations>

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Edge restraints

The type of edge restraint depends on whether the application is for pedestrian, residential driveway or vehicle use. For vehicular installations use a cast-in-place curb (typically 9 inches (225 mm)) that extends the full depth of the installation or to the top of the sub-base aggregate. If the paver installation is adjacent to existing impervious pavement the curb should extend to the full depth of pavement and aggregate base to protect the impervious installation base from excessive moisture and weakening. If the concrete curb does not extend the full depth an impermeable liner can be use to separate the two base materials (Smith, 2011).

Cast-in-place concrete curbs or dense-graded berms to provide a base to secure spiked metal or plastic edge restraints can be used for pedestrian and residential driveway applications. An additional option for pedestrian and light parking application is a sub-surface concrete grade beam with pavers cemented to the concrete beam to create a rigid paver border.

Paver installation

- Pavers should be installed immediately after base preparation to minimize introduction of sediment and to reduce the displacement of bedding and base material from ongoing activity (Smith, 2000).
- Place pavers by hand or with mechanical installer. Paver joints are filled with No. 8, 89 or 9 stone. Spread and sweep with shovels and brooms (small jobs) or small track loaders and power brooms or sweepers (larger installations). Fill joints to within ¼ inch (6 mm) and sweep surface clean for final compaction to avoid marring pavers with loose stones on the surface.
- To maximize efficiency and reduce cost of mechanical installation, consult with the supplier to deliver pavers layers, that will be picked up by the installation machine, in the final installed pattern.
- For installations over 50,000 ft2 (5,000 m2) that are installed with mechanical equipment, consult with the paver manufacturer to monitor paver dimension and consistency of paver layers so that layers continue to fit together appropriately throughout installation.
- Cut pavers along borders should be no smaller that than one-third of a whole paver if subject to vehicle loading,
- NOTE: do not use sand to fill paver openings or joints unless specified by the manufacturer. Sand in paver openings and joints clogs easily and will significantly reduce surface infiltration and system performance.

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- Compact pavers with a 8 kN (4,000 lbf), 75-90 Hz plate compactor. Use a minimum of two passes with each subsequent pass perpendicular to the prior pass.
- If aggregate settles to more than ¼ in. from the top of the pavers, add stone, sweep clean, and compact again. The small amount of finer aggregate in the No. 8 stone will likely be adequate to fill narrow joints between pavers in pedestrian and vehicular applications. Sweep in additional material as required. ASTM No. 89 or 9 stone can be used to fill spaces between pavers with narrow joints. In all cases, however, the bedding material should be ASTM No. 8 stone (Smith 2011).
- For vehicular installations, proof roll with at least two passes of a 10 ton rubber-tired roller.

<Figure 6-3-27: mechanical paver installation photo>

- Do not compact pavers within 6 ft of unrestrained edges (Smith 2011).

For detailed design guidelines and a construction specification see *Permeable Interlocking Concrete Pavements* (Smith, 2011).

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4. Plastic or concrete grid systems

Plastic or concrete grid systems come in several configurations. The goal for all plastic grid systems is to create a stable, uniform surface to prevent compaction of the gravel or soil and grass fill material that creates the finished surface (see figure ??? for examples). Of all the permeable paving systems, grid systems have the largest void space available for infiltration in relation to the solid support structure.

<Figure 6-3-28: photo of 2-3 paver types>

<Figure 6-3-29 Typical cross section>

Design and construction

Flexible grid systems conform to the grade of the aggregate base, and when backfilled with appropriate aggregate top course, provide high load bearing capable of supporting fire, safety and utility vehicles. These systems, when properly installed and maintained, are not impacted by freeze-thaw conditions found in the Puget Sound region and have an expected service life of approximately 20 years (Bohnhoff, 2001).

Application: Typical uses include alleys, driveways, utility access, loading areas, trails, and parking lots with relatively low traffic speeds (15-20 mph maximum).

Soil infiltration rate:

- See Appendix 1 section 8 of the Municipal Stormwater Permit for minimum infiltration rates. Soils with lower infiltration rates may require under-drains or elevated drains to prevent prolonged saturated conditions within 6 inches (15 cm) of the bottom of the pavement (wearing course) section.
- Surface flows directed from adjacent areas to the pavement subgrade or surface can introduce excess sediment, increase clogging, result in excessive hydrologic loading, and should be considered with particular attention to sediment control and infiltration capacity of the subgrade.

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Subgrade

- Soil conditions should be analyzed for load bearing given anticipated soil moisture conditions by a qualified professional.
- See section ??? Common components and design criteria for permeable pavement systems for guidelines and construction techniques to reduce compaction.

Aggregate base/storage bed materials

- Minimum base thickness depends on vehicle loads, soil type and stormwater storage requirements. Typical minimum depth is 4-6 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 if needed to meet flow control goals.
- Base aggregate is a sandy gravel material typical for road base construction

Example aggregate grading:

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

Aggregate base/storage bed 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 (if possible) to allow even distribution of water and maximize infiltration across entire parking area (terrace parking area if sloped).
- Geotextile fabric (optional):
  - See section ??? Common components and design criteria for permeable pavement systems for guidelines and construction techniques to reduce compaction.
- Install aggregate in 6-inch lifts maximum. Use back dumping method described in section ??? Common components and design criteria for permeable pavement systems to protect subgrade from compaction.

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- Compact each lift of dense-graded aggregate base to 95% standard proctor. (Note: For dense-graded bases in lightly trafficked grid applications, only standard Proctor density is required. Modified proctor requires more compactive force and expense and is not needed for the light loads to which grid pavements are constructed.
- For open-graded aggregate bases, compact with a minimum 10-ton roller with the first two passes in vibratory mode and the last two in static mode until there is no visible movement of the aggregate.

Top course aggregate

Aggregate should be clean, washed and hard angular stone.

Example 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 if not integral to the plastic grid. 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.
- 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.
- Aggregate fill
    - 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).

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- Grass fill
  - For plastic grids, sand (usually with a soil polymer or conditioner), sandy loam or loamy sand are typical fill materials.
  - For concrete grids, fill the openings with topsoil.
  - Spread sand or soil using power brooms, flat bottom shovels or wide asphalt rakes. A stiff bristle broom can be used for finishing.
  - Lay sod or seed. Grass installation procedures vary by product. Consult manufacturer or supplier for specific grass installation guidelines.
- Provide edge constraints along edges that may have vehicle loads (particularly tight radius turning). Cast-in-place or pre-cast concrete is preferred.
- Concrete grids require edge restraints along edges in all applications. Plastic grids require restraints when exposed to vehicles. Edge restraints for concrete or plastic grids in such applications should be cast-in-place or pre-cast concrete.

6.3.3 Maintenance

Maintenance is an essential element for the successful, long-term application of permeable pavement. Objectives of a comprehensive maintenance program for permeable pavement should include:

- Clear, enforceable guidelines for maintenance on private and public right-of-ways.
- Education materials describing the materials, function and proper maintenance of permeable pavements on private property.
- Mechanisms to supply new homeowners with educational materials
- Effective sediment and erosion control.
- Location of facilities, timing of, and equipment for, maintenance activities.
- Methods for testing pavement infiltration rates over time.

The following provides maintenance recommendations applicable to all permeable paving surfaces and specific permeable pavement systems.

Maintenance recommendations for all facilities

- 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.
- Installations can be monitored for adequate or designed minimum infiltration rates by observing drainage immediately after heavier rainstorms for standing water or infiltration tests using ASTM C1701.
- Clean permeable pavement surfaces to maintain infiltration capacity at least once or twice annually following recommendations below.
- 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).
- Ice build up on permeable pavement is reduced and the surface becomes free and clear more rapidly compared to conventional pavement. For western Washington, deicing and sand application may be reduced or eliminated and the permeable pavement installation should be assessed during winter months and the winter traction program developed from those observations. Vacuum and sweeping frequency will likely be required more often if sand is applied.

Maintenance recommendations for specific permeable paving surfaces.

Porous asphalt and pervious concrete

- Clean surfaces using suction, sweeping with suction or high-pressure wash and suction (sweeping alone is minimally effective). 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.

Permeable pavers

- ICPI recommends cleaning if the measured infiltration rate falls below 10 in.hr (250 mm0hr) (Smith, 2011).
- Use sweeping with suction when surface and debris are dry 1-2 times annually (see next bullet for exception). Apply vacuum to a paver test section and adjust settings to remove all visible sediment without excess uptake of aggregate from paver openings or joints. If necessary replace No 8, 89 or 9 stone to specified depth within the paver openings.

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Washing or power washing should not be used to remove debris and sediment in the openings between the pavers (Smith, 2000).

- For badly clogged installations, wet the surface and vacuumed aggregate to a depth that removes all visible fine sediment and replace with clean aggregate.
- I f necessary use No 8, 89 or 9 stone for winter traction rather than sand (sand will accelerate clogging).
- Pavers can be removed individually and replaced when utility work is complete.
- Replace broken pavers as necessary to prevent structural instability in the surface.
- 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.
- For a model maintenance agreement see *Permeable Interlocking Concrete Pavements* (Smith, 2011).

Plastic or concrete grid systems

- Remove and replace top course aggregate if clogged with sediment or contaminated (vacuum trucks for stormwater collection basins can be used to remove aggregate).
- Remove and replace grid segments where three or more adjacent rings are broken or damaged.
- Replenish aggregate material in grid as needed.
- Snowplows should use skids to elevate blades slightly above the gravel surface to prevent loss of top course aggregate and damage to plastic grid.
- For grass installations, use normal turf maintenance procedures except do not aerate. Use very slow release fertilizers if needed.

6.3.4 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 ??? for infiltration plotted with precipitation for one of the permeable paving test surfaces (turfstone).

<Figure 6-3-29: permeable concrete grid system infiltration>

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 ???: Permeable Paving Research are summarized below. To provide context for the infiltration rates below, typical rainfall rates are approximately 0.05 inches/hour in the Puget Sound region with brief downpours of 1-2 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 has been collected to quantify observations (personal communication Mark Blosser, August 2004).

Permeable pavers: highest initial infiltration rate (new installation): 1158.75 cm/hr
lowest initial rate (new installation): 317.75 cm/hr
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 permeable 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

Permeable Paving Research (see Appendix ???) 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 10.8 cm per hour (4.25 inches per hour) (Borgwardt, 1994). David Smith from Interlocking Concrete Pavement Institute, however, recommends using a conservative 25 cm/hr (10 in/hour) infiltration rate for the typical 20-year life span of permeable paver installations (Smith, 2011).

The lowest infiltration rate reported for an in-service permeable paving surface that was properly installed was approximately 0.58 in/hr (Uni Eco-Stone parking installation). Results from the three field studies evaluating cleaning strategies indicate that infiltration rates can be improved to various degrees. Permeable paver research in Ontario indicates that infiltration rates can be maintained for Ecostone with suction equipment (see Appendix ???: Permeable 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 can 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 rates of 89-98% for dissolved lead, 74-98% for dissolved cadmium, 89-96% for dissolved copper, and 72 -98% for dissolved 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 PAH's, and elevated, but still low concentrations of mineral oil in the underlying soil (Dierkes et al., 2002).

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<Figure 6-3-30: pollutant concentrations under permeable paver installation in Germany, Dierkes>

Pratt, Newman and Bond (1999) recorded a 97.6% removal rate for 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).

<Figure 6-3-31: hydrocarbon degradation in permeable pavement>

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 0.5 mm for the pavers. Table ??? summarizes pollutant concentrations from the study (Clausen and Gilbert, 2003).

Table ???: 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

Adopted from Clausen and Gilbert, 2003

*Total or dissolved form not reported.

In the Puget Sound region, a six-year permeable parking lot demonstration project conducted by University of Washington found toxic concentrations of dissolved copper and zinc in 97% of the surface runoff samples from an asphalt control parking stall. In contrast, dissolved 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).

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6.4 Urban Trees

Urban trees provide several environmental, aesthetic and economic benefits. In an extensive urban tree study of five cities across the US, McPherson et al (2005) found that the benefits from trees including energy conservation, air quality, carbon sequestration, increased property values, and stormwater management significantly outweighed the costs of installation and maintenance. The stormwater reduction benefits (dollars per gallon saved on construction and maintenance of retention or detention structures) ranged from approximately $37,000 to $496,000 annually.

Increasingly, jurisdictions are providing stormwater flow volume and peak flow attenuation for trees in the form of impervious surface reduction. Trees reduce surface flow from impervious and compacted landscape areas by intercepting and storing precipitation until evaporated, directing intercepted precipitation from foliage and branches to the trunk and surrounding soil, and by improving stormwater retention with extensive root systems that penetrate soil, build soil structure and provide conduits for infiltration.

<Figure 6-4-1: urban tree canopy>

6.4.1 Applications

This section examines individual trees protected or placed in the urban and suburban setting. Properly placed new trees and protected existing trees can intercept precipitation and reduce associated surface flow on residential, urban and commercial streets, commercial and urban parking lots and on urban sidewalks and promenades.

For native soil and vegetation protection and management information see Chapter ???: Vegetation Protection, Reforestation and Maintenance.

6.4.2 Assessment and Design

Planting new or preserving existing trees to achieve optimum vigor, canopy structure and life span in the urban environment is challenging. Canopy growth can be restricted by adjacent structures. Urban soils are often highly compacted and inhibit root penetration, and soil

volume is often limited for supporting adequate root structure. And while several factors may inhibit urban tree health (increased temperatures and associated water demand, atmospheric pollutants, salt and deicers, and physical damage), inadequate underground rooting space is a primary factor for impaired growth and premature mortality of city trees (Lindsey and Bussuk, 1992; Grabosky and Gillman, 2004). Additionally, trees are typically surrounded by impervious surface limiting soil moisture, nutrients and oxygen exchange.

Four broad concepts are considered throughout the recommendations below: 1) larger mature trees provide more stormwater (and other) benefits than small trees; 2) evergreen trees provide greater stormwater management benefit than deciduous trees; 3) adequate soil volume and quality are critical design elements for trees to reach mature size; and 4) if stormwater is directed to the tree planting area, too much water can kill a tree faster than too little water and special attention to adequate drainage is necessary for development of a healthy tree (Urban, 2008).

The following design section is divided into five parts: site assessment, drainage, soil strategies selecting trees, and protecting existing trees. Appendix ??? provides a matrix of various trees and some of the characteristics important to consider for successful placement. Some of the specific techniques for successfully placing and managing trees in the urban environment are beyond the scope of this document. Important is to engage qualified designers (landscape architects, certified arborist, etc.) at the early stages of design. Other valuable resources include: Matheny, N., & Clark, J.R. (1989). *Trees and development: A technical guide to preservation of trees during land development*; and Urban, James (2008) *Up by Roots: Healthy Soils and Trees in the Built Environment.*

6.4.2.1 Site Assessment and planning

Trees require significant space and investment for placement and maintenance. Realizing the substantial benefits of mature trees requires engaging the designer from planning through construction phases whether new construction or a retrofit. Above and below ground site assessment to inform soil strategies and species selection is important to grow healthy trees and reduce potential problems with competing uses. The initial site assessment for location and type of tree should include:

- Available above ground growing space.
- Below ground root space and ground level planting area.

- Type of soil and availability of water.
- Overhead wires.
- Vehicle and pedestrian sight lines.
- Proximity to paved areas and underground structures.
- Proximity to neighbors, buildings, and other vegetation.
- Prevailing wind direction and sun exposure.
- Maintenance.
- Additional environmental, economic and aesthetic functions such as shade (reduced heat island effect), windbreak, privacy screening, air quality, and increased property value.

Many of the key decisions for designing for trees will depend on the existing soil conditions. Good urban soil analysis for trees should include: understanding historic uses, extent and result of disturbances, soil texture, compaction, permeability, barriers and interfaces in the soil profile, and chemical characteristics (Urban, 2008). Once the basic site assessment and soil analysis is compiled the following guidelines can be applied for site layout to incorporate trees (Urban, 2008):

- Plant in the best or appropriate places first with the highest quality soils and adequate soil volume.

<Figure 6-4-2: from Urban: 2.1.1 >

- Plan for larger planting spaces by reducing pavement through well designed vehicle and pedestrian infrastructure, and by designing with the circulation patterns. For example, design planting areas longer in direction of travel. While several good strategies exist to improve soil volume and quality under pavement, larger planting spaces are the most effective strategy for growing healthy, mature trees (see section ??? for increasing soil volume under pavement).

<Figure 6-4-3: pic like figure 2.2.3 from Urban>

- Do not pave or restrict within the projected area of the mature tree's trunk flare. The trunk flare is the transition area between the base of the trunk and root crown and is often 2-3 times the trunk diameter measured at four feet above ground.

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<figure 6-4-4: trunk flare>

- Use pervious pavement for hard surfaces surrounding tree to allow oxygen exchange and increase soil moisture.
- Protect the tree installation from surrounding activities in the development (see section ???: Soil Strategies for more detail).

6.4.2.2 Drainage

Without stormwater directed to the planting area

Design for appropriate drainage (saturated conditions can create more problems and more expensive problems than dry conditions). If water is not directed to the tree pit from surrounding impervious areas and the tree pit volume is adequate to support a healthy mature tree, under-drains may not needed because: 1) significant precipitation volume that would otherwise fall on that area is intercepted and evaporated; and 2) the reduced volume that enters the enlarged area of the tree pit can be slowly infiltrated in subgrade soils with lower permeability. However, careful assessment of subgrade soils, groundwater levels and site drainage patterns should be used to determine soil water and optimum tree planting conditions. In general the tree planting pit or reservoir above the under-drain (if installed) should drain down within 48 hours to encourage aerobic conditions and good root distribution through planting pit for many tree species (Bartens, 2009). However, there are species more tolerant of prolonged saturated conditions. If the site assessment determines that there is potential for extended ponding or dense, compacted soils are present consult the designer for appropriate drainage strategies. Where additional drainage is necessary several strategies are available, including:

- Where subgrade soils have low infiltration rates install under-drain(s) with an accessible control structure to adjust flow and soil water conditions as needed. This is inexpensive backup compared to retrofitting planting areas to ensure proper drainage. See section ??? for more detail on under-drain design.
- Elevate drain to maintain an unsaturated area in the upper soil profile where most roots are located and a wetter area below the drain for improved retention and available soil moisture for the tree in drier periods.
- In wetter areas where under-drains are not feasible mound the planting area or plant at top of the slope if present, install dry wells (preferably with connection to more permeable soils) or sand/gravel filled percolation trenches.

- In dry sites plant in low areas, improve water holding capacity of soil (compost and mulch) and flatten slopes.

With stormwater directed to planting area

With adequate subgrade infiltration rates tree planting areas can be used to collect stormwater from small contributing areas. Careful assessment of subgrade soils, groundwater levels and site drainage patterns should be used to determine soil water and optimum tree planting conditions. Too much water can kill trees (Urban, 2008).

Increasing the volume of soil in the tree planting areas for roots also increases the volume for stormwater storage and treatment. Structural soils and rigid cell systems (see section ???) can increase storage volume significantly under paved areas. In fact, many installations will connect tree pits for individual trees and result in much or all of subsurface area under a sidewalk as potential storage (see figure ???). SilvaCell received a **General Use Designation (GULD)** in 2009 and provides instructions for using that system with the Western Washington Hydrology Model (WWHM). The structural soil system provides approximately 25-30% void space at compaction which can be used to calculate available storage.

If stormwater from adjacent impervious area is directed to the tree pit then, in many ways, flow control considerations are similar to bioretention. Important to consider for tree health is adequate drain-down. Limited research in this area indicates that the soil reservoir should drain down within 48 hours to encourage good root distribution through planting pit (Bartens, 2009). However, there are species more tolerant of prolonged saturated conditions. If the site assessment determines that there is potential for extended ponding or dense, compacted soils are present consult the designer for appropriate drainage strategies. In poor-draining or compacted urban soils this may require an under-drain. See drainage discussion above in section ???: Drainage without stormwater directed to the planting area, Figure ??? for section details and Bioretention: section ??? for details on under-drain design. Discharge from the under-drain should be to an approved location.

Calculating the appropriate amount and directing stormwater to the tree planting area are likely some of the more important design considerations for managing adjacent impervious area in tree pits. Several strategies are possible depending on flow control or water quality treatment goals, setting and local regulations and include:

- Permeable pavement
- Sloped sidewalks
- Curb inlets
- Roof drains

6.4.2.3 Soil Strategies

Urban soils are often highly compacted and inhibit root penetration, and soil volume is often limited for supporting adequate root structure. Several factors may inhibit urban tree health (increased temperatures and associated water demand, atmospheric pollutants, salt and deicers, and physical damage); however, inadequate underground rooting space is a primary factor for impaired growth and premature mortality of city trees (Lindsey and Bussuk, 1992; Grabosky and Gillman, 2004).

<Figure 6-4-5: tree growth with different soil volume (figure 1.6 from reference #14)>

Reducing compaction for new trees

Soil management to maintain infiltration and adequate growing characteristics in the built environment, and particularly urban areas, requires careful planning and attention of the designer from planning through construction phases and protection once the project is completed.

Construction sequencing and staging in order to protect existing (and particularly high quality) soils from compaction and contamination in tree planting areas is critical. Protection techniques include:

- Clearly mark protection areas, soil storage/staging areas, existing tree protection areas, etc. on plans.
- Review plans with the construction foreman and crews.
- Coordinate throughout construction process with contractor to reduce compaction and coordinate soil storage and reuse.
- Robust fencing and signage declaring protection objectives and penalties for violating protected areas. Fencing will likely include sediment control combined with larger barriers to prevent entry.
- Where construction operations unavoidably require temporary access over tree root zones or other soil protection areas, provide protection as follows:

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- *For foot access or similar light surface impacts*, apply a 6 inch layer of **arborist wood chip mulch** and water regularly to maintain moisture, control erosion, and protect surface roots.
- *For any vehicle or equipment access*, apply a minimum 1" steel plate or 4" thick timber planking over 2-3" of arborist wood chip mulch, or a minimum ¾" plywood over 6-8 inches of mulch, to protect roots and root zone soil from disturbance or compaction. Protect tree trunks and above-ground root flare with solid barriers such as plywood boxes.

In tree planting areas where soil is disturbed from previous activity or from current construction, depth of compaction should be assessed to determine appropriate strategies. If heavy machinery accessed the tree planting areas when soils are wet compaction, that could inhibit root penetration, may reach depths of 2-3 feet (cite). Surficial compaction can be mitigated by tilling (effective to approximately 6 inches) and incorporating compost. For deeper compaction double spading, excavator turning, sub-soiling or trench sub-soiling is necessary to reduce density. Reducing surface and deep compaction should only be done during drier periods and soil is **friable**.

Long-term protection is necessary to reduce compaction of the tree planting area. Tree grates are a common strategy for protecting soil around trees; however, grates are expensive and difficult to enlarge as the tree grows, and the elevation of the root ball must be below the elevation of the pavement (in poor draining soils this can kill the tree). Better strategies to protect soil in tree planting areas include:

- Mulch tree planting bed with 2-4 inches of arborist wood chips (mixed green and woody chips from tree-trimming operations). Keep the mulch 1 inch back from the trunk and replenish every 1-3 years. Arborist chips is the preferred mulch because it maintains surface porosity, conserves moisture, controls weeds, and slowly feeds the soil while supporting beneficial mycorrhizal fungi development. Coarse compost can also be used to improve poor soils, but it does not suppress weeds as well. Layering compost at the soil surface with wood chips on top for weed control is an effective strategy. Bark mulch does not improve the soil as much as arborist chips, and finely ground bark should be avoided because it can reduce air and water penetration (Lindsey and Bussuk, 1992; Seattle Public Utilities 2007, 2009 and 2011).
- Wheel stops to restrict vehicle access in roadside applications.

- Low fencing, curbs or other barriers to exclude excessive foot traffic (see figure ???).

<Figure 6-4-6: barrier (low fencing) to prevent soil compaction>

Reducing compaction around existing trees

Reducing compaction where tree roots are present will often require consulting with an arborist, specialized equipment and possibly significant expense. Accordingly, good soil assessment is necessary to determine extent of compaction and effective remedies that protect larger roots from mechanical damage. Soil probes and test pits to examine the soil profile and level of compaction are the most effective tools for compaction analysis and locating large roots for protection. Ground penetrating radar can also be used (Urban, 2008). Techniques for reducing compaction in a tree root zone include (Urban, 2008):

- Air and hydro excavation: air excavation uses compressed air to blow soil apart and hydro excavation uses high pressure water to erode soil.
- Vertical mulching: uses a series of holes in the compacted soil that are 5-6 inches in diameter and 6-9 inches deep. Holes are filled with compost or compost and expanded shale, clay or slate where pedestrian traffic is present.
- Radial trenching: trenches 5-6 inches wide and 6-12 inches deep are excavated with a air excavation tool and vactor truck. The trenches extend radially to the edge of the tree canopy and are filled with compost or compost and expanded shale, clay or slate where pedestrian traffic is present.

If compaction is not limiting root growth, compost or biologic amendments (e.g. compost tea, humic acid) can be used to improve tree health. Biologic amendments are likely more effective when used with the above techniques to reduce compaction. A 2-3 inch compost mulch should be applied over the root zone in conjunction with the biologic amendments (Urban, 2008).

Soil amendments

Initial site assessment should provide necessary information on soil texture, compaction, permeability and chemical characteristics of soil. If possible stockpile and reuse existing soils for tree planting. Relatively fine grained soils can be reused and support healthy tree growth. For adequate drainage and tree health Urban (2008) recommends avoiding topsoil that has more than 35% clay, 45% silt or 25% fine sand. Loam, sandy loam and sandy clay loam are

good textural classifications for supporting healthy tree growth (Urban, 2008).
If stormwater is directed to the tree planting area, a designed soil mix may be necessary to achieve adequate infiltration and drain-down characteristics. The water holding, organic matter and chemical characteristics of the soil must be compatible with the water needs and other cultural requirements of the tree.

Several materials are available to amend existing soils or design a specific soil mix. Mineral soil amendments alter soil texture and are used to improve infiltration and water holding characteristics. Common materials used in tree planters and planting areas include: sand, expanded shale, clay and slate, and diatomaceous earth (see Urban, 2008 for detailed descriptions for using mineral amendments).

Disturbed urban soils are often low in organic matter (OM). Biologic and organic amendments are used to improve OM content, infiltration capability, nutrient availability, soil biota, and cation exchange capacity. Biologic amendments include mycorrhizal fungi spores, kelp extracts, humic acids, organic fertilizers, and compost tea. If tree planting soil is poor quality, biologic amendments generally only offer a temporary improvement for tree growth. The most common and effective amendment for soils deficient in nutrients and improving water holding capacity and infiltration rates is organic compost. For tree planting areas, 10-15% compost by volume is recommended for soil profiles deeper than 12 inches. Up to 25-35% compost by volume can be incorporated into the top six inches of the soil profile to promote the formation of new topsoil (Urban, 2008)

Soil depth and volume

Urban (2008) recommends a minimum depth for planting soil of 30-48 inches. This depth should extend for a 10 foot radius around tree in lawn areas.

Recommendations for adequate soil volume vary significantly for trees planted in conventional soil. Lindsey and Bussuk (1992) recommend approximately 0.24 m3 per 1m2 of **canopy projection** for a typical silt loam soil to provide the volume necessary to support adequate root structure. Urban (2008, 2010) recommends a soil volume of 1-3 ft3 per 1 ft2 tree canopy area depending on irrigation schedule (1 ft3 for soil that is reliably irrigated and 3 ft3 for non-irrigated trees in drier areas). Approximately 0.38 m3 of soil per 1m2 of canopy projection is recommended for a loam soil with good drainage and no irrigation in an area with 30 inches of

rainfall. Accordingly, about 28.5 m3 is necessary to support a large tree (a tree with a canopy of approximately 75 m2) under this guideline.

The volume of soil available for supporting tree growth varies depending on the soil system. For native soils 100% is available for tree growth. For rigid cell systems that provide soil volume under pavement (see below for description) use 90%. Structural soils are mostly larger aggregate for structural support mixed with approximately 20% soil to support plant growth. Accordingly, structural soils designed for high compaction have less soil and will not support as large a tree canopy as a loam at lower compaction per unit volume (Urban, 2008).

Increasing soil and rooting volume

There are four primary strategies to improve the subsurface environment for trees and provide stormwater infiltration in compacted urban soils: 1); rigid, load-bearing cells that are filled with uncompacted soil; 2) structural soils; 3) creating root paths; and 4) connecting to adjacent soil volume (Urban, 2008).

Rigid cell systems

Rigid cell systems are modular frames (base and pillar) with a deck that supports the pavement above and creates large spaces for uncompacted soil and tree roots. SilvaCell is a common type of rigid load-bearing system for trees. The decks are often designed for **AASHTO H-20** loading. Many utilities can be installed within and through the cells; however, utilities do require planning and careful consideration (see figure ???). Many types of soil can be used to fill the cells for a rooting media including imported soils designed for the specific tree or excavated soils (including heavier dense soils with higher clay content) amended with compost if necessary (ASLA, 2010). An advantage with rigid cells is that much of the volume created by the cell is available for soil. In contrast, the structural soil aggregate (discussed below) uses approximately 80% of the available space, therefore, requiring more overall volume to provide an equal volume of soil as a rigid cell.

<Figure 6-4-7: rigid cell section and pic from Shoreline>

Structural soils

Structural soils provide a porous growth media and structural support for sidewalks and street edges. Cornell University (CU Structural Soil™) developed one of the first structural soils in

the early 1990's and others have since developed load-bearing growth media (e.g. Stalite). Structural soils are a mix of mineral soil (typically a loam or clay loam with at least 20% clay for adequate water and nutrient holding capacity) and coarse aggregate (typically uniformly graded ¾ to 1 ½-inch angular crushed stone) that, after compaction, maintains porosity (typically 25-30%) and infiltration capacity (typically >20 in/hr). Current research and installation experience suggests the following when designing with structural soil:

- *Soil volume*: 2 ft3 for every 1 ft2 of canopy projection (mature tree). Structural soil can be used under all or part of the paved surfaces adjacent to trees to provide the necessary soil volume. Where structural soil is placed adjacent to open graded base aggregate, geo-textile should be used to prevent migration of the fine aggregate in the structural soil to the more open graded material (Bassuk, 2005).
- *Soil depth*: 24 inches (minimum) to 36 inches (recommended) (Bassuk, 2005)
- *Compaction*: 95% proctor (Bassuk, 2005)
- *Tree pit opening*: if the tree pit opening is at least 5 ft x 5 ft a well drained top soil can be used in the planting area. If opening is smaller, structural soil can be used immediately under and up to root ball (see figure ???) (Bassuk, 2005).
- In planters with impervious walls, openings filled with uncompacted soil can be used to allow roots to access surrounding structural soil (see figure ???) (Bassuk, 2005).
- Use species that are tolerant of well-drained soil and periodic flooding.
- Structural soil reservoir should drain down within 48 hours to encourage good root distribution through planting pit (Bartens, 2009).

<Figure 6-4-8: Structural Soil with porous asphalt parking (cover image from ref #15)>

Contact authorized distributors for guidelines on specific structural soil products.

<figure 6-4-9: typical parking lot island and structural soil section from CU>

<Figure 6-4-10: typical parking lot island structural soil plan view from CU>

Many structural soils are proprietary mixes distributed through licensed providers. Sand-based Structural Soil (SBSS) is an urban tree planting system that is not proprietary. SBSS consist of a uniform gradation of sand (typically 30 inches deep), a subsurface irrigation port that can be accessed from the surface of the tree pit, crushed stone between the sand

layer and pavement, and the pavement (ASLA, 2010). The uniformly graded sand maintains porosity when compacted for load-bearing structural support (see figure ???).

<Figure 6-4-11: Sand Based Structural Soil section>

Structural soils can be used in conjunction with permeable pavement (Haffner, 2007).

Creating root paths

Root paths are a technique to connect planting areas and interconnect tree roots or guide roots out of confined areas to soil under pavement or adjacent to paved area that has the capability to support root growth (e.g. uncompacted, adequately drained loams). The actual root paths add only small amounts of rooting volume. The path trenches are typically 4 inches wide by 12 inches deep filled with a strip drain board and topsoil (see figure ???) Root paths are excavated with a standard trenching machine, placed approximately 4 feet on center and compacted with a vibrating plate compactor to retain subgrade structural integrity for pavement. The trenches should be extended into the tree planting pit a minimum of 1 foot and preferably within a few inches of the tree root ball (Urban, 2008).

<Figure 6-4-12: root path section>

Connecting to adjacent soil volume

Soil trenches are used to increase soil and root volume, connect to other tree planting areas and importantly, connect to larger areas with soil that has the capability to support root growth (e.g. uncompacted, adequately drained loams). The trenches are typically 5 feet wide with sloped sides for structural integrity and filled with topsoil or a designed soil mix. The installed soil is lightly compacted (e.g. 80% Proctor) and a gravel base placed on top of the soil for the sidewalk. The sidewalk is reinforced with rebar and thickened to span the soil trench. The thickened portion should extend a minimum 18 inches onto the compacted subgrade (see figure ???). An under-drain may be necessary depending on subgrade soil with low infiltration rates and if stormwater is directed to the tree planting area (see section ??? and consult with the designer for drainage requirements). Provide subsurface irrigation conduit preferably from stormwater or harvested water in areas with less than 30 inches of annual precipitation (Urban, 2008).

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<Figure 6-4-13: soil trench section>

6.4.2.4 Protecting existing trees

Complete later

6.4.3 Tree selection

Local jurisdictions often have specific guidelines for the types and location of trees planted along public streets or rights-of-way. For example most jurisdictions require minimum sight distances at intersections and setbacks of trees from street corners. Consult local regulations for sight distances, setbacks and other design guidelines.

Several constraints in the urban environment (some discussed above) limit the list of urban trees. Urban (2008) suggests that instead of simply selecting the right tree for the right place that designs should strive to make the place right and then select the right tree for that place.

Several resources (books and online) provide cultural and tree physical characteristics are available for tree selection. However, the most important selection resource is local knowledge and observing successful tree installations and failures. Some of the primary tree selection criteria include:

- The extent and growth pattern of the root structure in the context of adjacent paved areas or underground utilities.
- Cultural requirements including temperature hardiness, soil type, pH, ability to withstand wind, tolerance to drought, seasonally saturated soils and poor soils, and lighting.
- Tolerance for urban pollutants.
- Growth rate.
- Tolerance for pruning (in some settings pruning may be necessary to reduce conflicts with adjacent utilities or to maintain site distances.
- Deciduous or evergreen (evergreen trees intercept and evaporate more precipitation than similar size deciduous trees).
- Canopy spread and density (interception and evapotranspiration increase with increasing canopy size and density).
- Foliage texture and persistence.

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- 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).

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

6.4.4 Planting size

A 3-4 inch caliber tree is the optimum size for planting in the urban landscape (Urban, 2008)

The time to recover from transplant shock is approximately 6-12 months per caliber inch depending on latitude. For example at x latitude 6 months and y latitude y months per inch (Urban, 2008). Planting larger trees is appealing to provide a more finished appearance immediately after project completion; however, transplant shock may be longer and maintenance during recovery more extensive. In contrast 3-4 inch trees will likely recover faster and surpass the larger planting with less initial care (Urban, 2008).

6.4.5 Spacing

Urban (2008) recommends a spacing of 30-35 feet for a single row of street trees. For two rows of trees a minimum of 30 and preferable 50-60 feet is recommended to support adequate light for internal branches, canopy structure and symmetry of the tree.

6.4.6 Performance

Trees reduce surface flow from impervious and compacted landscape areas by:

- *Interception and evaporation*: intercepted precipitation is held until evaporated (in winter months evaporation is primarily from wind moving through the canopy) or intercepted precipitation moves from the foliage and branches to the trunk and surrounding soil.
- *Infiltration*: extensive root systems penetrate soil, build soil structure and provide conduits for infiltration.
- *Transpiration*: the uptake of soil moisture into the tree as part of the growth process and eventual release through stomata (small pores) in the leaves or needles. Transpiration rates for stand-alone trees in western Washington urban settings during winter are not known and assumed to be negligible. For general context three reported transpiration rates

for the Pacific Northwest and Great Britain conifers and New Hampshire deciduous trees were 10%, 15% and 25% respectively. These studies were conducted in summer months (Herrera, 2008).

The influence of trees on local hydrology and soil characteristics can be significant. <get infiltration study>. Lindsey and Bassuk (1992) cite studies that measured transpiration rates of 132 L/day for a 10 m tree and 946 L/day for tree with a 19 m diameter <check this>. Wullschleger (2000) measured a maximum transpiration rate of 160 Kg/day and a total volume of 6350 Kg in red maples over an 89-day study period (growing season). Bauer and Mastin (1997) found that interception and evaporation from vegetation during the winter months (approximately 50%) 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.

Most evapotranspiration studies are either in forest settings or during the warmer growing season. The following tree stormwater management performance is focused on literature for stand-alone trees in urban or suburban settings and does not include research from forest settings. Performance from forest studies provide important context, but may not be applicable given the differences in canopy structure, wind patterns, sun exposure and temperatures.

Interception, evaporation and stem flow

Urban tree canopy interception is influenced by three factors (Xiao, 2000):

- *Rainfall intensity, frequency and duration.*
- *Tree species and architecture*: deciduous or evergreen and stem orientation.
- *Other meterological factors:* including temperature, relative humidity, solar radiation and wind speed that control the rate at which water is evaporated from the tree.

In the central California valley (Mediterranean climate) Xiao (2000) found that for a single deciduous tree, 15% of the annual rainfall was intercepted and evaporated, 8% was **stemflow** and 77% **throughfall**. In the same experiment for a broad-leaf evergreen tree, 27% went to interception and evaporation, 15% to stemflow and 58% to throughfall. Rainfall frequency was more significant for determining interception loss than rainfall rate and duration.

In a study likely most applicable to western Washington, Asadian (2009) measured interception loss for Douglas fir and western red cedar located in various urban Vancouver, BC settings during seven storm events (October to June 2007-2008). For the seven events (377 mm total rainfall) interception loss ranged from 17 to 89%. Interception loss was generally greater for western red cedar than Douglas fir. Time for throughfall to penetrate the canopy (flow attenuation) ranged from 0.2 to 45.5 hours for individual storms. The authors note that interception loss is greater in their study than temperate forest studies that report 9 to 48% annual interception loss. Increased temperatures in the urban setting may be a primary driver for higher evaporation rates.

Herrera Environmental Consultants (2008) reviewed the literature on tree interception loss, transpiration and infiltration in the forest and urban settings and recommends a 30% reduction in annual precipitation volume for evergreen trees due to the above processes. Tree type (deciduous or evergreen), size or canopy and proximity to impervious surface were determined to be the primary factors driving runoff reduction attributed to trees. See Appendix ??? for City of Seattle's stormwater reduction credit guidelines for trees that is based on the Herrera report.

Infiltration

Trees do have the ability to penetrate and improve infiltration of relatively dense soil. Bartens et al. (2008) found that Black oak (*sp*) with a coarse root structure and red maple (*sp*) with more fibrous roots penetrated soils in containers with bulk densities of 1.3 and 1.6 g/cm3. In the soil with lower compaction, infiltration rates were 63% higher on average than controls with no plants and in the soil with higher compaction, infiltration rates were 153% higher than controls after approximately eight months.

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6.5 Vegetated Roofs

Vegetated roofs (also known as ecoroofs and green roofs) are thin layers of engineered soil and vegetation constructed on top of conventional flat or sloped roofs. Vegetated roofs can provide multiple benefits, some of which include: extending the life of the roof membrane; improving the aesthetic of the roof-scape; increasing the energy efficiency within the building; biodiversity and wildlife value; and stormwater volume reduction and flow attenuation (Dunnett and Kingsbury, 2004) No two green roofs behave the same. The range of benefits for a green roof depends on a number of design factors such as plant selection, depth and composition of soil mix, location of the roof, orientation and slope, weather patterns, and the maintenance plan.

Vegetated roofs have been mandated by many cities in Europe. The City of Toronto, Ontario is the first city in North America to mandate green roofs. Cities such as Chicago, Illinois, Washington, D.C., Vancouver, British Columbia, and Portland, Oregon are currently considering similar measures. Cities such as Chicago, Vancouver, B.C., Quebec City, Montreal, and Portland, Oregon offer incentives for their design and installation. The green roof industry in North America has continued to grow even in the face of economic downturns (see Figure ???).

<Figure 6-5-1: green roof industry growth>

History

The documented existence of vegetated roofs starts in 3500 B.C. in Ireland in the form of domed ceremonial chambers (see Figure ???). Civilizations such as the Mesopotamians, Vikings, and indigenous peoples in Asia and North America embraced this building approach. In the early to mid-twentieth Century various early applications of vegetated roofs started to emerge. Buildings like Rockefeller Center (1932), the residential architecture of Roland Terry in the late 1950's and 1960's on the West Coast are examples of early applications in the U.S. European cities such as Stuttgart and Bremen, Germany, and rural areas of Switzerland started exploring the idea in the early 1950's.

<Figure 6-5-2: Ireland green roof>

With the advent of single ply membrane waterproofing technology in the late 1960's a critical element to the vegetated roof assembly and development became available. Organizations like the F.L.L. in Germany started to systematically study the elements of green roof design. This research and experimentation lead to green roof specialty companies in Europe in the 1970's and 1980's. Several of these companies (e.g. Famos, Zinco, Optigtrun, Erisco-Bauder, among others), teamed up with waterproof membrane companies in North America such as Sarnafil, Garland, and Hydrotech, to provide complete green roof systems.

In 2003, 13.5 million square meters of vegetated roofs were installed in Germany (Grant et al., 2003; Peck, Callaghan, Kuhn and Bass, 1999; and Peck, Kuhn and Arch, n.d). Recent data show the North American vegetated roof industry growing at 16 to 28 percent annually. An industry survey estimated that over 4,300,000 square feet of vegetated roofs were installed in North America in 2010 and approximately 8,000,000 have been installed to date (Green Roofs for Healthy Cities, 2011). In 2010 the most prevalent type of vegetated roof was extensive, and the most common building types with vegetated roofs were institutional and commercial uses. The top three U.S. cities for vegetated roof installations in 2010 were Chicago, Washington, D.C., and New York (see Figure ???).

<Figure 6-5-3: urban vegetated roofs>

6.5.1 Applications

The range of design options for vegetated roofs has dramatically increased with recent research and experimental applications. Early applications conservatively selected narrow ranges of plant species, very low slope roof decks, and very light weight assemblies. As the potential functions of green roofs increased, so did the design approaches. Slopes up to and including completely vertical applications (known as living walls), depths appropriate for food production, and weight appropriate for **phytoremediation** are now being designed, allowing green roofs to perform many functions simultaneously. The scope and intensity of green roof research and experimentation is accelerating. Every year new green roof systems and elements are brought to the market.

<Figure 6-5-4: vegetated roof examples>

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6.5.2 Design

Because of their location, vegetated roofs typically require more planning and coordination to implement than ground-level landscaping. For new construction a critical path approach is highly recommended to establish the sequence of tasks to be carried out during the construction of the system. New construction involves many trades each with its particular role, with potential conflicts during the installation of the vegetated roof. For example, construction may require coordination of a general contractor, landscape contractor, roofing contractor, leak detection specialist, irrigation specialist, HVAC contractor, and construction inspectors, all of whom require access to the roof areas at various times during the process.

6.5.2.1 Planning

Stockpiling, storage, and conveyance of materials should be addressed during the planning and coordination process. During storage, plants should be protected by screens when possible to prevent overexposure and excessive drying. Growing media can be procured in small sacks that can be moved manually, in large “super sacks” that can be manipulated with a crane, or in bulk and distributed by blowers. When storing materials on the roof, it is important to check the structural limitations to prevent overloading the roof.

<Figure 6-5-5: placing growing media>

During construction, it is vitally important that the waterproof membrane be protected once installed. The waterproofing should be tested prior to placement of the growth media and other subsequent vegetated roof materials. Electronic leak detection systems are an optional technology designed to precisely locate a leak if one occurs after construction. Using a leak detection system reduces the likelihood that the significant portions of the vegetated roof materials will have to be removed in the event of a leak. Incorporating this technology should be evaluated for feasibility during the design process. Making the roofing contractor responsible for the vegetated roof installation, either directly or by means of subcontracted services, can help to ensure that the integrity of the waterproof membrane is maintained during construction.

The vegetated roof is a combination of an architectural system, an engineered system, and a living landscape; therefore, it is important to address the specific site characteristics and goals

for the roof in the design of the various subsystems and the selection of the components. Site characteristics that influence the design include climate, strength of the supporting structure, orientation to sun and shade, slope, size and dimensions, type of waterproofing, public access, roof drainage elements such as drains and scuppers, wind patterns, and fire safety. The goal for a vegetated roof is typically to provide one or more specific benefits, such as stormwater management, energy efficiency, aesthetics and amenity value, and biodiversity and habitat. An additional design objective should be to incorporate fall protection and safety provisions both during construction and during regular maintenance. To address these factors and considerations, a typical vegetated roof is designed by an experienced professional who is knowledgeable about the techniques and materials used in constructing these systems.

As the design of a vegetated roof is developed, a number of disciplines will likely need to be involved. The architect typically establishes dimensions, slopes, and roof drainage patterns with which the vegetated roof must be compatible. A mechanical engineer typically designs the roof drainage elements and building plumbing and locates HVAC equipment and maintenance access zones for rooftop equipment. A structural engineer will be required to analyze the loads on the roof and identify areas where materials can safely be stockpiled and staged during construction. A civil engineer may be involved to analyze the effect of the vegetated roof on the site drainage and stormwater control systems. A landscape designer may be extensively involved to create a unique planting palette and design, or less involved if a utilitarian roof is desired. An irrigation designer may also be needed, depending on the planting scheme and the climate.

Key steps in the installation of a vegetated roof are:

- Preparing the roof deck.
- Waterproofing the roof deck.
- Testing the waterproofing.
- Installing a root barrier, protection layer, and edging materials.
- Installing the drainage layer.
- Conveying and spreading the growing medium.
- Installing the plants and erosion control materials.

6.5.2.2 Types of vegetated roofs

Green roofs are typically divided into three categories, “extensive” (from 1.5” to 6” in depth),

“intensive” (anything deeper than 6”), and “semi-intensive” (some combination of intensive and extensive depth ranges). These distinctions are somewhat arbitrary. However, in the past they have indicated the kinds of plants and functions the green roof is to provide. Native soils are heavy and poorly drained and would exert unnecessarily heavy loads for an extensive vegetated roof installation, particularly when wet. Extensive roofs typically use light-weight soil mixes to reduce loads. Installations often range from 2 to 6 inches in depth, and research in Germany indicates that, in general, a 3-inch soil depth offers the best environmental and aesthetic benefit to cost ratio (Miller, 2002), depending on the climate. Data from vegetated roofs installed in Seattle and Vancouver, B.C., show that a 4-inch soil depth is nearly as effective as 6- and 8-inch depths in mitigating runoff from storm events in the Pacific Northwest (BCIT, 2006; Taylor, 2008).

One of the first steps in the design is to establish the allowable weight of the vegetated roof system. For existing buildings, the building structure should be evaluated by a structural engineer to determine the available capacity to bear the additional weight of the vegetated roof. For new buildings, the structural design calculations should account for the weight of the proposed roof system.

While vegetated roofs 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. Roofs with slopes greater than 10 degrees (2:12) require an analysis of engineered slope stability (Green Roofs for Healthy Cities, 2006), and those greater than 20 degrees require a structural reinforcement system and additional assemblies to hold the soil substrate and drainage aggregate in place (Scholtz-Barth, 2001).

All vegetated roofs consist of four basic components: a waterproof membrane, a drainage layer, a light-weight growth medium, and vegetation. (see Figure ???). In addition to these basic components, many systems may also incorporate a protection layer and root barrier to preserve the integrity of the waterproof membrane, a separation/filter layer to stabilize fine particles, capillary mats and mulch/mats to retain moisture and prevent surface erosion due to rain and wind scour.

<Figure 6-5-6: typical vegetated roof section>

There are two types of vegetated roof assemblies, modular and loose layed. Modular assemblies are either containers or pre-vegetated mats. The containers are from 3 to 6 inches deep and are approximately 3-4 feet wide. Pre-vegetated mats are usually high density polypropylene filament mesh approximately 3/4 inches thick that is planted with vegetation whose roots intertwine with the filaments. Loose laid assemblies are ones that have each element independently installed (see Figure ???). There are advantages and disadvantages to each approach and modular and loose laid assemblies can be incorporated into one installation.

<Figure 6-5-7: tray system for placing drainage layer, growing media and plants >

Finally, there are three common roof deck assemblies that influence the green roof design approach, inverted roof membrane assembly, conventional roof membrane assembly, and cold roof assembly. Each of these is defined by the relationship among the roof insulation, the roof deck, and the waterproof membrane. In an inverted roof membrane assembly the insulation is placed above the membrane with the geotextiles, growth media, and plants placed above. In a conventional roof membrane assembly the membrane is on top of the insulation which, in turn, rests on the roof deck. A cold roof assembly has the membrane on top of the roof deck and the insulation placed under the deck and separated from the underside of the deck by a ventilation space.

Two new American National Standard Institute (ANSI) standards are available for vegetated roof design. ANSI/SPRI VF-1 External Fire Design Standard for Vegetative Roofs describes design, methods, materials and maintenance for external fire resistance. ANSI/SPRI RP-14 Wind Design Standard for Vegetative Roofing Systems describes the wind forces prevalent on roofs and design, methods, materials and maintenance to prevent scouring of the growth media and other wind damage.

6.5.3 Components

6.5.3.1 Roof deck

The roof deck can be made of steel, concrete, plywood, or any other material sufficiently strong to support the load of the green roof between framing members and provide an acceptable substrate for the membrane. Its drainage planes must be slightly more aggressive than those

designed for a typical flat roof because minor ponding will not evaporate as quickly under a green roof assembly. The deck may also be supplemented by other materials, such as fiber cement board, used to provide a bondable surface for certain membrane types.

6.5.3.2 Waterproof membrane

The waterproof membranes used for vegetated roofs are generally slightly thicker than those used for standalone applications. Built-up roofing is still used in some instances; however, most of the current waterproof membranes fall under the following categories(see Figure ???):

- Single ply membranes such as:
  - EPDM (Ethylene propylene diene monomer), a rubber that comes in either reinforced or non-reinforced varieties.
  - TPO (Thermoplastic polyolefin) or PVC (Polyvinyl chloride). Both of these are thermoplastics.
- Multi-ply membrane applications such as:
  - SBS (styrene butadiene styrene).
  - APP (Attactic polypropylene).
- Fluid or spray applied membranes of various chemical compositions such as re-sins, Urethanes, EPDM, butyl-modified bitumen, among others.

<Figure 6-5-8: Assembling a waterproof membrane>

Different manufactures of the same type of membrane may produce different qualities of product. So, all TPO's, for instance, are not identical. Asphaltic membranes contain a carbon that is attractive to plant roots. Most asphaltic membranes, therefore, require a root barrier to be installed if they are used in a green roof assembly. Different membranes may have more recycled content, may be more readily recyclable, have less embodied energy, or have less impact on the environment in general, making them more green than the alternatives. In a retrofit scenario, some membranes may be chemically incompatible with materials in the previous application. For example, asphaltic materials are chemically incompatible with materials such as TPO and PVC.

Membranes can be mechanically fastened or adhered to the roof deck; however, it is generally recommended that they be fully adhered. In conjunction with the field membrane (the

membrane that covers the large areas of the roof) there is also the flashing membrane. Flashing membrane is generally thinner, more flexible, and not reinforced in order for it to fit around various shapes like corners and roof deck penetrations. Like the field membrane, it is waterproof. When leaks occur, the vast majority of them are in areas around flashing. Membrane manufacturers have developed pre-molded flashing elements to reduce leakage in these areas.

Each of the membrane types mentioned has its own process to bond waterproof seams. EPDM use solvents and adhesives – like a tire patch kit. TPO and PVC use hot air to melt plies into each other. SBS uses open flame torches. Many membrane applications can involve several different types of adhesion or bonding. For example, TPO and PVC can use both hot air and adhesives to bond in different situations. In addition to membrane applications like field membrane and flashing membrane there is also count-flashing that is not waterproof and is designed to shed water away from vulnerable areas such as membrane terminations. Details for membrane roofing are readily available from membrane manufactures and also from organizations like SMACNA and NRCA. Membrane manufacturers have warranty details that must be used in their assemblies in order to qualify for warranty coverage.

6.5.3.3 Drainage layer

All green roofs should have a drainage component. Usually this takes the form of a drain mat or granular drainage media. Drain mats come in many configurations, from polyethylene dimpled sheets with cups that hold water to polypropylene filament (see Figure ???). They rest on the waterproof membrane and in some situations serve as a membrane protection. Granular drainage material is free from organics and usually rests on a protection fabric placed on the membrane.

<Figure 6-5-9: Drainage mats>

Drainage elements serve two functions. They remove excess water from saturated growth media (soil mix) and they help to provide aeration to the bottom layer of growth media. They are designed to resist the compressive forces of the growth media and vegetation above. Drain mats are also frequently used under non-vegetated areas such as inert border areas to protect the membrane as well as to ensure good drainage on the entire roof.

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Many drain mats come with an adhered filter fabric. The role of filter fabric is to contain the fines and organics within the planted area. Filter fabric is non-woven polyethylene, polystyrene or other inert material. In time roots will penetrate the fabric; however, the critical time for its proper functioning is within the first 5-10 years of the roof's development. Filter fabric must be placed between the growth media and any other element, horizontal or vertical. If the vegetation is not bounded by a parapet, some other kind of border or soil restraint is placed on top of the drainage and filtration layers and around the perimeter of the planted area. Frequently this is an aluminum angle to the height of the soil depth. This restraint must be inert and sturdy enough to withstand the overturning forces of the adjacent soil mix. Placing the perimeter restraint on the drain mat/layer allows drainage water to freely flow below it. <clarify this>

6.5.3.4 Growth media

Growth media is considered by many to be the most complex component of green roofs. The growth media must support the chemical, biological, and physical requirements of the plants even though it is designed as a thin layer without the thermal, biological, and hydrologic advantages of soil at grade.

The growth media should never be confused with top soil. In general it is composed of porous and light weight mineral aggregate such as pumice, lava rock, expanded shale and expanded slate. The gradation of the mineral aggregate particles and the general composition will vary in order to achieve different performance characteristics. The mineral aggregate will be from 70% to 90% of the total mix. Organic content, frequently in the form of bio-stable compost, makes up the bulk of the remaining material. Other elements such as root stimulators, shock reducers, soil biota, bacterial washes, and soil shear enhancers are sometimes used as well.

Excessive organic content should be avoided. Target levels are based on experience with vegetated roofs that indicates the amount of organic material that will be stable and result in a system that achieves a balance between annual growth and dieback. The volatile organic content is typically less than 10 percent. Greater organic content can lead to system instability over time as the materials decompose and the depth of the growth media is correspondingly diminished.

Saturated loads of 15 to 50 pounds/square foot are typical for extensive roofs with 2 to 6-inch

soil depths (Scholtz-Barth, 2001). Vegetated roofs weighing 15 pounds/square foot (comparable to typical gravel ballast roofs) have been installed and are currently functioning in the U.S. At 15 to 50 pounds, many roofs can be retrofitted with no or minimal reinforcement, depending on the type of roof and the building structure (MKA, 2007). Separating the growth medium from the building perimeter and roof penetrations with a non-combustible material (e.g., gravel) can provide increased protection against the spread of fire, easier access to flashing and membrane connections, and additional protection from root penetration (Peck et al., n.d.).

F.L.L. has a comprehensive standard specification for three growth media; however, these specifications while useful should be reviewed carefully because North America has a wider distribution of climates and plant ecologies than Germany. In specifying growth media ASTM E2396 through E2400 are referred to for evaluating various growth media and granular drainage characteristics.

6.5.3.5 Vegetation

The plants on vegetated roofs are typically succulents, grass, herbs, and/or wildflowers adapted to the harsh conditions (minimal soils, seasonal drought, high winds, and strong sun exposure—i.e., alpine conditions) prevalent on rooftops. Plants should have a proven capacity to tolerate rooftop growing conditions, such as extreme temperatures and drought. Some examples of plant species are sempervivum, sedum, creeping thyme, allium, phloxes, and anntenaria. (Scholtz-Barth, 2001).

Green roofs are not native environments. As a result many native plants that do well at grade do very poorly on adjacent green roofs. Two identical green roofs very close to each other may develop differently due to subtle differences in their microclimates. The designer should identify the different zones of exposure and moisture on the roof prior to developing the planting scheme. Rooftops have many micro-climates to consider. Vertical surfaces such as walls and parapets may shade or reflect light and heat onto plantings depending on their orientation. The parts of the roof near the top of a slope are frequently drier and more prone to drought conditions than the areas at the toe of a slope and around roof drains, where moisture tends to collect.

As the growth media becomes deeper, a wider variety of plants can be used. At 2 to 3 inches

mosses, sedums, and some grasses are possible. At 3 to 5 inches a wider array of sedums and grasses are possible with the addition of some herbaceous perennials. And at 6 to 8 inches a relatively wide variety of the genera is possible. The varieties of plants can start to approximate the plants at grade when the growth media is deeper than 8 inches (see Figure ???).

<Figure 6-5-10: various green roof vegetation>

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 or a hydro-mulch paper emulsion.

6.5.4 Maintenance

Proper maintenance and operation are essential to ensure that the designed performance and benefits continue over the full life cycle of the installation. Each vegetated roof 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 vegetated roof performance. Note that some maintenance recommendations are different for extensive versus intensive vegetated roof systems. The procedures outlined below focus on extensive roof systems, and different procedures for intensive roofs 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 system.
- The manufacturer or designer should provide the maintenance and operation plan and the inspection schedule.

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- All elements should be inspected no less than two times per year for extensive installations and four times annually for intensive installations. Some manufacturers suggest monthly inspections.
- The facility owner or maintenance contractor 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., before major weed varieties disperse 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 the drain pipe inlet for cracks, settling, and proper alignment, and correct and re-compact soils or fill material surrounding the 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. before weed varieties disperse seeds).
- Weeding should be performed manually and without herbicide applications when possible.
- Extensive roof gardens should be designed to require minimal fertilization after plant establishment. If fertilization is necessary during plant establishment or for plant health and

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survivability after establishment, use an encapsulated, organic slow release fertilizer (excessive fertilization can contribute to increased nutrient loads in the stormwater system and receiving waters). If possible, test the growth medium prior to fertilization. Some membranes are resistant to fertilizers and others are not; check with the membrane manufacturer prior to fertilizer application.

- Intensive vegetated roofs typically require more fertilization than extensive roofs. Follow manufacturer's and installer's recommendations.
- Avoid application of mulch on extensive roofs. Mulch should be used only during plant establishment and in unusual situations and according to the roof manufacturer's guidelines. In conventional landscaping, mulch enhances moisture retention; however, moisture on a vegetated roof should be controlled by means of proper growth media design. Mulch can also increase the establishment of weeds.

Irrigation

- Plant selection directly affects the water requirements for the vegetated roof.
- 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 roofs 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 vegetated roof 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.

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- Any cause of pollutant release should be corrected as soon as identified and the pollutant removed. Contact the membrane manufacturer regarding potential damage to the membrane due to contaminants.

Insects

- Properly designed vegetated roofs will provide drainage rates that do not allow pooling of water for periods that are long enough to promote the development of insect larvae. If standing water is present for extended periods, inspect the drainage elements and correct the 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; personal communication, Charlie Miller, February 2004).
- Safety procedures appropriate for maintaining the roof should be clearly identified and should include training of workers, fall prevention systems, and safety harnesses.

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6.6 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 interflow 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 connecting component at, or above, grade. The piles allow the foundation system to reach or engage deeper load-bearing soils without having to dig out and disrupt upper soil layers, which convey, 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, King and Snohomish counties and the Cities of Olympia, Tacoma and Bellingham.

6.6.1 Applications

Minimal excavation foundations in both pier and perimeter wall configurations are suitable for residential or commercial structures up to three stories high (See figures ???). 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 open spaces 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 6-6-1: pin foundation in grade beam>

<Figure 6-6-2: pin pier section>

<Figure 6-6-3: finished building example, Lotus Medical Building>

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.

6.6.2 Design

Based on the type of structure to be supported and the specific site or lot topography, a pier type foundation or perimeter wall type foundation must first be selected.

6.6.2.1 Pier applications

Piers using pin piles can be used for various structure types including residential and light commercial buildings. When designing with piers, the engineer or vendor supplies the structural requirements (pile length and diameter and pier size) for the pier system. The architect then determines the number and location of piers given the structure size, loads and load bearing location (see Figure ???).

<Figure 6-6-4: pin pier foundation and finished house on Bainbridge Island>

Grading for piers

Pier applications require grubbing, and in some cases, blading to prepare the site. The permeability of some soil types can be significantly reduced even with minimal equipment activity; accordingly, the lightest possible tracked equipment should be used for preparing or grading the site. Consult a licensed engineer with soils experience for specific recommendations.

On relatively flat sites, blading should be limited to shaping the site for the best possible drainage and infiltration. Removing the organic topsoil layer is not typically necessary. On sloped sites, the soils may be bladed smooth at their existing grade to receive pier systems, again with the goal of achieving the best possible drainage and infiltration. This will result in the least disturbance to the upper permeable soil layers on sloped sites.

6.6.2.2 Wall applications

Piling combined with pre-cast walls with sloped bases, or slope cut forms for pouring continuous walls, may be used on sites with only minimal topography changes similar to the pier applications. Rectilinear wall systems (flat bottom sections) combined with piles, may also be used, but require more site preparation and soil disturbance.

Grading for flat-bottomed walls

While creating more soil disturbance, sloped sites should be terraced to receive conventional flat-bottomed 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. See Section ??? for details on flow control analysis minimal excavation foundations. As with the pier systems, consult a licensed engineer with soils experience for specific recommendations.

With wall systems 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 wall components (see Figure ???). 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 6-6-5: buffer material and pin pile guide placed before concrete pour >

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 when evaluating runoff conditions.

6.6.2.3 Dispersing roof stormwater with minimal excavation foundations

Roof runoff and surrounding storm flows may be allowed to infiltrate without the intervention of man-made conveyance where the selection of the proper foundation type and grading strategy results in the retention of the top layers of soils without significant loss of the permeability and storage characteristics.

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 (see Figure ???). 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 runoff are preferred; however, active systems can be used if back-up power sources are incorporated and a consistent and manageable maintenance program is ensured. See Section ??? for details on flow control analysis minimal excavation foundations.

<Figure 6-6-6: dispersion graphic>

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.

6.6.3 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.

<Figure 6-6-7: post pile application>

Soil conditions are determined by a limited geotechnical analysis identifying soil type, water content at saturation, strength and density characteristics, and in-place weight. However, depending on the pile system type, the size or scale of the supported structure, and the nature of the site and soils, a more complete soils report including slope stability and **liquifaction** analysis may be required.

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 very 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 also allow for the removal and replacement of pilings, which can extend the life of the support indefinitely.

<Figure 6-6-8: driving pins with hammer on mini excavator>

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6.6.4 Performance

From 2000 to 2001 subsurface flows under a minimal excavation foundation system and crawl space moisture were 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 pre-existing subsurface path downslope below the structure (see figure???).

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 (5 to 15 cm) of existing 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 comparison, but statistically equivalent, given the variance of the monitoring equipment (Palazzi, 2002).

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

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6.7 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).

The evolution of rainwater harvesting policy in western Washington

Many of the existing and permitted systems in western Washington operate under a blanket exemption where potable water may not be accessible (e.g. residential development on islands) or as a tool to reduce combined sewer overflows (e.g. City of Seattle). One of the largest barriers to broader application of rainwater collection systems has been state permitting. Until recently a water right permit was required for any rainwater collection system; however, monitoring and enforcing compliance for potentially thousands of systems was impractical. With no clear guidance for rainwater collection within the context of the water right process, the region had operated under a policy of allowing *de minimus (small or negligible)* use where small scale collection of rainwater was ignored.

In late 2009 the Department of Ecology issued an Interpretive Statement to clarify that a water right permit is not required for onsite storage and use of rooftop derived rainwater. There is no volume or use limitation (the size of the roof acts as a limiting factor). The Department of Ecology reserves the right to regulate the storage and use of new rainwater collection systems (those systems not up and running prior to the regulation) where the cumulative impact of new systems may negatively impact instream values or existing water rights (Ecology, 2009).

6.7.1 Applications

Typically, rainwater collection is used where rainfall or other environmental conditions limit the availability of domestic water supply. Rainwater collection systems can provide multiple benefits, some of which include:

- Reducing summer peak demand.

- Maintaining summer instream flows by reducing residential and commercial surface and groundwater water withdrawals.
- Reducing costly water distribution infrastructure by collecting water close to end use;
- Combined winter sewer overflows (CSO) reduction in urban areas.
- Providing a sustainable source of potable water where groundwater and surface water is degraded (Texas Water Development Board, 2005).
- Reducing runoff in urban retrofits or redevelopment where space is limited and other LID BMPs are infeasible
- Reducing runoff in urban retrofits or redevelopment where space is limited and other LID IMPs are infeasible.

6.7.1.1 Rainwater harvesting in the stormwater management context

Depending on the physical setting and regulatory requirements rainwater harvesting systems can be used to meet various flow control goals.

New suburban development

In medium to high-density development with detached single family homes, the roof is likely to be equal to or greater than the road, driveway, and sidewalk impervious surface contribution. If the soils in this setting have very low permeability, the primary LID objective of approximating pre-development (forested or prairie) hydrology is likely not feasible without reducing or eliminating the stormwater contribution from rooftops through rainwater harvesting and indoor use of that water or other applications (see section ???: Performance for design examples).

Urban CSO reduction

Large capital improvement projects to reduce CSO events are often extremely expensive. In the dense urban setting rainwater harvesting can provide an additional tool to reduce stormwater volume and/or detain storm flows at the source. For detention, rainwater cistern outlets can be fitted with an orifice to reduce peak flows and the outlet directed to an additional infiltration facility or to the storm sewer. During the growing season months, the cistern outlet can be closed and collected water used for irrigation.

Regardless of the physical setting and stormwater management goals, rainwater collection should not impair freshwater beneficial uses, but rather be used to reduce increased flow volumes, peak volumes and associated pollutant loads from developed areas that degrade

stream, wetlands or marine waters. For heavily developed watersheds where a significant contribution to stream or wetlands is from stormwater outfalls and rainwater collection is implemented for a significant percentage of the roof area, a water balance analysis should be conducted by local government to assess the effects on channel habitat and wetland hydroperiods.

Roof rainwater harvesting systems can be used in residential, commercial, institutional or industrial development for new or retrofit projects. The technology for rainwater harvesting 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.

Rain barrels are a type of rainwater collection typically used for small storage volumes and garden irrigation and provide a valuable tool to engage the public in water conservation. However, large storage volumes (2,000-10,000 gallons typical) not available in rain barrels are required to provide adequate storage for the stormwater volume and peak flow reduction necessary to meet stormwater management goals discussed in this section.

<Figure 6-7-1: cisterns on Capitol Hill>

6.7.2 Design

Rainwater 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 roof contribution, downstream LID flow control practices and overall costs of the stormwater management 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. In the Maritime Northwest rainwater collection should be sized to store as much rainfall as possible in April and May to provide water as far into the summer months as possible. Where stormwater is a primary incentive for installation and

municipal or groundwater supplies are available, the rainwater collection system can be installed with, and augmented by, a conventional water source.

In 2009, The State Building Code Council adopted the 2009 edition of the Uniform Plumbing Code. Significant changes were made to Chapter 16, which governs the use of reclaimed water. Previous plumbing code did not distinguish reclaimed water from rainwater. The new adopted code has a separate set of regulations that governs some aspects of rainwater harvesting (for indoor use only). Where applicable, such code will be referenced below. This code went into effect July 1, 2010 and is codified in WAC 51-56-1600. Rainwater harvesting systems should only collect water from roof surfaces and not from vehicle or pedestrian areas, surface water runoff or bodies of standing water (WAC 51-56-1400, Section 1627.1)

6.7.2.1 Components of a rainwater collection system

Specific components and configurations used in a rainwater harvesting system will depend on the rainfall pattern, physical setting, water needs and stormwater management goals. General components and system layout are provided in Figure ???

<Figure 6-7-2: rainwater collection systems graphic with main components>

Catchment or roof area

The roof material should not contribute contaminants (such as zinc, copper or lead) to the collection system (WAC 51-56-1628.1). 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). Rainfall present in the Pacific Northwest is surprisingly acidic and will tend to leach materials from roofing material.

The following general guidelines are used for calculating rooftop area and 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 10 to 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, 2005). Precipitation loss is the least with metal, more with composition, and greatest with wood shake or shingle.

Roof materials

Currently, few roof materials have been tested and the only recommendation for common roof coverings is to not use treated wood shingles or shakes.

- Enameled standing seam 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.

Gutters and downspouts

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. Do not use lead solder for gutter seams. WAC 51-56-1628.2 states that copper or zinc gutters and downspouts shall not be used; however, if existing gutters and downspouts are already in place, the interior shall be coated with an NSF-quality epoxy paint.

Screens should be installed in the top of each downspout. Screens installed on gutters prevent coarse (e.g. leaves and needles), but not fine debris (pollen and dust) from entering the gutter.

Gutters will still require cleaning and access should be considered when selecting gutter screens.

<Figure 6-7-3: gutter screen>

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).

First flush diverters

First flush diverters collect and route the first flush away from the collection system. The initial flow from a storm can contain higher levels of contaminants from particulates settling on the roof, bird droppings, etc. A simple diverter 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.

<Figure 6-7-4: first flush diverter>

The Texas Rainwater Guide recommends that the first 10 gallons of water be diverted for every 1000 square feet of roof (applicable for areas with higher storm intensities) (Texas Water Development Board, 2005). 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 (e.g. roof washers) 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).

Roof washers

Roof washers are placed just before the storage cistern to filter coarse and fine debris. Washers consist of a tank (typically 30-50 gallons), a course filter/strainer for leaves and other

organic material and a finer filter (typically 30-microns or less). Roof washers should be cleaned regularly to prevent clogging, as well as prevent the development of pathogens (Texas Water Development Board, 2005).

WAC 51-56-1628.3 governs roof washers. The following provisions apply:

- All rainwater harvesting systems using impervious roof surfaces shall have at least one roof washer per downspout or prefiltration system. A roof washer or prefiltration system is not required for pervious roof surfaces such as green roofs. Roof washers and prefiltration systems shall meet the following design requirements.
    1. All collected rainwater shall pass through a roof washer or prefiltration system before the water enters the cistern(s).
    2. If more than one cistern is used, a roof washer or prefiltration system shall be provided for each cistern. EXCEPTION: Where a series of cisterns are interconnected to supply water to a single system.
    3. The inlet to the roof washer shall be provided with a debris screen that protects the roof washer from the intrusion of waste and vermin.
    4. The roof washer shall rely on manually operated valves or other devices to do the diversion.
    5. Roof washers shall be readily accessible for regular maintenance.
    6. Pre-filtration screens or filters shall be maintained consistent with manufacturer's specifications.

<Figure 6-7-5: roof washer>

Storage tank or cistern

The cistern is the most expensive component of the collection system. 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 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 tanks and the multi-reservoir configurations can continue to operate if one of the tanks needs to be shut down for maintenance (see Figure ??? for cistern examples).

WAC 51-56-1628.4 governs cisterns. The following provision apply:

1. All cisterns shall be listed for use with potable water and shall be capable of being filled from both the rainwater harvesting system and the public or private water system (WAC 51-56-1628.4).
2. The municipal or on-site well water system shall be protected from cross-contamination in accordance with Section 603.4.5 of the Uniform Plumbing Code.
3. Backflow assemblies shall be maintained and tested in accordance with Section 603.3.3.
4. Cisterns shall have access to allow inspection and cleaning.
5. For above grade cisterns, the ratio of the cistern size shall not be greater than 1:1 height to width, provided that for an engineered tank with an engineered foundation, the height may exceed the width, subject to approval of the Authority Having Jurisdiction. The ratio for below grade cisterns is not limited.
6. Cisterns may be installed either above or below grade. All cisterns shall be installed in accordance with the manufacturer's installation instructions. Where the installation requires a foundation, the foundation shall be flat and shall be capable of supporting the cistern weight when the cistern is full.
7. Below grade cisterns shall be provided with manhole risers a minimum of 8 inches above surrounding grade. Underground cisterns shall have tie downs per manufacturer's specifications, or the excavated site must have a daylight drain or some other drainage mechanism to prevent floating of the cistern resulting from elevated groundwater levels.
8. Cisterns shall be protected from sunlight to inhibit algae growth and ensure life expectancy of tank.
9. All cistern openings shall be protected from unintentional entry by humans or vermin. Manhole covers shall be provided and shall be secured to prevent tampering. Where an opening is provided that could allow the entry of personnel, the opening shall be marked, "DANGER - CONFINED SPACE."
10. Cistern outlets shall be located at least 4 inches above the bottom of the cistern.
11. The cistern shall be equipped with an overflow device. The overflow device shall consist of a pipe equal to or greater than the cistern inlet and a minimum of 4 inches below any

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makeup device from other sources. The overflow outlet shall be protected with a screen having openings no greater than 0.25 inches or a self-sealing cover

<Figure 6-7-6: Steel, cement and wall mounted cisterns>

Pumps and pressure tanks

Adequate elevation to deliver water from the storage tank to the filtration and disinfection system and the house at adequate pressure is often not available. Standard residential water pressure is 40 to 60 pounds per square inch. Two methods are used to attain proper pressure: 1) a pump with a pressure tank, pressure switch and check valve; or 2) an on-demand pump. The first system uses the pressure tank to keep the system pressurized and the pressure switch initiates the pump when pressure falls below a predetermined level. The check valve prevents pressurized water from returning to the tank. The on-demand pump is self priming and incorporates the pressure switch, pressure tank and check valve functions in one unit (Texas Water Development Board, 2005).

Where a pump is provided in conjunction with the rainwater harvesting system, the pump shall meet the following provisions per WAC 51-56-1628.5:

1. The pump and all other pump components shall be listed and approved for use with potable water systems.
2. The pump shall be capable of delivering a minimum of 15 psi residual pressure at the highest outlet served. Minimum pump pressure shall allow for friction and other pressure losses. Maximum pressures shall not exceed 80 psi.

Back flow prevention

Rainwater is most commonly used to augment an existing potable supply for uses that don't require treatment to potable. Typically such systems augment an existing supply due to the fact that the cistern will likely run dry or near dry in the summer. Chapter 16 The Uniform Plumbing Code as adopted by Washington State has provisions that govern how to dual plumb such systems so as to prevent backflow prevention and subsequent contamination of the potable water supply.

Water treatment

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

1. 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 gutters to exclude leaves and other debris, routing the first flush through first flush diverters, roof washers, and cistern float filters. Cistern float filters are placed in the storage tank and provide filtration as water is pumped from the tank to the disinfection system and the house. The filter is positioned to float 10-16 inches below the water surface where the water is cleaner than the bottom or surface of the water column (Texas Water Development Board, 2005).

<Figure 6-7-7: float filter graphic>

Types of filters for removing the smaller remaining particles include single cartridges (similar to swimming pool filters) and multi-cartridge filters. These are typically 5-micron filters and provide final mechanism for removing fine particles before disinfection. Reverse osmosis and nanofiltration are filtration methods that require forcing water through a semipermeable membrane. Membranes provide disinfection by removing/filtering very small particles (molecules) and harmful pathogens. Some water is lost in reverse osmosis and nanofiltration with concentrated contaminants. The amount of water lost is proportional to the purity of the feed water (Texas Water Development Board, 2005).

2. Disinfection

- *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.

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- *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 (this 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).

For potable systems, water must be filtered and disinfected after the water exits the storage reservoir and immediately before point of use (Texas Water Development Board, 2005).

<Figure 6-7-8: filter array>

3. 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.

6.7.3 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 at 0.2ppm to 0.5ppm or 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.

6.7.4 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 depression 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 fully 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. Important to note is that for the conventional project constructed at this site, additional property had to be purchased where stormwater was conveyed and retained because site conditions were extremely poor.

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 evaluated. 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 ??? contains a breakdown of average daily water use per person/day.

Table ??? 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. (see figure ???). 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.

<Figure 6-7-9: graph of storage and water use by month>

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