Environmentally Critical Areas: Best Available Science Review
February 2021

INTRODUCTION

Purpose of Report

The purpose of this report is to provide a compilation and review of selected literature that is representative of the best available science regarding urban stormwater management. It has been prepared for the proposed revisions to the City of Seattle (City) Stormwater Code (Seattle Municipal Code [SMC] 22.800 – 22.808). It is intended to fulfill the provisions of Revised Code of Washington (RCW) 36.70A.172, which requires that cities and counties "include the best available science in developing policies and development regulations to protect the functions and values of critical areas" and the Washington Administrative Code (WAC) 365-195-900 through WAC 365-195-925, which contain rules designed to assist cities and counties in identifying and including the best available science in adopted policies and regulations.

Scope of Report

The Stormwater Code and associated joint Seattle Public Utilities/Department of Planning and Development (SPU/DPD) Directors' Rules are being revised in order to comply with the requirements of the City's coverage under the 2019-2024 Phase I Municipal Stormwater Permit (MS4 Permit, Ecology 2019a), as well as to incorporate related City policy changes and to improve usability. The MS4 Permit was issued by the Washington State Department of Ecology (Ecology) under both the National Pollutant Discharge Elimination System (NPDES) program established by the federal Clean Water Act and the State of Washington Water Pollution Control Law. The MS4 Permit was issued on July 1, 2019 and became effective on August 1, 2019. The MS4 Permit requires that the City's Stormwater Code and associated Stormwater Manual (to be contained in the Directors' Rule) include minimum requirements, thresholds, definitions, and other specified requirements, limitations, and criteria, determined by Ecology to be equivalent to Appendix 1 of the MS4 Permit for new development, redevelopment, and construction. In addition, maintenance provisions must be at least as protective of facility function as, and source control provisions must be functionally equivalent to, Ecology's Stormwater Management Manual for Western Washington (SWMMWW, Ecology 2019b).

The MS4 Permit requirements (and the proposed 2021 Stormwater Code Updates) follow a set of previous MS4 Permit requirements that became effective in January 2015 (Ecology 2014a). The technical basis for the 2016 Stormwater Code update was well established, and the associated best available science documentation was thorough. Most is still applicable. As such, a substantial portion of this document repeats and incorporates information presented in the 2015 Best Available Science Review (Supplemental Report) (Seattle 2015). This February 2021 update to the 2015 Best Available Science Review (Supplemental Report) refers to additional literature on the general impacts of stormwater management, as well as selected information related to particularly notable 2021 Stormwater Code Update elements.

This document also supplements the City's Environmentally Critical Areas: Best Available Science Reviews (Seattle 2005, Seattle 2007, Seattle 2013a), which present detailed reviews of the best available science regarding wetlands, fish and wildlife conservation areas, geologic hazard areas, flood-prone areas, abandoned landfills, and critical aquifer recharge areas.

Overview of Report

This report provides a summary of the impacts of urban stormwater runoff on receiving waters relating to changes in flow rates and volumes, and water quality. It then presents a review of selected scientific literature related to urban stormwater management, focusing on BMPs related to stormwater runoff flow control and water quality treatment. It includes literature regarding wetland protection, flow control in creek basins, low impact development, stormwater quality treatment facilities, and construction site stormwater pollution prevention.

This report is not intended to present an exhaustive review of the scientific literature on the subject of urban stormwater runoff management. Creating such an all-inclusive compilation would result in a multi-volume document that would duplicate existing resources. Readers interested in more comprehensive compilations regarding the science of managing urban stormwater runoff should consider: Ecology (2014b), Minton (2002), Sheldon (2005), Washington State University/Puget Sound Partnership (WSU and PSP 2012), Shaver et al. (2007), National Research Council (2009), and Puget Sound Partnership (2010), among many others.

EFFECTS OF URBAN STORMWATER

Impacts of Urban Stormwater Runoff on Flow

Prior to Euro-American settlement, the landscape tree canopy, other vegetative cover, and forest duff layer limited damaging high stormwater runoff flows through interception, evapotranspiration, and absorption of rainfall. As the human population increased and commerce grew in Seattle, the overall nature of the landscape was changed. Trees were logged, land was cleared, buildings and roadways were built, and the soil was compacted. The overall impact of these changes resulted in:

- Increased flow rates of stormwater runoff
- Increased volumes of stormwater runoff
- Decreased time for stormwater runoff to reach a downstream receiving water
- Greater in-stream flow velocities.
- Reduced groundwater recharge
- Increased frequency and duration of high stream flows and wetland inundation during and after wet weather
- Reduced stream flows and wetland water levels during the dry season.

Schueler (1987) provides an illustrative graph showing the relationship between pre-developed stream flow rates and post-development stream flow rates, which is provided below in Figure 1.

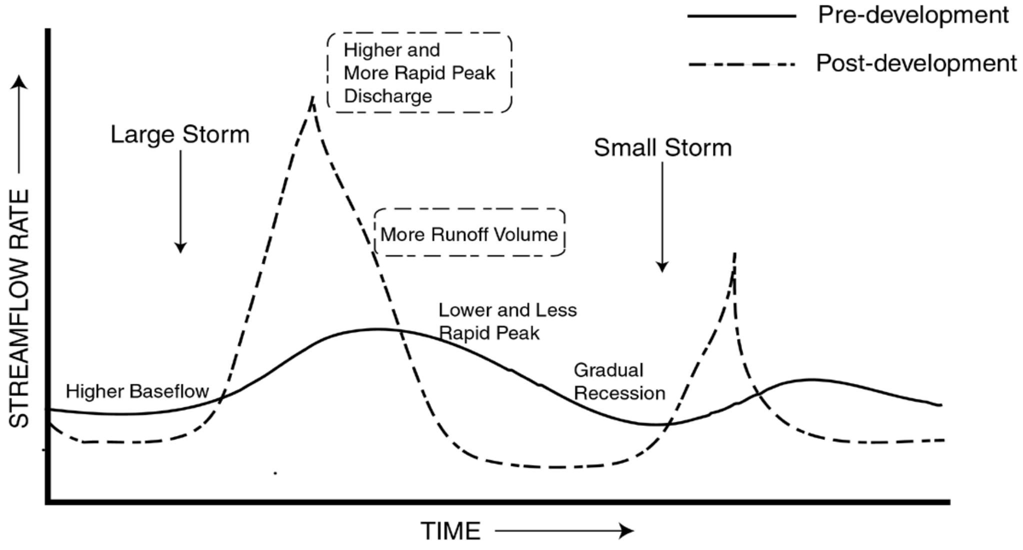

Figure 1. Changes in Hydrology after Development (Schueler 1987)

The relationship between changes in effective imperviousness and the quality of streams is well documented (see, for example, Dunn and Leopold 1978, Booth and Jackson 1997, Arnold and Gibbons 1996, McMahon and Cuffney 2000, USGS 2009). High stream flows, caused by increases in imperviousness in a catchment, can result in channel erosion and stream bank instability. Booth and Jackson (1997) showed that increased flows can occur even when the catchment has undergone relatively small changes in the percent of effective imperviousness. For example, Figure 2 illustrates how runoff from a 2-year storm in an urban catchment with approximately 10 percent impervious surface is equal to the runoff from a 10-year storm in a forested catchment (ibid).

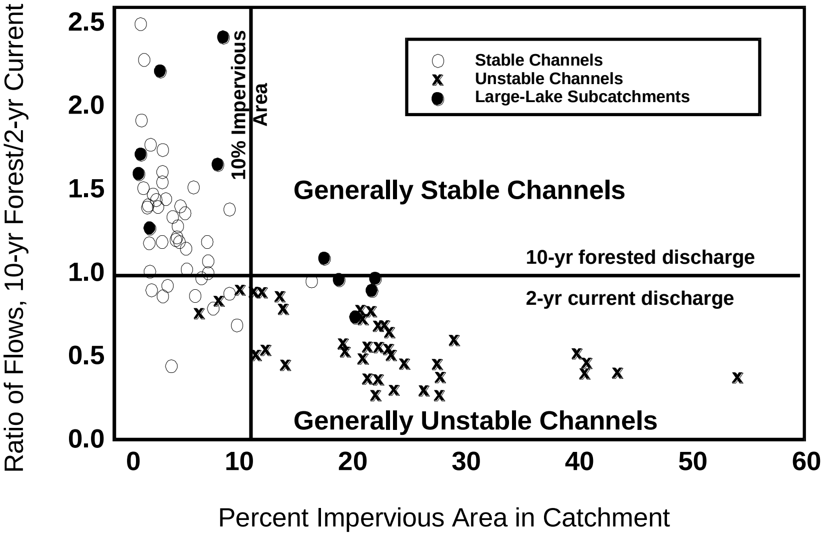

Figure 2. Channel Stability and Land Use: Hylebos, East Lake Sammamish, and Issaquah Basins (Booth and Jackson 1997)

The changes in hydrologic regime associated with urban stormwater runoff can also significantly impact aquatic life. When a stream changes its physical configuration and substrate due to increased flows, habitats are altered. Significant and detectable changes in the biological community of Puget Sound lowland streams have been observed early in the urbanization process. This is due to a combination of changes in flow conditions, as well as water quality conditions (discussed further in the next section). May (1996) and May et al. (1997) reported observable biological changes in the 5-10 percent total impervious area range of a watershed (Figure 3). Using the Benthic Index of Biotic Integrity (B-IBI) developed by Karr (1991) and Kleindl (1995), May et al. (1997) evaluated the relationship between B-IBI and the extent of watershed urbanization as estimated by the percentage of total impervious area (Figure 3). Also shown in Figure 3 is the correlation between the abundance ratio of juvenile Coho salmon to cutthroat trout (Lucchetti and Fuerstenberg 1993) and the extent of urbanization.

The biological communities in wetlands are also severely impacted and altered by the hydrological changes. Relatively small changes in the natural water elevation fluctuations can cause significant shifts in vegetative and animal species composition (Reinelt and Taylor 2000, Azous and Horner 2001).

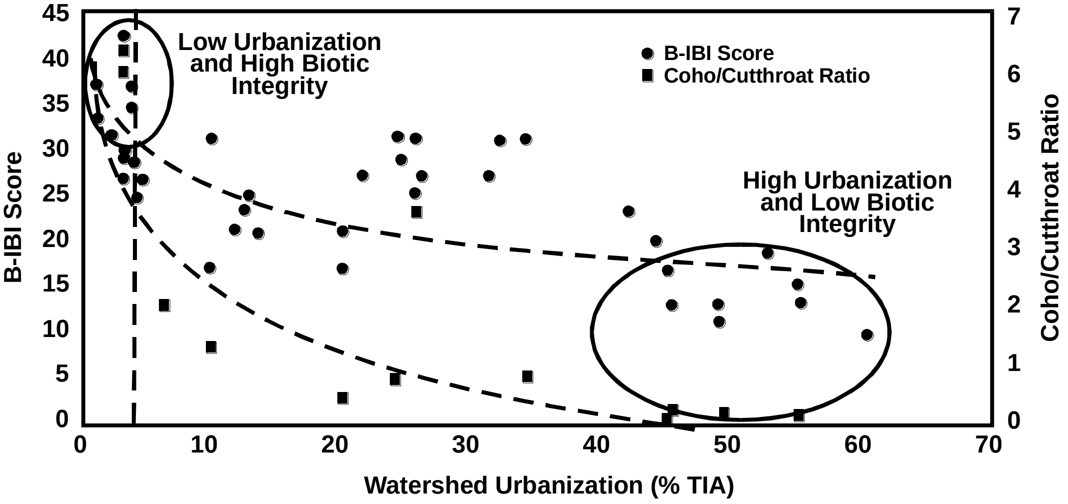

Figure 3. Relationship between Basin Development and Biologic Integrity in Puget Sound Lowland Streams (May et al., 1997)

Impacts of Urban Stormwater Runoff on Water Quality

Stormwater runoff and associated contaminants from developed areas have been identified as one of the leading threats to aquatic life supported by the Puget Sound ecosystem. Reducing surface water runoff pollutant loading and runoff from the built environment is a key priority action for the restoration of Puget Sound (Puget Sound Partnership 2010). Stormwater runoff from developed areas can contain pollutants that can contaminate surface, marine, and groundwaters (Ecology 2011a). The type of pollutant depends on the nature of activities in those areas as follows:

- **Roads**: Runoff from roads is typically contaminated with pollutants from vehicles. Oil, grease, polynuclear aromatic hydrocarbons (PAHs), lead, zinc, copper, cadmium, sediments (soil particles), associated nutrients, and road salts are all typical pollutants present in road runoff (Zawlocki et al. 1981, Mar et. al. 1982, Davis et al. 2001). Vehicles are the primary source of most of these pollutants. Most oil and grease come from vehicle leakage, while PAH's are primarily from vehicle exhaust. Lead is most commonly associated with wear of metallic parts, wheel balance weights (wearing and falling from wheels), and battery leakage due to car accidents. The primarily source of zinc is wear from tires, and copper primarily comes from brake pad wear. A highly toxic chemical (6PPD) associated with rubber tire residue is also associated with roadway runoff and may be linked to the acute mortality of adult migrating salmon (Tian et al 2020).
- **Commercial/Industrial areas**: Runoff from commercial and industrial areas typically can contain heavy metals, sediments, and a broad range of man-made organic pollutants including phthalates, PAHs, and other petroleum-based hydrocarbons (National Research Council 2009). Vehicles and pavement sealants are two common sources of pollutants from these areas. Other sources depend on the types of operations that are present on the property.
- **Residential areas**: Runoff from residential areas can include the same road-based pollutants outlined above, as well as herbicides, pesticides, surfactants, nutrients (from fertilizers), bacteria and viruses (from animal waste, Engstrom 2004), as well as sediment from dirt and gravel driveways. These contaminants can be entrained in stormwater runoff directly, or can reach downstream surface water bodies and marine environments via shallow groundwater flows. In addition, curtain and foundation drains often discharge to municipal systems and can contribute pollutants to surface water bodies. Zinc strips and other zinc based products are commonly used in residential areas to prevent and treat moss, and can add additional zinc to runoff from residential areas. Bleach and detergents are also commonly used for moss treatment. Most detergents contain phosphorus, which can contribute to eutrophication of surface water bodies (because productivity in fresh water bodies is typically phosphorus limited). Other pollutants from residential areas include insecticides, copper from copper roofs, zinc from composite roofs, and deicers.
- **Construction sites**: Runoff from construction sites can include sediments and other suspended material, which can increase turbidity or cloudiness in downstream receiving waters and can be deposited over the natural sediments of the receiving water and affect streams and wetlands (Barrett et al. 1995, Ecology 2014b, Horner et al. 2002a). The City has also given attention to concerns associated with construction demolition activities and the potential for heavy metals contamination and dust fall. Jacobs et al. (2013) found that "lead dust suppression is feasible and important in single-family housing demolition where distances between houses are smaller and community exposures are higher." Though they also indicate that additional research is needed to determine the likelihood of potential for stormwater contamination. Several agencies and groups provide guidance on control of pollution from demolition activities, including East Baltimore Development's 2006 *Operations Protocol for Salvage, Deconstruction, Demolition and Site Preparation Activities* (EBDI 2006).

Stormwater pollutants resulting from development can be dissolved in the water column or can be attached to particulates that settle in streambeds, lakes, wetlands, or marine estuaries. The toxic pollutants in the water column can have both immediate and long-term lethal impacts (Baldwin et al. 2003; Hansen et al. 2002). In addition, development can increase water temperatures by heating stormwater runoff as it passes over exposed surfaces, before being discharged to receiving waters (Foulquier et al. 2009). A rise in water temperature can have direct lethal effects on aquatic organisms by reducing the available dissolved oxygen and potentially causing algae blooms that further reduce water clarity and the amount of dissolved oxygen in the water (McCullough et al. 2001).

STORMWATER FLOW CONTROL AND WATER QUALITY TREATMENT

Overview

Stormwater runoff is widely recognized in the scientific literature as an agent for physical, chemical, and biological degradation (Booth et al. 2006), and stormwater research is an ongoing, evolving field of study. Consider, for example, how the best available science regarding flow control performance standards for stormwater discharges into creeks in western Washington has changed over the past three decades. Early flow control requirements were based solely on limiting the post-development *peak flow rates* to below a set value – a value independent of the pre-developed condition (King County 1979). Booth (1990) advocated a different post-development peak flow rate standard that was linked to a percentage of the pre-development peak flow rate. Soon thereafter, and as a result of research indicating that peak flow control alone was insufficient to mitigate stormwater impacts to creeks, a post-development flow control standard based on a pre-development *flow-duration standard* was proposed (Booth 1991). Less than 10 years later, additional research indicated that this proposed flow-duration standard was not achieving all the objectives for protecting creeks from channel incision and sediment transport, owing to overall disruption of the natural hydrologic regime (Booth and Jackson 1997). More recently, low impact development (LID) techniques have been promoted as the preferred means for managing urban stormwater runoff and mimicking pre-development flow regimes (Booth 2007, Horner 2007, Holz 2007, NRDC 2006, Ecology 2014b), with an emphasis on mitigating the impacts of small and less-frequent storm events. Thus, in the space of roughly 30 years of research and assessment, four different types of flow control requirements have been presented in the scientific and professional literature as representative of the best available science for urban runoff management for flow control for creek basins in western Washington alone.

The sections that follow provide a review of selected citations that address two critical aspects of urban stormwater runoff management: flow control and water quality treatment. Flow control is important to mitigate the impacts of urban development on changes in hydrologic regime in wetlands and creek basins. Water quality treatment focuses on 1) permanent/constructed stormwater treatment facilities designed to remove chemical contaminants from runoff, and 2) operational BMPs to reduce stormwater contamination and minimize the transport of sediment to receiving waters from construction sites and grading activities. Note that although specific constructed facilities described below are included under one of the two categories of flow control or water quality treatment, many facilities (such as those involving infiltration) often serve a dual role, providing both flow control and water quality treatment, depending on how these facilities are designed (Ecology 2014b, Ecology 2019b).

Flow Control

The following sections build on the information presented previously to elaborate on the aspects of stormwater runoff impacts and mitigation measures related to flow control. Information is discussed relating to wetland and creek protection, followed by an expanded discussion on low impact development (LID) and LID BMPs related to flow control.

Wetland Protection

The following information is derived from a report prepared by Sheldon et al. (2005), which provides a comprehensive summary and synthesis of the literature relevant to the science and management of wetlands in the state of Washington.

> *Urbanization is recognized as both increasing and decreasing the flows that reach down-gradient aquatic systems such as wetlands. Greater volumes of water are generated more quickly while smaller, long-duration flows that would occur under less developed conditions are reduced or perhaps eliminated. Research has shown that collecting stormwater through modern storm drains, culverts, and catchments results in the rapid transport of large volumes of stormwater runoff into rivers, lakes, and wetlands at much faster rates and higher volumes than under predevelopment conditions (Dunn and Leopold 1978, Booth 1991, May 1996). Although some of the research has focused on the effects of urbanization on streams, the findings on changes in flow volumes, rates, and frequency apply equally to wetlands that receive storm drainage. Streams and wetlands are "intimately interconnected in the watersheds of western Washington" (Booth 1991).*

Changes to hydrologic conditions can negatively impact the ecology of a wetland. Reinelt and Taylor (2000) used water level fluctuations as a primary factor in evaluating wetland hydroperiod. "Water level fluctuation is perhaps the best single indicator of wetland hydrology, because it integrates nearly all hydrologic factors." Increases in impervious surface coverage reduce infiltration, thereby reducing interflow (shallow, subsurface flow) and base flow, which may influence the hydroperiod of down-gradient wetlands if they are fed by that shallow subsurface flow. Similarly, reductions in watershed infiltration correspond to increases in surface water runoff, which also impact the hydroperiod of downstream wetlands. These increased water level fluctuations have been associated with declines in the biotic diversity of wetlands (Reinelt et al. 1998, Azous and Horner 2001). Likewise, although many hydric soils (i.e., wetland soils) may be anaerobic, changing the length of time the soils are inundated results in changes in wetland soil chemistry, which in turn can influence the survival of vegetation and microbes in the soil that were adapted to shorter periods of inundation (Thom et al. 2001). The wetland protection standards outlined in the MS4 Permit and SWMMWW aim to minimize these fluctuations in hydroperiod through control of the changes in the volume of stormwater runoff delivered to a wetland pre- and post-project development.

The *Washington State Wetland Rating System for Western Washington* (Hruby 2014) provided an updated wetland rating system to provide a more accurate rating of functions and values.

Flow Control in Creek Basins

As noted previously, a growing body of research confirms that urbanization alters the hydrologic regime (Dunne and Leopold 1978, Schueler 1987, Booth and Jackson 1997, Ecology 2014b). These alterations result in higher volumes of stormwater runoff, delivered at higher flow rates for longer durations than under pre-development conditions (Booth 1991, May 1996). Research by Konrad and Booth (2002) in the Puget Sound lowlands showed statistically significant correlations between urbanization in a watershed and altered creek hydrologic regimes. Even small changes in watershed imperviousness can have measurable influences on flows in a creek system (Azous and Horner 2001). Booth (1991) concluded that urbanization could cause peak flow rates to increase by up to five-fold for a given storm event. These altered hydrologic regimes adversely impact creek systems through channel erosion and incision (May 1996, May et al. 1997). These effects are spread across a wide range of storm event sizes, with smaller and more frequent events often having the greatest cumulative effect on creek morphology.

Stormwater flow control BMPs are designed to reduce the volume, flow rate, and timing of stormwater flows released from developed sites. Some facilities function by storing stormwater and controlling the release rates so that post-development hydrology more closely resembles pre-development hydrology. Other facilities use infiltration, evapotranspiration, and stormwater reuse in an attempt to better mimic natural hydrologic regimes.

Flow Control Performance Standards to Protect Creeks

The term *flow control performance standard* is used to represent the combination of flow rates, volumes, and durations that are allowed to be discharged from a site. Per the MS4 Permit, these standards must be met for projects that exceed certain regulatory thresholds, most generally based on the amount of new and replaced impervious surfaces, but which can also be dependent on the type of project, size of project, area disturbed, and the drainage basin in which the project is located. Flow control performance standards are intended to reduce the impacts of changes in hydrologic regime on creek systems caused by changes in land cover, impacts that can include: erosion, sedimentation, instability, flooding, and other damage to the streambank and riparian corridor.

The Stormwater Management Manual for the Puget Sound Basin (Ecology 1992) required the use of a single-rainfall-event hydrologic model to calculate pre-development and post-development runoff, and associated flow control performance standards. The following post-development peak flow rate conditions, based on selected storm statistics, were required if stormwater infiltration was not feasible on site:

- 100-year/24-hour storm – post-development peak flow rate could not exceed the pre-development peak flow rate
- 10-year/24-hour storm – post-development peak flow rate could not exceed the pre-development peak flow rate
- 2-year/24-hour storm – post-development peak flow rate could not exceed the 50 percent of pre-development peak flow rate.

The intent of the “50 percent of the pre-development peak flow rate” component of the standard was to prevent stream channel destabilization by controlling sediment transport, based on research by Sidle (1988) and Booth (1990). (The other two standards were focused more on flooding and property protection.) While this flow control approach provided more environmental protection than having no standards, it is now widely acknowledged to have some fundamental flaws in achieving its intent, among them:

- It assumed that flow statistics correlated to rainfall statistics. That is, the X-year peak flow was assumed to correlate to the X-year, 24-hour peak rainfall depth. The results of continuous simulation models, which use many years of rainfall data rather than individual 24-hour events, show that this assumption is not always valid.
- It assumed that controlling the peak flow from a storm (i.e., preventing the peak flow from exceeding some standard), would prevent channel instability. This is not true, since the peak flow standards do not address the increase in total runoff volume that occurs with urbanization, which translates into an increase in total time that elevated storm flow rates will work on the channel to transport sediment.
- It did not address alteration of the pre-development hydrologic regime related to total rainfall infiltration, evapotranspiration, and inter-storm runoff.

Booth (1991) discussed the shortcomings of single-event model and a peak flow detention standards, and proposed using a “flow duration control” standard. Rather than limiting only the peak flow rate, a flow duration control standard limits the total amount of time over a relatively long period (e.g., months) during which the flow rate could exceed selected flow rates of concern. Designing a project site to meet a flow duration control standard requires a continuous simulation hydrologic model.

Six years later, Booth and Jackson (1997) discussed the shortcomings of flow duration control standards. Among these is the premise that for all streams there is a flow rate below which no sediment transport occurs, and that a flow rate below this index rate would not cause channel incision regardless of the flow duration. Booth and Jackson (1997) state that “For gravel-bed stream channels, this threshold discharge is real and can be determined on a site-specific or generic basis. In sand-bedded channel, however, the threshold of sediment motion occurs at impracticably low discharges, and so increases in the net transport of bed material virtually unavoidable in such systems.”

In 1998, King County promulgated a stormwater technical manual and associated regulations that used flow duration control standards to mitigate impacts from stormwater flow, specifically intended to reduce impacts related to transport of sediment and stream channel erosion (Booth 1991, King County 1998). To implement this performance standard, King County developed a continuous modeling tool, the King County Runoff Time Series (KCRTS) program, which was based on the Hydrological Simulation Program-Fortran (HSPF) model developed by the US Geological Survey (USGS). Ecology followed suit in 2001, incorporating a flow duration control standard into the minimum requirements flow control contained in the Stormwater Management Manual (Ecology 2001) and the subsequent iterations of the SWMMWW (Ecology 2005, Ecology 2014b). Based in part on results of in-depth investigations performed by King County on the Juanita Creek watershed (O’Brien 2014), the 2014 version of the SWMMWW has reinforced the emphasis on both flow duration and small/frequent storm events by including an added *Low Impact Development Performance Standard* requiring that stormwater discharges match developed discharge durations to pre-developed durations for the range of pre-developed discharge rates from 8 percent of the 2-year peak flow to 50 percent of the 2-year peak flow. This captures an expanded range of storm events, including storms below (i.e., smaller and more frequent than) those targeted by the flow control duration standard in the previous (2005)

SWMMWW.

The recommended parameters were updated due to the smaller project sites typical within the City of Seattle. The parameters are within the range of possible values cited in *EPA Basins Technical Note 6 Estimating Hydrology and Hydraulic Parameter for HSPF* (EPA 2000). Reports also consulted includes *Characterization and Simulation of Rainfall-Runoff Relations for Headwater Basins in Western King and Snohomish Counties, Washington* (Dinicola 1990) and *Validation of a Numberical Modeling method for Simulating Rainfall-Runoff Relations for Headwater Basins in Western King and Snohomish Counties, Washington* (Dinicola 2001).

Low Impact Development, Green Stormwater Infrastructure, and Flow Control

The term *low impact development* (LID) refers to a range stormwater management measures that are intended to limit impacts of development on hydrologic regime. Ecology (2014a) defines LID as follows:

> *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, use of on-site natural features, site planning, and distributed stormwater management practices that are integrated into a project design.*

Green stormwater infrastructure (GSI) is the term Seattle generally uses to describe LID approaches in the city. Complicating things somewhat, Ecology uses the term *On-site Stormwater Management* as a "synonym" for LID in the MS4 Permit (Ecology 2014a) when referring to required LID management practices on development sites. As such, Seattle has decided to use the term on-site stormwater management in the 2016 Stormwater Code Update and 2021 Stormwater Code Update in reference to the suite of BMPs required to meet the applicable elements of the MS4 Permit. For clarity, general discussions in this document about LID/GSI approaches and benefits use the term LID or GSI. The term on-site stormwater management will only be used to refer to discussions specific to the MS4 Permit requirements and associated 2016 Stormwater Code Update.

As with LID, one of the key components of GSI in the City of Seattle is trying to replicate as much as feasible the natural hydrologic function by slowing and/or reducing the volume and rate of stormwater runoff through small, distributed runoff management controls and other best practices close to where precipitation lands. By meeting this objective, GSI reduces the capacity, flow, and volumetric demand on the City's stormwater and sanitary systems. GSI also helps provide resiliency and climate adaptation, as a long-term solution to managing the impacts of precipitation and stormwater runoff. According to the US EPA, as communities develop and climate patterns shift, existing stormwater conveyance and treatment infrastructure needs are expected to grow (US EPA 2014). While grey stormwater infrastructure is largely designed to move urban stormwater away from the built environment, GSI reduces (and often treats) stormwater runoff at or near its source (often while providing other environmental, social, and economic benefits).

Over roughly the past decade, an increasing body of literature has promoted LID as a preferred means for addressing urban stormwater runoff in the Puget Sound region (Booth 2007, Horner 2006, Horner 2007, and Holz 2007). Moreover, as part of the municipal appeals of the 2007 MS4 Permits, the Washington State Pollution Control Board (PCHB) concluded in the Phase I MS4

Permit decision that "…based on the great weight of testimony, reference documents, and technical manuals, that low impact development represents AKART [all known, available and reasonable methods of prevention, control and treatment] and is necessary to reduce pollutants in our state's waters to the maximum extent practicable, the federal standard…" (PCHB 2008). The Low Impact Development Technical Guidance Manual for Puget Sound (WSU and PSP 2012) – first published in 2005 and substantially updated in 2012 – contains extensive LID-specific information on site assessment; site planning and layout; vegetation and soil protection; reforestation; site preparation, construction, and inspection; and integrated management practices tailored to the Puget Sound region. It also contains information on hydrologic modeling for LID flow control measures. Much of this information is also contained in the updated version of Ecology's SWMMWW (Ecology 2019b). Ecology has also developed a guidance document focused on the unique operation and maintenance requirements of LID facilities (Ecology 2013a). Likewise, Seattle has been and remains at the forefront of GSI studies and implementation, and plays an integral role in defining and evaluating the best available science as it relates to LID and GSI in the region. In particular, the City has funded several recent studies focused on evaluating and monitoring bioretention facilities, as well as green roofs (Seattle 2014, WSU 2014, Seattle 2012a). Pertinent outcomes from these studies are discussed further in subsequent sections.

Nationwide, the emphasis on LID has been equally persistent and growing. Similar to the term LID and GSI, *green infrastructure* is the term used by US EPA to refer to the use of "vegetation, soils, and natural processes to manage water and create healthier urban environments. At the scale of a neighborhood or site, green infrastructure refers to stormwater management systems that mimic nature by soaking up and storing water" (US EPA 2015). (The definitions of LID, GSI, and green infrastructure are essentially the same, and used by various agencies and groups nationwide interchangeably.) The amount of literature, technical documentation, guidance manuals, design tools, monitoring information, and educational material focused on LID and green infrastructure is substantial. As such, it is beyond the scope of this document to catalog the full extent of LID resources that are available and the current state of the science for this rapidly evolving technology. Rather, the following sections summarize elements most pertinent to the 2016 Stormwater Code Update and 2021 Stormwater Code Update. Extensive additional information and resources on LID can be found at the US EPA's green infrastructure website: <water.epa.gov/infrastructure/greeninfrastructure> and Seattle's GSI website: <www.seattle.gov/util/EnvironmentConservation/Projects/GreenStormwaterInfrastructure/index.htm>. The Low Impact Development Technical Guidance Manual for Puget Sound (WSU and PSP 2012) is also one of the most current and comprehensive sources of additional detailed information and references related to LID in the Puget Sound region.

Applications of Green Stormwater Infrastructure

Green stormwater infrastructure can be an important component of stormwater management strategies, as they may be effective at reducing stormwater discharge volumes and rates of flow through infiltration, evapotranspiration, and capture and reuse. The following sections describe the common applications of GSI.

Creek systems. Proper implementation of GSI measures in creek systems has provided stream erosion protection and preservation, water quality treatment, and watershed habitat improvements (NRDC 2006, ASCE *In Press*). National data is supported locally. University of

Washington monitoring of creek watershed projects showed significant reductions of stormwater volumes, rates, and pollutant loads due in part to the use of GSI (Horner and Chapman 2007). In case studies in the City of Seattle, the 110th Street Cascade and SEA Street projects recorded a runoff volume reduction of 50-98 percent and a peak flow reduction of at least 60 percent. The 110th Street Cascade was monitored for 235 precipitation events, and 79 percent of these events produced no discharge from the bioretention facility (Horner and Chapman, 2007). Monitoring of a typical block of bioretention with underdrain at the High Point redevelopment (till soils) within the Longfellow Creek watershed (December 29, 2006 through September 30, 2007) concluded that the test bioretention cell “treated all runoff from storm events with precipitation totals below the 6-month, 24-hour and 2 year, 24-hour design storms for water quality treatment and flow control, respectively” (Herrera 2009a). The City continues to collect and monitor GSI performance.

CSO reduction. The flow control benefits that are observed in creek systems are also critical in combined sewer systems – with an emphasis on providing volume reduction in wet weather flow conditions to reduce combined sewer overflows (CSOs). In some situations, GSI can be used instead of, or in conjunction with, grey infrastructure depending on the costs and level of control required within a CSO basin. By preventing the rainfall runoff that is generated from impervious sites from quickly entering the piped conveyance system, GSI has been shown to reduce the volume of flow that is conveyed to the treatment plants, thereby reducing both CSOs and general treatment loads during storm events (Dearmont et al. 1998, NRDC 2006, US EPA 2012, ASCE *In Press*).

Local monitoring (September 2012 through April 2013) of a CSO reduction project in the Ballard neighborhood showed significant stormwater runoff volume reduction and delay. Bioretention cells without an underdrain functioned as well as or better than they were designed for by capturing and infiltrating events in excess of a 1-year recurrence interval (over 95 percent of the volume that would otherwise enter the combined system). Even a bioretention cell retrofitted with an underdrain also exceeded design expectations and was found to provide significant volume reduction (approximately 50 percent in 2012-2013, and up to 89 percent average annual volume loss in 2013-2014) during most storms with variability occurring depending on the season, storm patterns, and antecedent moisture conditions (Hutchinson and Atchison 2014).

National studies conducted in North Carolina and Maryland found that six different bioretention cells with underdrains each reduced runoff volume by 20-50 percent, in addition to delaying and reducing peak flows (Li et al. 2009). A modeling effort by the San Francisco Public Utilities Commission found that their 30-year plan for GSI implementation – including green roofs, street trees, bioretention, and permeable pavement – could reduce annual CSO amounts by 200-400 million gallons, equating to a 14-27 percent volume reduction in CSO events (US EPA 2014).

Pipe capacity/flooding. Benefits to other piped conveyance systems can also be realized through GSI implementation. Depending on the causes of piped capacity limitations for a particular system, GSI approaches may be used in conjunction with traditional grey infrastructure improvements and capacity management strategies to help reduce the rate of runoff delivered to piped conveyance systems. Locally, modeling of GSI within the Pipers Creek conveyance network found GSI facilities sized to achieve the City’s peak flow control goal (reducing the 2-year event to pre-developed pasture conditions) reduced the 10-year peak stormwater runoff rate by 36 percent and the 50-year peak rate by 15 percent (Scheller 2014). Nationally, the Milwaukee Metropolitan Sewerage District reported in their 2020 Facilities Plan that GSI could reduce the 100-year storm peak runoff rates by 22 percent, and the peak for smaller storms could be reduced even further (Sands and Chapman 2011).

Some municipalities have also observed a reduction in flood risk with the implementation of GSI (CNT 2013, US EPA 2014). A study in the southeastern United States found that although GSI does not have a large impact on flooding during very large events (e.g., a 100-year event), smaller events such as the 5-year event can be noticeably mitigated through the use of GSI (Medina et al. 2011). The study also found that targeting a GSI capture volume of 1.2 inches of rainfall, the cost of damage from a 5-year event was reduced from $13 million to $8 million average annualized loses.

Types of On-Site Stormwater Management Practices

The following on-site stormwater management BMPs are included in various requirements of the 2016 Stormwater Code Update and 2021 Stormwater Code Update. Note that all of the below facilities are already included in the existing Stormwater Code and are required as part of the City's MS4 Permit obligations (Ecology 2019a).

As mentioned previously (and referenced in this report), there is ongoing research and resultant technical information dedicated to the design, performance, and monitoring of LID facilities in order to ensure that the best available science is incorporated into local guidance and requirements. There have been dozens of ongoing LID monitoring and assessment projects in the Puget Sound region alone (notable results, where available, are discussed herein). Moreover, the PCHB decision referenced previously (PCHB 2008) clearly established LID as constituting AKART. Notably, soon after that decision, Ecology acted on the LID-based portions of the PCHB's decision by forming committees of LID experts from across the region to assist in developing LID portions of the next round of MS4 Permit requirements. Among other items, Ecology (with the assistance of these LID Committees) evaluated various site conditions and LID BMPs with the goal of establishing a system that derived the most benefit from a LID BMP. Focusing on the site and subdivision level, Ecology prepared a list of LID BMPs and sought input from the LID Committees on the question of which of the listed BMPs were AKART (O'Brien 2014). These discussions ultimately led to the on-site stormwater management requirements of the 2016 Stormwater Code and 2021 Stormwater Code Update.

As such, the intent of this section is not to document the absolute state of the science of on-site stormwater management BMP design and performance but to briefly highlight some of the region's history and science associated with those BMPs included in the 2016 Stormwater Code Update and 2021 Stormwater Code Update. For additional detailed information on any of the following BMPs, the Low Impact Development Technical Guidance Manual for Puget Sound (WSU and PSP 2012) is an excellent resource.

Last, in addition to flow control benefits, several of these BMPs also provide significant water quality treatment benefits. Therefore, information pertaining to both flow control and water quality treatment may be presented below, rather than repeating information about a given BMP in both the flow control and water quality treatment sections of this report.

Bioretention

The term *bioretention* is used to describe various designs using soil and plant complexes to manage stormwater runoff. The healthy soil structure and vegetation associated with bioretention facilities promote infiltration, storage, slow release, and treatment of stormwater runoff to more closely mimic natural conditions. In practice, bioretention facilities are also commonly referred to as “rain gardens.” (In the 2016 Stormwater Code Update and 2021 Stormwater Code, the terms bioretention and rain gardens have distinct differences that carry associated design and regulatory requirements for new and redevelopment projects specifically.) Bioretention can provide flow control via detention, attenuation, and losses due to infiltration, interception, and evapotranspiration. Treatment can be provided through sedimentation, filtration, adsorption, and phytoremediation. Early hydrologic performance of a bioinfiltration system in Maryland is discussed by Davis et al. (1998). Early design information was provided by Prince George’s County (1999 and 2002), with a multitude of agencies and groups (including Seattle) developing their own variations on bioretention design since that time.

In the late 1990s, the City constructed its first bioretention facility in a street right-of-way. The system consisted of a roadside swale filled with organically amended soil, in which a perforated drain was installed above the trench bottom so that some water would be retained before the drain was engaged. Water could also be held in the amended soil. The underlying soil was mostly glacial till but there was some sand as well. Approximately 2.3 acres of road and residential development drained to the swale. During the period between January 2000 and January 2001, the system retained all of the dry-season runoff and 98 percent of the wet-season runoff, and was capable of fully attenuating approximately 0.75 inches of rainfall on the catchment area (Horner et al. 2002b). Since that time, dozens of rain gardens and bioretention facilities have been installed on City and private property. Of the on-site stormwater management BMPs presented in the 2016 Stormwater Code Update, bioretention facilities probably receive the most attention in the Puget Sound region with regards to design variations and performance monitoring. The City has performed monitoring on several of these installations, most notably on two facilities from the Ballard Roadside Raingardens project (Seattle 2014). Monitoring of both facilities included continuous flow monitoring for one year, and controlled flow tests in the fall and spring. Monitoring of the bioretention facility on 30th Avenue NW showed that it more than met the design goal of removing the contributing area runoff for up to approximately a 1-year storm event, and that it captured all of the runoff for up to the 15-year storm event. It was also determined that the infiltration rates of the native soil at the 30th Avenue NW facility were higher than assumed during the facility design. The second bioretention facility monitored as part of the study was installed as part of one of the retrofitted blocks along 28th Avenue NW. After the original installation, the facility did not drain as designed and had to be retrofitted with an underdrain to meet the drawdown requirements. Monitoring was performed to determine what change in performance occurred due to the installation of the underdrain. The monitoring results demonstrated that significant flow control and volume reduction benefits were still provided by this system, even though it had an underdrain. The facility reduced peak flow rates by an average of 80 to 90 percent of approximately a 1-year storm event, and delayed discharge to the combined sewer system for 54 percent of the inflow volume. The facility also infiltrated the remaining 46 percent of the inflow volume, more than was originally expected for the retrofitted facility. The City is also tracking or involved in several regional bioretention studies. For example, Kitsap County et al. (2014) has been leading efforts to evaluate the performance of various compositions of bioretention soil media. Among other results, the studies have found that some (but not all) soil mixes may be leaching dissolved copper (Kitsap County et al. 2014). The studies are ongoing and are investigating which soil mixes are best for use in Washington State. As part of a closely related effort, the City is working with the Washington State University (WSU) LID research facility to evaluate the water quality treatment performance of the City Of Seattle bioretention soil media (BSM). The study (WSU 2014) consists of monitoring of four individual bioretention "mesocosms" (to provide replicate samples) built with the City of Seattle BSM. The study routed natural stormwater and synthetic stormwater (i.e., dosed influent) through the mesocosms and collecting samples of the effluent to evaluate water quality. The results were consistent with other studies around the region, showing higher percentages of pollutant removal with higher influent pollutant concentrations (typical of commercial, industrial areas), but evidence of export of some pollutants (e.g., TSS, dissolved copper, and phosphorus) with lower influent pollutant concentrations (more typical of residential areas). The export of TSS and dissolved copper appeared to decrease over time, but phosphorus release remained mostly steady during the course of the study. McIntyre et al. (In Press) also found bioretention facilities to be very effective at treating polluted runoff from roadway areas, with significant reductions in roadway runoff toxicity when the runoff is filtered through a bioretention facility.

Permeable pavement

Permeable pavement is a paving system which allows rainfall to percolate into an underlying aggregate storage reservoir, where stormwater is stored and infiltrated to the underlying subgrade or removed by a supplemental outlet/overflow system. The primary factors controlling the use of permeable pavement as an infiltration system are the long-term hydraulic capacity of the paving material, and the infiltration capacity of the underlying soil. Permeable pavement has been used for stormwater management worldwide for decades, though the technology has only gradually taken hold regionally. Booth and Leavitt (1999) documented the pollution removal capability and hydraulic performance of four types of permeable pavement in comparison to standard asphalt pavement at a municipal building parking lot in Renton, Washington. The test site was constructed in 1996 and data were gathered in the year following. The native soil at the site was deep and very permeable sand, such that overall infiltration capacity of the pavement/soil system was limited by the pavement. Booth and Leavitt observed no surface runoff from the permeable pavement. Brattebo and Booth (2003) reevaluated the hydraulic performance at the same pavement system during fifteen storms in the winter of 2001-2002. Virtually all water infiltrated for every observed storm; the most significant surface runoff event occurred during a 4.75-inch/72-hour storm, in which only 0.16 inches of surface runoff was generated from one type of pavement.

In the years since these early installations, permeable pavement (like bioretention) has become the focus of many additional design and performance studies. While the state of the science continues to evolve, some of the most significant findings can be found in the Low Impact Development Technical Guidance Manual for Puget Sound (WSU and PSP 2012).

Acceptable run-on ratios from several other juridictions' stormwater guidance manuals were reviewed, including from the City of San Francisco, CA; City of San Antonio, TX; City of Vancouver, BC; City of Portland, OR; City of Gresham, OR; City of Omaha, NE, City of Denver, CO and City of Tacoma, WA as well as *Permeable Pavement* (ASCE 2015).

Rainwater Harvesting

Rainwater harvesting is the capture and storage of rainwater for subsequent use. Runoff from non-pollution generating surfaces may be routed to cisterns for storage and beneficial nonpotable uses, such as irrigation, toilet flushing, and cold water laundry. Like other flow control BMPs, rainwater harvesting can be used to achieve reductions in peak flows, flow durations, and runoff volumes, and can be a particularly effective practice for projects where infiltration is not permitted or desired. The flow control performance of rainwater harvesting is a function of contributing area, storage volume, and rainwater use rate. While the City accepts rainwater harvesting systems with indoor water use for compliance with the flow control standards of the 2021 Stormwater Code, the indoor use of harvested water is regulated by WAC 51-56-1628.4.

Rainwater harvesting has been around for centuries, and (unlike bioretention and permeable pavement for example) is not subject to as frequent or numerous research studies. Depending on whether the design is for potable or non-potable uses, additional information can be obtained from various engineering or Department of Health documentation. For information most pertinent to the Puget Sound region, consult the Low Impact Development Technical Guidance Manual for Puget Sound (WSU and PSP 2012).

A technical memorandum (Herrera 2020) was prepared to evaluate allowing Rainwater Harvesting for Single-Family Residential and Parcel-based projects under Category 2 and 4 of the On-site list. Rainwater Harvesting is allowed under Category 2 if it is sized to meet the On-site performance criteria, similar to other Category 2 BMPs. The memorandum discusses the performance criteria that were evaluated for it to be used as a Category 4 BMP before settling on the criteria that Rainwater Harvesting must reduce the rooftop runoff volume by 25 perfect on an average annual basis and that the volume reduction must exceed that for a Vegetated Roof.

Vegetated Roofs

Vegetated roofs are areas of living vegetation installed on top of buildings, or other above grade impervious surfaces. Vegetated roofs are also known as ecoroofs, green roofs, and roof gardens. Used in Europe for decades, vegetated roofs have received significant attention in the US in the past decade or so as the focus on LID approaches (and green building in general) has increased.

As such, similar to bioretention and permeable pavement, extensive research has been dedicated to the design and performance of vegetated roof systems regionally, and nationwide, particularly over the past decade. For example, in one of the preliminary studies in Philadelphia, runoff monitoring was conducted for a nine-month period at a pilot-scale vegetated roof with a thickness of less than three inches (US EPA 2000). In this period there were 44 inches of rain and less than 16 inches of runoff. Similarly, in Portland, Oregon, monitoring of four storms (two in March 2001, and two in August 2001) at a full-scale commercial building vegetated roof showed between a three-fold and nine-fold reduction in per-storm runoff volume (Portland 2001). More recently, the City of Seattle has performed in-depth vegetated roof monitoring through a dedicated Green Roof Performance Study (Seattle 2012a). The study evaluated a range of vegetated roofing designs over five different site locations. Results indicated a reduction peak flow rates (relative to conventional roofs) ranging from 53 percent to 15 percent. The percentage reductions in rainfall volume ranged from near zero during the wetter seasons, but as high as 70 percent or greater during the dryer seasons.

Trees

Trees provide stormwater flow control via interception, transpiration, and increased infiltration. Additional environmental benefits include improved air quality, reduced heat island effect, pollutant removal, and habitat preservation or formation, although benefits can vary with seasonality (Xiao et al. 1998). Trees are a landscape amenity with flow control benefits that can be applied in most settings. The 2016 Stormwater Code Update and 2021 Stormwater Code Update includes flow control credits for retaining or planting trees on a development site, with higher credit applied when trees are proximate to impervious surfaces. The degree of flow control provided by a tree depends on the tree type (i.e., evergreen or deciduous), canopy area, and proximity to impervious surfaces. A report summarizing the results of a literature review on the effects of trees on stormwater runoff and recommendations regarding flow control credits is provided in Herrera (2008).

Dispersion

Downspout dispersion BMPs are splash blocks or gravel-filled trenches that serve to spread roof runoff over vegetated pervious areas. Dispersion attenuates peak flows by slowing entry of the runoff into the conveyance system, allows for some infiltration, and provides some water quality benefits. Although downspout dispersion in general has been used in Seattle for decades, to meet the specific design requirements of the MS4 Permit, downspout dispersion BMPs generally require large areas of vegetated ground cover and may not be feasible in most urban settings. Likewise, little performance monitoring data have been generated specific to downspout dispersion BMP performance, particularly in urban settings. Nonetheless, downspout dispersion is included as one of Ecology’s required on-site stormwater management BMPs, so it is included in this discussion.

Infiltration

Infiltration, where appropriate, is the City’s preferred method for stormwater management because it most directly attempts to restore the pre-development flow regime. Many on-site stormwater management BMPs discussed previously use infiltration as a primary or secondary mode of stormwater control. In addition, several types of non-vegetated systems are designed primarily for stormwater infiltration including infiltration trenches, vaults, basins, or drain fields. Given the significant role of infiltration processes in LID, on-site stormwater management, and stormwater flow control in general, this subsection presents a brief overview of infiltration considerations.

Massman (2003) performed full-scale “flood tests” conducted at four infiltration facilities in western Washington. Lateral flow along the sides of the ponds could be significant. Saturated hydraulic conductivity values estimated from measuring air conductivity and from regression equations derived from grain size parameters were compared to full-scale infiltration rates for 15 sites in western Washington. The estimated values for saturated hydraulic conductivity were up to two orders-of-magnitude larger than the full-scale infiltration rates for some sites and were two orders-of-magnitude smaller at others. These results show that long-term infiltration rates cannot be reliably estimated on the basis of soil properties alone; information related to the hydraulic gradient is also important.

Aside from the reduced area available for infiltration due to the construction of impervious surfaces, development typically results in the compaction or removal of the upper soil layers, which reduces the overall infiltration capacity of the remaining soil (Booth et al. 2002, Chollak and Rosenfeld 1997, Kosti et al. 1995). This effect also significantly reduces the ability of the soil to remove dissolved metals (Minton 2005). Other factors that may limit the long-term performance of these systems are clogging due to sediment input, or biological fouling, as described by Warner et al. (1994).

Given the significant role of infiltration in stormwater management, and the relative complexity of soil and general geologic conditions in Washington, Ecology has dedicated extensive time and energy to understanding and safeguarding infiltration facility designs. The 2014 SWMMWW (Ecology 2014b) includes extensive detail on the requirements for evaluating project area soil conditions and infiltration potential prior to designing and installing infiltration facilities. Seattle has generally followed these requirements, with modification as needed to accommodate local conditions and challenges. Due to the geologic and topographic conditions in Seattle, not all sites are suitable for stormwater infiltration. The City may limit the use of infiltration practices in some areas due to topography and potential landslide hazards. In addition, many locations in Seattle have soils that are underlain by hydraulically-restrictive materials. These relatively impervious layers may limit or preclude infiltration causing perched groundwater conditions during the wet season.

A memorandum *Recommendations for Infiltration Acceptance Testing During Construction for Select Infiltration BMPs* (Gibson and Martin 2018) provided information that informed the development of the infiltration acceptance testing guidelines. Studies related to modeling for hydraulic conductivity near saturation were reviewed (van Genuchten 1980, Schaap and van Genuchten 2005).Soil Amendment

Naturally occurring (i.e., undisturbed) soil and vegetation provide important stormwater management functions, including: water infiltration; nutrient, sediment, and pollutant adsorption; sediment and pollutant biofiltration; water interflow storage and transmission; and pollutant decomposition. These soils can also provide indirect benefit by providing a suitable growing medium for healthy plants and microbes, which themselves also provide important stormwater benefits. All of these functions are largely lost when development removes native soil and vegetation and replaces it with imported soil and sod with minimal depth. Not only are important stormwater management functions lost, but such altered landscapes themselves can easily become pollution-generating pervious surfaces. Pollutants can include pesticides, fertilizers, and other landscaping and household/industrial chemicals; pet wastes; and roadside litter.

Studies by Chollak and Rosenfeld (1997) developed guidelines for amending soils with compost in landscaping practices. Kosti et al. (1995) measured surface runoff and subsurface runoff from seven test plots of glacial till soil containing differing amounts of compost. During storm events from December 1994 to June 1995, two plots containing compost generated only 53 percent and 70 percent of the total runoff volume generated by a control plot with no compost. In addition to flow control benefits, amended soils in urban lawns can also have the benefits of reduced fertilizer requirements and reduced dry-season irrigation requirements (US EPA 1997). The MS4 Permit includes requirements for using soil amendment for disturbed areas, and the 2014 SWMMWW and a supplemental document produced by Soils for Salmon (Guidelines and Resources for Implementing Soil Quality and Depth BMP T5.13 in WDOE Stormwater Management Manual for Western Washington, Soils for Salmon 2012) include the latest guidelines for soil amendment in western Washington.

Sidewalk/Trail Compost-Amended Strips

Sidewalk/Trail Compost-Amended Strip is a new BMP focused on managing sheet flow from sidewalk and trail surfaces (Seattle Public Utilities 2020).

Water Quality Treatment

Urban stormwater runoff collects and conveys pollutants to receiving waters. Between 1978 and 1983, the Nationwide Urban Runoff Program gathered runoff pollution data from 2,300 storms from 28 project sites across the nation (US EPA 1983). The results from this large-scale study helped to initially quantify the nature and extent of stormwater pollution and influenced subsequent regulations requiring treatment of stormwater runoff from sites with pollution generating surfaces. Ongoing monitoring, analysis, and assessments have provided additional information regarding the nature of pollutants in stormwater. Chandler (1995, 1999) conducted an analysis of urban stormwater runoff event mean concentrations from 70 sites collected by eleven municipalities located in inland urban areas of western Washington and Oregon. Maestre and Pitt (2005) developed a database containing approximately 3,765 events from 360 sites in 65 communities throughout the US. Clark et al. (2007) provide a comprehensive literature review of urban wet weather flow literature for the eleven years from 1996 through 2006 that includes stormwater discharge water quality characterization.

Recent assessments of toxic contaminant in Washington State determined that the bulk of toxic chemicals that enter Puget Sound marine waters have done so through runoff from land surfaces (Ecology 2007b, Ecology 2011a, Ecology 2014c, Ecology 2015). Of particular note, during 2010, Ecology conducted a study to identify the primary sources of toxic chemicals in the Puget Sound basin and estimate annual releases of those chemicals (Ecology 2011a). Fourteen chemicals and chemical groups of concern were addressed, and the quantities of chemicals released annually from numerous sources were estimated. The study identified petroleum and zinc as two of the most significant chemicals of concern, with both chemicals released at a rate greater than 1,000 metric tons (t) per year. Lead, polycyclic aromatic hydrocarbons (PAHs), copper, and triclopyr were identified as additional chemicals of concern, released at rates greater than 100 t/year (ibid). Similarly, as part of the previous MS4 Permit requirements, stormwater and storm sediment discharge data were collected by Phase I MS4 permittees between 2007 and 2013 (Ecology 2015). The permittees collected storm-event data under a prescribed monitoring program that represented multiple land uses, storm characteristics, and seasons. Working from the combined analysis of 44,800 data records representing 597 storm events, up to 85 parameters were analyzed in the stormwater samples. Results indicated that metals, hydrocarbons, phthalates, total nitrogen and phosphorus, pentachlorophenol, and PCBs were detected more frequently and at higher concentrations from commercial and industrial areas than from residential areas. Residential areas exported stormwater with the highest dissolved nutrient concentrations (Ecology 2015).

Ecology also recently determined that artificial turf fields are to be considered a pollution generating pervious surface in western Washington (Ecology 2014a). Ecology indicated that their decision to list artificial turf fields as pollution generating was based primarily on two studies identified by King County (personal communication Rachel McCrea, July 2013). Those studies (Connecticut DEP 2010, Moretto 2007) suggest that dissolved metals and organics could

leach from the underflow from these types of artificial turf fields. However, further review of those studies and supplemental analyses of turf fields (Herrera 2010) raises questions about the pollutant generating potential of those surfaces. An additional study (Herrera 2019) found that drainage from crumb rubber infill playfields yields high water quality that does not need treatment prior to discharging into a surface water body, regardless of whether it is a new crumb rubber field or an old crumb rubber field. However, the study did not evaluate the recently discovered toxicant found in tires, 6PPD-quinone (Tian et al 2020). Additionally, as part of the study (Herrera 2019), it was determined that poor water quality of drainage from the tested cork infill playfield was likely due to contamination. Additional testing of drainage exclusively from a cork playfield with new base materials would be needed to accurately characterize pollutant concentrations and determine treatment requirements.
Additional information on BMPs designed to reduce water quality pollution from permanent and temporary (construction) sites is discussed below.

Types of Stormwater Quality Treatment Best Management Practices

Pollutants in stormwater can be reduced through source control activities, regulations prohibiting certain types of discharges, programmatic actions aimed at eliminating illegal dumping and illicit connections, and permanent water quality treatment BMPs designed to remove pollutants contained in stormwater runoff (Ecology 2014b, Ecology 2006, Ecology 2014a). This section focuses on permanent (constructed) water quality treatment BMPs, with a brief discussion at the end of this section on developments in pollutant source control related to street sweeping activities.

Common pollutants of concern targeted by water quality treatment BMPs include sand, silt, and other suspended solids; metals such as copper, lead, and zinc; nutrients (e.g., nitrogen and phosphorous); certain bacteria and viruses; and organics such as petroleum hydrocarbons and pesticides. Methods of pollutant removal include sedimentation/settling, filtration, plant uptake, ion exchange, adsorption, and bacterial decomposition. Floatable pollutants such as oil, debris, and scum can be removed with separator structures. Minton (2002, 2005) provides a thorough discussion of treatment mechanisms and their application in stormwater treatment. The American Society of Civil Engineers (ASCE) and the United States Environmental Protection Agency jointly prepared (and continue to manage) an extensive "International Stormwater BMP Database" of stormwater treatment system performance data (ASCE/US EPA 1996). The International Stormwater BMP Database is a primary resource for further information on the water quality treatment BMPs discussed below (<www.bmpdatabase.org>).

Infiltration and Bioinfiltration

Infiltration not only provides the flow control benefits discussed previously, but also can be a very effective pollutant removal mechanism. Infiltration and bio-infiltration systems remove pollutants primarily via physical filtration as stormwater passes through the underlying soil, but also via chemical adsorption and precipitation reactions. Biological uptake by plants may also occur in bioinfiltration. In addition, some pollutants such as nutrients may also be utilized by microbes present in the soil. A wide range of vegetated and non-vegetated BMPs utilize infiltration as a portion of their treatment designs. Following is a brief summary of a subset of the extensive infiltration performance studies available. The International Stormwater BMP Database contains extensive additional information for individual BMP types (ASCE/US EPA

1996).

A study of several stormwater infiltration system designs in Pierce County, Washington, showed that infiltration of stormwater through a biofiltration swale underlain by six inches of imported topsoil reduced total copper concentrations by 47 percent, total lead concentrations by 79 percent, and total zinc concentration by 50 percent (Tacoma-Pierce County Health Department/Pierce County Public Works Department 1995). Nineteen storm events were monitored over four years in the study. In contrast to these results, the study also found elevated concentrations of these metals in groundwater under infiltration systems that discharged directly to the gravelly native soils without any other treatment. These results together demonstrate the importance of properly absorptive soil or treatment medium, but also the efficacy of a relatively shallow layer of such soil in removing metals. Hathhorn and Yonge (1996) investigated the potential for groundwater pollution from stormwater infiltration systems using bench-scale systems containing soils found in Washington State and organic soil amendments. They found that copper and zinc tended to be removed by association with organic material, while adsorption onto soil minerals due to cation exchange was the dominant removal mechanism for cadmium and lead. Extensive reviews of the potential for and confirmation of groundwater contamination are provided in Minton (2002) and Pitt (1996).

As referenced previously regarding permeable pavement flow control performance, Booth and Leavitt (1999) also documented the pollution removal capability of infiltration below four types of commercially available permeable pavement systems in comparison to standard asphalt pavement at a municipal building parking lot in Renton, Washington. Total copper and total zinc concentrations in the sampled infiltrate were significantly lower than corresponding concentrations in runoff from the asphalt. Motor oil was detected in 89 percent of the samples from the asphalt runoff, but not in any water sample infiltrated through the permeable pavement. Brattebo and Booth (2003) reevaluated pollution removal at the same pavement system during nine storms in the winter of 2001-2002. Again, infiltration had a dramatic effect on water quality. Toxic concentrations of copper and zinc were present in 97 percent of the asphalt runoff samples, and in 14 percent of the infiltrate samples. A comparison of the data from the two studies showed that zinc concentrations increased with statistical significance in the later study for both permeable pavement and asphalt, whereas copper concentrations in infiltrate from two kinds of permeable pavement were significantly decreased in the later study (Brattebo and Booth 2003). While Ecology does not currently give water quality treatment credit for stormwater passing through a standard permeable pavement design (i.e., additional treatment design elements must be incorporated into the subgrade material), this and other research has shown that permeable pavement has considerable pollutant removal capabilities for common roadway pollutants such as metals and petroleum (Dierkes et al. 2001, Pratt et al. 1999, Clauson and Gilbert 2003).

Though infiltration can be a very reliable water quality treatment approach, the design and construction must also be carefully scrutinized to ensure appropriate water quality treatment is achieved and maintained. Studies of conventional infiltration trenches in Maryland indicate that up to half of newly constructed (5-years old or less) facilities failed to operate as designed do to clogging or inflow problems (Galli 1992). The study found that lifespan can be increased by proper design of pretreatment systems, use of a sand layer rather than filter fabric at the bottom of the trench, and rototilling the trench bottom to preserve infiltration rates. Other studies in the mid-Atlantic region indicate that infiltration basins also have high failure rates within five years of construction due to clogging (Maryland Department of Environment 1991, Maryland

Department of Environment 1986). Facility performance can be increased by constructing facilities with adequate pretreatment, shallow water depths, bypass systems for large storms, careful geotechnical investigations, sand surfacing for the trench bottom, and installation of underdrains (Schueler 1994).

As was noted previously, of the on-site stormwater management BMPs presented in the 2016 Stormwater Code Update, bioretention facilities probably receive the most attention with regards to design variations and performance monitoring. Bioretention BMPs have been demonstrated to provide considerable reduction in stormwater pollutants through infiltration and bioinfiltration, though there have been concerns with the impacts of various imported bioretention soil mixes and the effect they have on pollutant removal and or release from these BMPs, particularly dissolved metals (Ecology 2013b, Kitsap County et al. 2014, WSU 2014). Several recent and ongoing studies have been designed to evaluate and optimize the pollutant removal effectiveness of bioretention facilities, and the City is actively involved in those studies and/or tracking the outcomes as they become available.

Sand Filtration

Sand filtration is a water treatment technology that has been applied to stormwater for decades. A typical sand filtration facility consists of a pretreatment system, flow spreaders, a sand bed, and underdrain piping (Ecology 2014b). A sand filter vault is similar to an open sand filter except that the sand layer and underdrains are installed below-grade in a vault that consists of presettling and sand filtration cells. A linear sand filter is a long, shallow, two-celled and rectangular vault, with the first cell designed for settling coarse particles and the second cell containing the sand bed (Ecology 2014b). Useful references regarding sand filtration include: Austin (1990), Horner and Horner (1995), Bell et al. (1995), California Department of Transportation (2004), and Minton (2005). These studies show that sand filters can be designed to remove total suspended solids (TSS), metals, biochemical oxygen demand (BOD), petroleum, total nitrogen, and phosphorous.

Minton (2002) cites various studies showing the pollution removal effectiveness of sand coated with iron oxide and sand mixed with iron wool or calcitic lime. Wanielista and Cassagnol (1981) demonstrated that various amended sand media reduced BOD and TSS concentrations in detention pond effluent, and that some nitrogen removal took place in the filters as well. Stormwater filtration using peat mixed with sand is effective at removing metals (Clark et al. 1998). Severe clogging in a sapric peat/sand filter in Minnesota demonstrated the importance of using hemic or fibric peat (Tomasek et al. 1987). These hydraulic problems can be avoided by using commercially available peat pellets.

Basic sand filters are expected to achieve average pollutant removals of 80 percent TSS at influent Event Mean Concentrations of 300 mg/L (King County 1998, Chang 2000). Basic sand filters are also expected to reduce oil and grease to below 10 mg/L daily average and 15 mg/L at any time, with no ongoing or recurring visible sheen in the discharge (Ecology 2014b). Large sand filters are expected to remove at least 50 percent of the total phosphorous compounds (as total phosphorus) by collecting and treating 95 percent of the runoff volume (ASCE and WEF 1998). Pretreatment is necessary to reduce velocities to the sand filter and remove debris, floatables, large particulate matter, and oils. An underground filter should be considered in areas subject to freezing conditions (Urbonas 1999).

Wetpool Facilities – Wet ponds, Wet vaults, Combined Detention and Wetpool Facilities

Water quality facilities built as wetpool facilities – facilities that contain a permanent pool of water – include wet ponds, wet vaults, and combined detention and wetpool facilities. The primary design factor that determines a wetpool's treatment efficiency is the volume of the wetpool. The larger the wetpool volume, the greater the potential for pollutant removal (Ecology 2014b). These facilities provide runoff treatment by allowing settling of particulates during quiescent conditions (sedimentation) and, for above-ground facilities, by biological uptake and vegetative filtration. A wet pond is a constructed stormwater pond that retains a permanent pool of water at least during the wet season. A wet vault is an underground structure similar in appearance to a detention vault, except that a wet vault has a permanent pool of water that dissipates energy and improves the settling of particulate pollutants. A combined detention and wetpool facility has the appearance and design features of a detention facility, but contains a permanent pool of water to also perform water quality treatment functions. Because the wet vault is underground, it lacks any biological pollutant removal mechanisms, such as algae uptake, that would be present in surface wet ponds.

Studies of pollution removal in wetpool facilities in the Puget Sound region include King County (1995), Comings (1998), and Kulzer (1989). Other useful studies include Driscoll (1986), Gain (1996), Kantrowitz and Woodham (1995), Lawrence et al. (1996), Stanley (1996), Walker (1987), Whipple (1979), and Wu et al. (1996). These studies show that wetpool facilities can remove total suspended solids, total nitrogen, metals, and phosphorous. However, some of the studies showed a net release of some of these pollutants. Wetpools can also remove dissolved pollutants, although their long-term performance in this respect is problematic particularly with respect to dissolved phosphorus (Minton 2004, 2005). Minton (2002) discusses the difficulties in designing appropriate sampling strategies to comparing data from different treatment system evaluation studies. Wetpool facilities can pose a particular problem since they often have a storage volume greater than the influent volume from many storms, so samples of influent and effluent from a single storm do not represent batch treatment of a single test volume of water. A detailed discussion of performance and design elements on wetpool facilities is provided by Minton (2005).

A Florida study of the migration of soluble metals through sediments accumulated in the bottom of highway-runoff wet ponds showed that most of the metals are retained in the top 15-25 centimeters, and that removal of accumulated bottom sediments approximately every 25 years would be sufficient to minimize the potential of groundwater contamination (Yousef and Yu 1992). However, this study did not indicate the native soil type or sediment size distribution, which would affect the results. Most modern wet ponds are designed with an impermeable base layer to prevent any infiltration of stormwater through the bottom sediments.

Stormwater Treatment Wetlands

Water quality treatment in wetlands is achieved through sedimentation, filtration, soil adsorption, chemical precipitation, biological uptake by plants, and microbial transformation of nutrients. Wetland hydroperiod is the primary driver of these processes because hydrology is the most important factor for sustaining wetland processes and plant communities (Mitsch and Gosselink 1986). Hydroperiod of a wetland includes the water depth, flow, and duration and frequency of flooding. The hydroperiod affects species composition and richness, primary productivity, organic accumulation, and nutrient cycling.

Wetlands constructed for water quality treatment generally provide high quality treatment similar to the effectiveness of bioretention and infiltration, however with a lower risks of impact to groundwater quality. Although stormwater treatment wetlands typically require large amounts of surface area and are not common in urban areas. Constructed stormwater treatment wetland designs that incorporate long residence times and low velocities are typically the most effective at treating stormwater. Kadlec and Knight (1996) give the following expected pollutant removal performance (listed with constituent concentration) for parking lot runoff treated by constructed stormwater treatment wetlands:

- TSS: 88 – 98 percent (2-10 mg/L)
- Fecal coliform: 60-90 percent (20-500 colonies/100 mL)
- Total zinc: 25 to 95 percent
- Total phosphorus: 89-95 percent (0.02-0.05 mg/L).

The processes that occur in wetlands make them particularly capable of significant metals removal (Kadlec and Knight 1996). These metals removal processes include:

- Binding to soils, sediment, particulates, and soluble organics
- Precipitation as insoluble salts, principally sulfides and oxyhydroxides
- Uptake by plants, including algae and bacteria.

Wetland studies indicate that stormwater treatment wetlands are effective at removing between 21 percent and 95 percent of copper (by mass), with a median of 73 percent for all studies (Feijtel et al. 1989, Hendry et al. 1979, Schiffer 1989, Harper et al. 1986, Sinicrope et al. 1992, Noller et al. 1994, Gladden et al. 2002, Walker and Hurl 2002). Similarly, these studies also show wetlands can be very effective at removal of zinc, with documented removal rates of 33 percent to 96 percent (by mass), with a median of 79 percent for all studies.

Hydrocarbons in wetlands are removed through volatilization, photochemical oxidation, sedimentation, sorption, and biological (microbial) degradation (Kadlec and Knight 1996). Most studies on hydrocarbon removal focused on biological and chemical oxygen demand for municipal waste, but studies do indicate that wetlands are also effective for hydrocarbon removal (Litchfield and Schatz 1989, Litchfield 1993, Tang and Lu 1993, Knight et al. 1994, Fountalakis et al. 2009, Terzakis et al. 2008). Nonetheless, specific values are not presented in this report because of limited applicability to stormwater runoff.

Media Filtration

Media filtration systems typically consist of a vault or catch basin housing a material through which stormwater passed. The performance of a media filtration facility depends on many factors, including the type of media (e.g., diatomaceous earth, leaf compost, perlite, sand, Zeolite, etc.) and the physical properties of the granular media, including size, size distribution, sphericity, porosity, density, and hardness (Minton 2005). Leif (1999) and CSF Treatment Systems (1994) demonstrated that filtration using mature processed leaf compost effectively removed TSS and total metals. Phosphorous concentrations were higher in the effluent than in the influent in the tests by Leif (1999), probably due to degradation of vegetative material washed onto the filter and bird manure deposited on the filter bed. Since compost serves as a cation exchange medium, one would expect metals removal by adsorption, but not removal of phosphorous or nitrate, which are anions. Minton (2002) cited various studies showing the effectiveness of zeolite minerals as a filtration medium to remove metals by cation exchange and phosphorous by anion exchange in cases where the zeolites were amended to improve anion exchange capability. Minton (*ibid.*) also cited the studies on the use of activated alumina, cationic and anionic polymers, synthetic resins, and other media.

There are several proprietary cartridge-based media filters that have been approved for various levels of treatment in Washington by Ecology (see also the Proprietary and Emerging Technologies section below). These systems typically utilize a proprietary media to achieve targeted water quality treatment results. The list of available and approved technologies changes regularly, so designers are encouraged to visit Ecology's emerging technologies website for current information: <www.ecy.wa.gov/programs/wq/stormwater/newtech/technologies.html>.

Ecology's SWMMWW (2014b) also provides guidance for design and construction of media filter drains (previously known as ecology embankments). The media filter drain consists of a roadside embankment constructed with a wedge of media (aggregate, perlite, dolomite, and gypsum) that dispersed runoff must pass through before entering an underdrain system. Studies conducted by the Washington State Department of Transportation (WSDOT) indicated that media filter drains can remove greater than 80 percent of influent TSS, greater than 50 percent of total phosphorus, and approximately 50 percent of dissolved copper and zinc (Herrera 2006, Herrera 2009b).

Biofiltration Swales

Basic biofiltration swales typically have a trapezoidal or parabolic shaped cross-section and are commonly designed to be an in-line treatment facility. These facilities are designed to remove low concentrations of pollutants such as TSS, heavy metals, nutrients, and petroleum hydrocarbons (Ecology 2014b). A wet biofiltration swale is a variation of a basic biofiltration swale and used where the longitudinal slope is slight, water tables are high, or continuous low base flow is likely to result in saturated soil conditions. Vegetation specifically adapted to saturated soil conditions is needed, which in turn requires modification of several of the design parameters for the basic biofiltration swale (Ecology 2014b). A continuous inflow biofiltration swale is used in situations where water enters a biofiltration swale continuously along the side slope rather than discretely at the head. This type of facility requires an increased swale length to achieve an equivalent average residence time (*ibid.*).

The performance of biofiltration swales is highly variable (Ecology 2014b, Minton 2005). Local biofiltration studies include Goldberg et al. (1993), King County (1995), and Horner (1988). These studies generally showed that TSS and total metals are removed in biofiltration swales, with phosphorous removal possible to a more variable degree. Field inspection of thirty-nine biofiltration swales in King County found only nine to be in "good" condition; that is, having relatively complete and uniform vegetation cover (King County 1995). While unvegetated systems that contain standing water may remove pollutants through settling under low flow conditions, sediment would likely be resuspended in these systems during higher flows (*ibid.*). Flow-through grass swales function as treatment devices if vegetation remains sufficiently erect to reduce the shear stresses in the channel, thereby reducing its capacity to carry sediment (Carollo et al. 2002).

Non-Infiltrating Bioretention

Typical minimum non-infiltration bioretention planter box widths were reviewed from other jurisdictions in the Pacific Northwest (Clean Water Services 2016, Gresham 2007).

Filter Strips

Filter strips are vegetated treatment systems (typically grass) which are designed to remove low concentrations and quantities of total suspended solids (TSS), heavy metals, petroleum hydrocarbons, and/or nutrients from stormwater by means of sedimentation, filtration, soil sorption, and/or plant uptake. They are typically configured as linear strips that receive dispersed sheet flow from roads or other surfaces. Contaminated stormwater is distributed as sheet flow across the inlet width (Ecology 2014b).

Newberry and Yonge (1996) found that a vegetated strip removed significant amounts of TSS and metals from simulated stormwater. WSDOT developed a compost amended vegetated filter strip (CAVFS) and found that the system infiltrated more water than a standard roadside embankment. However, the effluent concentrations were not lower in the CAVFS system compared with the unimproved control (Herrera 2009c). In a separate study, WSDOT monitored the performance of unimproved filter strips along Interstate 5 (Herrera 2009d). They found that even 42-year old embankments that were not designed for stormwater treatment removed 94, 83, and 71 percent of influent TSS, total zinc, and total copper, respectively.

Oil Control Facilities

Oil control facilities are designed to remove oil and other water-insoluble hydrocarbons and settleable solids from stormwater runoff. These facilities typically consist of three bays: forebay; separator section; and the after bay. The American Petroleum Institute (API) separator, also called a baffle type separator, contains two baffles. The sludge retaining baffle rises from the floor of the oil/water separator chamber and settled solids are trapped behind this baffle. The oil retaining baffle descends from the top of the chamber and extends at least 50 percent below the depth of the oil/water volume. The floating oil and other hydrocarbons are trapped behind this baffle as the relatively cleaner water flows under and exits the facility (American Petroleum Institute 1990, Ecology 2014b). The coalescing plate separator consists of a series of parallel and inclined plates that provide quiescent conditions for settling and a depth separation to trap oils at the surface (Ecology 2014b).

Proprietary and Emerging Technologies

Proprietary stormwater treatment technologies increasingly are being used to treat stormwater, especially in highly urbanized areas where there is limited space for traditional facilities. The performance of these facilities depends on many factors including but not limited to: sizing, maintenance frequency, installation location, treatment mechanism, treatment media, inlet pollutant concentrations, rainfall intensity, and seasonality. Ecology, in concert with stormwater professionals from the Puget Sound region, developed a protocol for evaluating emerging treatment systems – Technology Assessment Protocol Ecology (TAPE, Ecology 2011b) – and publishes an extensive list of approved technologies (and their technical evaluation study results) on the Ecology website at: <www.ecy.wa.gov/programs/wq/stormwater/newtech/index.html>. Through this process, Ecology approves BMPs and technologies that can be used for several types of water quality treatment, including pretreatment, oil treatment, basic treatment, enhanced treatment, phosphorus treatment, and treatment at construction sites.

The evaluation process requires rigorous field testing of the new stormwater treatment technologies, after which the vendor submits a technology evaluation report (TER) to Ecology for review and approval. Under the technology assessment process, Ecology assigns “Use Level Designations” to emerging technologies based on the results of the evaluation. These designations are described below (Ecology 2014b).

- **GULD – General Use Level Designation**. A General Use Level Designation (GULD) assigned to technologies for which the performance monitoring demonstrates with a sufficient degree of confidence, that the technology is expected to achieve Ecology’s performance goals. Use is subject to conditions documented in a use level designation letter prepared by Ecology.
- **CULD – Conditional Use Level Designation**. A Conditional Use Level Designation (CULD) is assigned to technologies that have considerable performance data not collected per the TAPE protocol. Ecology will allow the use of technologies that receive a CULD for a specified time, during which performance monitoring must be conducted and a TER submitted to Ecology. Units that are in place do not have to be removed after the specified time period. Use is subject to conditions documented in a use level designation letter prepared by Ecology.
- **PULD – Pilot Use Level Designation**. A Pilot Use Level Designation (PULD) is assigned to new technologies that have limited performance monitoring data or that only have laboratory performance data. The PULD allows limited use of the technology to allow performance monitoring to be conducted. PULD technologies may be installed provided that the vendor and/or developer agree to conduct performance monitoring per the TAPE protocol at all installations. Use is subject to conditions documented in a use level designation letter prepared by Ecology.

In addition, Seattle recently evaluated several catch basin storm filters and found good performance when not clogged; however clogging was a concern at many of the installations in the city (Seattle 2012b, 2013b). National studies and evaluations of the performance of stormwater treatment technologies are also found on the International Stormwater BMP Database (<www.bmpdatabase.org>).

Street Sweeping and Water Quality

Street sweeping with high-efficiency or regenerative air sweepers can be an effective means of removing pollutants from roadways before they become entrained in stormwater runoff. The effectiveness of street sweeping depends on many factors including but not limited to: type of sweeper, sweeping frequency, pavement condition, pollutant build-up, parking restrictions, and season. Studies of street sweeping effectiveness in the Puget Sound region include Seattle Public Utilities (SPU) and Herrera (2009), Seattle (2012c), and Kurahashi & Associates (1997). Other useful studies include Bannerman (2008), Depree (2008), Eisenberg et al (2007), Florida Department of Environmental Protection (2004), Kalinosky et al. (2012), Law et al. (2008), Nevada Tahoe Conservation District (2011), Pitt (1979, 1985, 2013), Sansalone (2011), Selbig et al. (2007), URS (2010, 2011), Weston Solutions (2010), and Zarriello et al. (2002).

Types of Construction and Grading Site Best Management Practices

Soil erosion from construction sites and grading activities has long been identified as a significant source of sediment and other suspended solids in runoff in many parts of the United States (Ellis 1936, Hagman et al. 1980, Yorke and Herb 1976, Becker et al. 1974) and the primary stormwater pollutant at a construction site remains sediment (US EPA 2007). Sediment from construction and grading sites with poor stormwater control can harm aquatic environments, adjacent properties, public and private roadways, and drainage systems. Numerous studies at large sites (greater than five acres) have shown that the amount of sediment transported by stormwater runoff is significantly greater from sites with no erosion control practices than from sites with erosion controls (US EPA 1999; Owens et al. 2000). Similarly, results of a USGS/Dane County Land Conservation study (Owens et al. 2000) indicate that small sites can also be significant sources of sediment. Sediment loads in stormwater runoff from two monitored construction sites were 10 times greater than that which is typical from rural and urban land uses in Wisconsin. Total and suspended solids concentration data indicate the active construction phase produced concentrations that were orders of magnitude higher than pre- and post-construction periods.

The best way to minimize erosion during land-disturbing and other construction activities is to employ BMPs that keep the soil in place through existing vegetation, erosion control blankets, or other methods. These BMPs help prevent the soil from becoming dislodged during rain events (Ecology 2014b). Erosion and sediment control BMPs can be grouped according to three broad categories:

1. **Cover practices** – temporary or permanent cover that are designed to stabilize disturbed areas
2. **Erosion control practices** – physical measures that are designed and constructed to prevent erosion at the project site
3. **Sediment control practices** – temporary measures designed to prevent eroded soils from leaving the project site by trapping them in a depression, filter, or other barrier.

Ecology has developed a training program to design and inspect erosion and sediment control BMPs to assure they are reducing erosion and sedimentation from construction sites, including all sites subject to NPDES requirements (sites generally over one acre in size). BMPs must be inspected by a Certified Erosion and Sediment Control Lead (CESCL).

In addition to sediment, construction sites can also be sources of other pollutants, such as phosphorus, petroleum products, and products that can affect pH. Source control practices designed for construction sites can reduce the use of these potential pollutants and/or prevent them from contaminating stormwater (Ecology 2010). Pollutants other than sediment are primarily controlled using good housekeeping practices (such as maintaining vehicles and checking them regularly for leaks, keeping a spill kit on site, controlling concrete washout onsite) and other operational methods to reduce both the risks of pollutants contacting stormwater and the risks and impacts of accidental spills. For example, work can be phased to minimize the amount of soil that is exposed and subject to erosion at any given time. In Washington State it is practical to follow different procedures in the wet season when rain is frequent than in the dry season. West of the Cascade Mountains, Ecology defines the wet season as October 1 to April 30 and the dry season as May 1 to September 30. Extensive information on stormwater BMPs for construction sites can be found in the SWMMWW (Ecology 2014b).

Several documents were reviewed to update mass loading ratios for proprietary water quality treatment technologies. These include *Stormwater Management StormFilter (StormFilter) with Perlite Media* (Contech Engineered Solutions LLC, 2016), *Oldcastle PerkFilter System with SPC Media* (Oldcastle Infrastructure, 2017), *Filterra Bioretention System* (Contech Engineered Solutions, 2020), *BayFilter Enhanced Media Cartridge* (BaySaver Technologies, LLC), BioPod Biofilter with StormMix Media (Oldcastle Infrastructure, 2018), *Kraken Membrane Filtration System* (Bio Clean Environmental Services, Inc., 2016).

Sea Level Rise and Climate Change

Projected sea level rise was assessed using Projected Sea Level Rise for Washington State- a 2018 Assessment (Miller et al 2018 and Mayhew 2020). The *Colorado-New Mexico Regional Extreme Precipitation Study Summary Report Volume VI Considering Climate Change in the Estimation of Extreme Precipitation for Dam Safety* (Colorado Division of Water Resources, 2018) and *Assessment of 2-Hour, 6-Hour and 48-Hour precipitation Time Series for Non-Stationarity and Implications of Assessing Spillway Adequacy for Dams in Washington State* (Schaefer, 2019) were reviewed to assess the potential for changes in precipitation-frequency due to climate change.

REFERENCES [1]

American Petroleum Institute. 1990. "Design and Operation of Oil-Water Separators" Publication 421. February 1990.

Arnold, C.L. and G.J. Gibbons. 1996. Impervious surface coverage: the emergence of a key environmental indicator. American Planners Association Journal 62:243-258.

ASCE. In Press. Seattle Public Utilities Case Study. In Case Studies of LID Implementation in CSO Programs - Committee Report. David Sample, Editor. American Society of Civil Engineers Press. Reston, VA.

ASCE. 2015. Permeable Pavement. Bethany Eisenberg, Kelly Collins Lindow and David R. Smith, Editors. American Society of Civil Engineers and Environmental & Water Resources Institute.

ASCE/US EPA. 1996. International Stormwater Best Management Practices (BMP) Database. <http://www.bmpdatabase.org> (assessed July 3, 2015).

ASCE and WEF. 1998. Urban Runoff Quality Management, WEF Manual of Practice No. 23. American Society of Civil Engineers (ASCE) and Water Environment Foundation (WEF).

Austin, City of. 1990. Removal efficiencies of stormwater control structures; final report. Environmental Resource Management Division. Austin, TX.

Azous, A.L. and R.R. Horner (eds.). 2001. Wetlands and Urbanization: Implications for the Future. New York: Lewis Publishers.

Baldwin, D.H., J.F. Sandahl, J.S. Labenia, and N.L. Scholz. 2003. Sublethal Effects of Copper on Coho Salmon: Impacts on Nonoverlapping Receptor Pathways in the Peripheral Olfactory Nervous System. Environmental Toxicology and Chemistry 22(10):2266-2274.

Bannerman, R. 2008. Reducing the Uncertainty in the Calculations of Street Cleaner Performance for Wisconsin Municipalities.

Barrett, M.E. 2005. BMP Performance Comparisons: Examples from the International Stormwater BMP Database. In: World Water Congress 2005, May 15, 2005, Anchorage, Alaska.

BaySaver Technologies, LLC. 2017. BayFilter Enhanced Media Cartridge. December 2017.

Becker, B.C., Nawrocki, M.A., and Sitek, G.M. 1974. An executive summary of three EPA demonstration programs in erosion and sediment control: Washington, D.C., US Environmental Protection Agency Report EPA-660/2-74-073

Bell, W., L. Stokes, L.J. Gavan, and T.N. Nguyen. 1995. Assessment of the pollutant removal efficiencies of Delaware sand filter BMPs. Department of Transportation and Environmental Services, Alexandria, VA.

---

[1] References that were available in digital format have been provided to Council as pdf files. Other references are either very large documents (e.g., textbooks or sections of textbooks) or documents that are not available for electronic distribution without a fee. Digital or hard copies of any references not included as pdfs can be provided upon request.

Bio Clean Environmental Services, Inc. 2016. Kraken Membrane Filtration System. February 2016 with April 2016 Addendum.

Booth, D.B. 1990. Stream-channel incision following drainage-basin urbanization. Water Resources Bulletin, American Water Resources Association, 26(3):407-417.

Booth, D.B. 1991. Urbanization and the natural drainage system – impacts, solutions, and prognoses. Northwest Environmental Journal, Institute for Environmental Studies, 7(1):93-118.

Booth, D.B. 2007. Deposition upon oral examination of Derek Booth, Ph.D., Volume I and Volume II. Puget Soundkeeper Alliance, et al. vs. State of Washington, et al. Cause No. 07-021, et al. taken December 6, 2007 (Volume I) and December 7, 2007 (Volume II). Seattle, WA.

Booth, D.B. and C. Rhett Jackson. 1997. Urbanization of aquatic systems: degradation thresholds, stormwater detention, and the limits of mitigation. Journal American Water Resources Association, 35(5):1077-1090.

Booth, D.B. and J. Leavitt. 1999. Field evaluation of permeable pavement systems for improved stormwater management. J. Am. Planning Assoc., 65(3):314-325.

Booth, D.B., D. Hartley, and R. Jackson. 2002. Forest cover, impervious-surface area, and the mitigation of stormwater impacts. Journal American Water Resources Association, 38(3):835-845

Booth, D.B., B. Visitacion, and A.C. Steinemann. 2006. Damages and Costs of Stormwater Runoff in the Puget Sound Region. Report. The Water Center, Department of Civil and Environmental Engineering, University of Washington. August 30, 2006. Seattle, WA.

Brattebo, B.O., and D. Booth. 2003. Long-term stormwater quantity and quality performance of permeable pavement systems. Water Research No. 37. 2003.

CSF Treatment Systems. 1994. Three-year Performance Summary - 185th Avenue. Portland, OR.

California Department of Transportation. 2004. BMP Retrofit Pilot Program, Final Report, CTSW-RT-01- 050.

Carollo, F. G., V. Ferro, and D. Termini. 2002. Flow Velocity measurements in vegetated channels. Journal of Hydraulic Engineering, Volume 127, No. 7. p. 664.

Center for Neighborhood Technology (CNT). Green Infrastructure Demonstration Projects, United Church of Rogers Park. 2013. http://www.cnt.org/water/projects/green-infrastructure/demonstration-projects/

Chandler, R.D. 1995. Improving Urban Stormwater Runoff Monitoring Practices, Dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, University of Washington, Seattle, Washington.

Chandler, R.D. 1999. “The Case Against Representative Stormwater Runoff Monitoring. Proceedings of the 26th Annual Water Resources Planning and Management Conference held in Tempe, Arizona, June 6-9, 1999

Chang, George C. 2000. “Review of Stormwater Manual – Sand Filtration Basins for Department of Ecology, State of Washington.” November 5, 2000.

Chollak, T. and P Rosenfeld. 1997. Guidelines for landscaping with compost-amended soils. Chollak Services. Seattle, WA.

Clark, S.E., R. Pitt, P. Brown, and R. Field. 1998. Treatment by filtration of stormwater runoff prior to groundwater recharge. Presentation at WEFTEC 1998, Orlando, Florida. Sponsored by the Water Environment Federation.

Clark, S.E., R. Pitt, S. Burian, R. Field, E. Fan, J. Heaney, and L. Wright. 2007. Annotated Bibliography of Urban Wet Weather Flow Literature from 1996 through 2006. September 10, 2007.

Clauson, J.C., and J.K. Gilbert. 2003. Annual report: Jordan Cove urban water section 319 national monitoring program project. Storrs-Mansfield, CT: University of Connecticut, College of Agriculture and Natural Resources.

Clean Water Services. 2016. Low Impact Development Approaches Handbook. Tualatin Basin Natural Resources Coodinating Committee. Hillsboro, OR. 2016.

Colorado Division of Water Resources. Colorado-New Mexico Regional Extreme Precipitation Study Summary Report Volume VI Considering Climate Change in the Estimation of Extreme Precipitation for Dam Safety. November 30, 2018.

Comings, K.J., D.B. Booth, and R. Horner. 1998. Stormwater pollutant removal by two wet ponds in Bellevue, WA. Department of Civil and Environmental Engineering, University of Washington. Seattle, WA.

Connecticut Department of Environmental Protection. 2010. Artificial Turf Study: Leachate and Stormwater Characteristics, Final Report. July 2010.

Contech Engineered Solutions LLC. 2016. Stormwater Management StormFilter (StormFilter) with Perlite Media. November 2016.

Contech Engineered Solutions LLC. 2020. Filterra Bioretention Systems. October 2020.

Davis, A.P., M. Shokouhian, H. Sharma, and C. Minami. 1998. Optimization of bioretention design for water quality and hydrologic characteristics, final report. Project No. 01-4-31032. University of Maryland. College Park, MD.

Davis, A.P., M. Shokouhian, H. Sharma, and C. Minami. 2001. Laboratory study of biological retention (bioretention) for urban storm water management. Water Environment Research, 73(1):5-14.

Dearmont, D., McCarl, B.A., and D.A. Tolman. (1998). Costs of Water Treatment due to Diminished Water Quality: A Case Study in Texas. 34 Water Resources Research 4, 849-53.

Denver. 2016. Ultra-Urban Green Infrastructure Guidelines. City and County of Denver, CO. March 1, 2016.

Depree, C. 2008. Contaminant characterisation and toxicity of road sweepings and catchpit sediments: Towards more sustainable reuse options. Land Transport NZ Research Report 345. Hamilton, New Zealand.

Dierkes, C., Kuhlmann, L., Kandasamy, J., and Angelis, G. 2001. Pollution retention capacity and maintenance of permeable pavements. Global solutions for urban drainage, Proceedings of the Ninth International Conference on Urban Drainage. September, 2002. Portland, OR.

Dinicola, R. S. 1990. Characterization and Simulation of Rainfall-Runoff Relations for Headwater Basins in Western King and Shonomish Counties, Washington. U.S. Geological Survey. Water-Resources Investigations Report 89-4052.

Dinicola, R.S. 2001.Validation of a Numerical Modeling Method for Simulating Rainfall-Runoff Relations for Headwater Basins in Western King and Shonomish Counties, Washington. U.S. Department of Interiors. U.S. Geological Survey. Water Supply Paper 2495.

Driscoll, E. D. 1986. Detention and retention controls for urban runoff. Urban Runoff Quality – Impact and Quality Enhancement Technology, B. Urbonas, and L. A. Roesner, ed., ASCE, 381-393.

Dunne, T. and L.B. Leopold. 1978. Water in Environmental Planning. New York: W.H. Freeman and Company.

EBDI. 2006. East Baltimore Development, Inc. 2006 Operations Protocol for Salvage, Deconstruction, Demolition and Site Preparation Activities. April 2006.

Ecology. 1992. Stormwater Management Manual for the Puget Sound Basin: The Technical Manual. Washington State Department of Ecology Publication 91-75. February 1992.

Ecology. 2001. Stormwater Management Manual for Western Washington. Olympia, WA.

Ecology. 2005. Stormwater Management Manual for Western Washington. Washington State Department of Ecology.

Ecology. 2006. Washington State Department of Ecology, Fact Sheet: Phase I Municipal Stormwater Permit: National Pollutant Discharge Elimination System and State Waste Discharge General Permit for discharges from Large and Medium Municipal Separate Storm Sewer Systems. Permit Issued January 17, 2007. Permit modification issued June 17, 2009. Fact Sheet dated March 22, 2006.

Ecology. 2007a. Washington State Department of Ecology Phase I Municipal Stormwater Permit: National Pollutant Discharge Elimination System and State Waste Discharge General Permit for discharges from Large and Medium Municipal Separate Storm Sewer Systems. Permit Issued January 17, 2007. Permit modification issued June 17, 2009.

Ecology. 2007b. Phase I: Initial Estimate of Toxic Chemical Loadings to Puget Sound. Washington State Department of Ecology Publication Number 07-10-079. October 2007.

Ecology. 2010. Fact Sheet for Construction Stormwater General Permit. Washington State Department of Ecology. July 21, 2010.

Ecology. 2011a. Control of Toxic Chemicals in Puget Sound – Phase 3: Primary Sources of Selected Toxic Chemicals and Quantities Released in the Puget Sound Basin. Washington State Department of Ecology. Publication No. 11-03-024. November, 2011.

Ecology. 2011b. Technical Guidance Manual for Evaluating Emerging Stormwater Treatment Technologies Technology Assessment Protocol – Ecology (TAPE). Washington State Department of Ecology. August 2011 revision of Publication no. 02-10-037. Publication no. 11-10-061.

Ecology. 2013a. Washington State Department of Ecology, Guidance Document – Western Washington Low Impact Development (LID) Operation and Maintenance (O&M). Prepared by Herrera Environmental Consultants and the Washington Stormwater Center. July, 2013.

Ecology. 2013b. Washington State Department of Ecology - Focus on Bioretention Monitoring. Publication Number: 13-10-017. March, 2013.

Ecology. 2014a. Washington State Department of Ecology Phase I Municipal Stormwater Permit: National Pollutant Discharge Elimination System and State Waste Discharge General Permit for discharges from Large and Medium Municipal Separate Storm Sewer Systems. Permit Issued August 1, 2012. Permit modification issued December 17, 2014.

Ecology. 2014b. Stormwater Management Manual for Western Washington. Washington State Department of Ecology. December 2014.

Ecology. 2014c. Roofing Materials Assessment: Investigation of Toxic Chemicals in Roof Runoff from Constructed Panels in 2013 and 2014. Washington State Department of Ecology Publication No. 14-03-033. September 2014.Ecology. 2015. Western Washington NPDES Phase I Stormwater Permit, Final S8.D Data Characterization 2009-2013. Washington State Department of Ecology Publication No. 15-03-001. February, 2015.

Ecology. 2019a. Washington State Department of Ecology Phase I Municipal Stormwater Permit: National Pollutant Discharge Elimination System and State Waste Discharge General Permit for discharges from Large and Medium Municipal Separate Storm Sewer Systems. Permit Issued July 1, 2019. Effective Date: August 1, 2019.

Ecology. 2019b. Stormwater Management Manual for Western Washington. Washington State Department of Ecology. July 2019.

EPA. 2000. EPA Basins Technical Note 6 Estimating Hydrology and Hydraulic Parameters for HSPF. EPA-823-R00-012. July 2000.

Eisenberg, Olivieri and Associates, Inc. 2007. Pollutant Load Removal From Street Sweeping Best Management Practices: Development of Typical Concentration Values for Pollutants of Concern in Contra Costa County, CA. Prepared for Contra Costa Clean Water Program. May, 2007.

Ellis, M.M. 1936. Erosion silt as a factor in aquatic environments. Ecology. 17:29-42.

Engstrom, A. 2004. Characterizing Water Quality of Urban Stormwater Runoff: Interactions of Heavy Metals and Solids in Seattle Residential Catchments. M.S. Thesis, University of Washington, Department of Civil and Environmental Engineering, Seattle, Washington, 117 pp.

Feijtel, T.S., R.D. Delaune, and W.H. Patrick, Jr. 1989. Seasonal pore water dynamics in marshes of Barataria Basin, Louisiana. Soil Sci. Sot. Am. J. 52:59-67.

Florida Department of Environmental Protection. 2004. Guidance for the Management of Street Sweepings, Catch Basin Sediments and Stormwater System Sediments. May 2014. Tallahassee, FL.

Foulquier, A., F. Malard, S. Barraud, and J. Gibert. 2009. Thermal Influence of Urban Groundwater Recharge from Stormwater Infiltration Basins. Hydrological Processes 23(12):1701-1713.

Fountoulakis, M.S., S. Terzakis, N. Kalogerakis, and T. Manios. 2009. Removal of polycyclic aromatic hydrocarbons and linear alkylbenzene sulfonates from domestic wastewater in pilot constructed wetlands and a gravel filter. Ecological Engineering. Volume 35, Issue 12, pp. 1702-1709.

Gain, S. W. 1996. The effects of flow-path modification on water-quality constituent retention in an urban stormwater detention pond and wetland system, Orlando, Florida. USGS, Water-Resources Investigations Report 95-4297, Tallahassee, Florida.

Galli, F.J. 1992. Preliminary Analysis of the Performance and Longevity of Urban BMPs installed in Prince George County, Maryland. Prepared for the Department of Environmental Resources. Prince George's County, Maryland.

Gibson and Martin. 2018. Claire Gibson, Clarity Engineering LLC and Richard Martin Richard, Martin Groundwater LLC emailed memorandum to Shanti Colwell and Eric Dripps, Seattle Public Utilities. Recommendations for Infiltration Acceptance Testing During Constructoin for Select Infiltration BMPs. September 14, 2018.

Gladden, J.B., W.L. Specht, and E.A. Nelson. 2002. Comparison of Constructed Wetland Mesocosms Designed for Treatment of Copper-contaminated Wastewater. Westinghouse Savannah River Company (Contract no. DE-AC09-96SR18500 with the US Department of Energy).

Goldberg, J.S. 1993. Dayton Avenue Swale Biofiltration Study. City of Seattle Engineering Department. Seattle, WA.

Gresham. 2007. Green Development Practices for Stormwater Management. An Implementation Guide for Development Projects in the Pleasant Valley and Springwater Plan Districts. City of Gresham, OR. Department of Environmental Services & Community Development Department. July 2007

Gresham. 2018. Stormwater Management Manual An Implementation Guide for Development Projects. City of Gresham, OR. October 2018.

Hagman, B.B., Konrad, J.G., and Madison, F.W. 1980. Methods for controlling erosion and sedimentation from residential construction activities, in National Conference on Urban Erosion and Sediment Control—Institutions and Technology, October 10-12, 1979, St.

Paul, Minnesota: US Environmental Protection Agency Report EPA-905/9-80-002, January, 1980. p. 99–105.

Hansen, J.A., P.G. Welsh, J. Lipton, and D. Cacela. 2002. Effects of Copper Exposure on Growth and Survival of Juvenile Bull Trout. Transactions of the American Fisheries Society 131(4):690-697.

Harper, H.H., B.M. Fries, D.M. Baker, and M.P. Wanielsta. 1986. Stormwater Treatment by Natural Systems. Florida Department of Environmental Regulation Report 84-026.

Hathhorn, W.E. and D.R. Yonge. 1996. The assessment of groundwater pollution potential resulting from stormwater infiltration BMPs. Final Technical Report, Research Project T9902. Washington State Department of Transportation / US Department of Transportation.

Hendrey, G.R., J. Clinton, K. Blumer, and K. Lewin. 1979. Lowland Recharge Project Operations, Physical, Chemical, and Biological Changes 1975-1978. Final Report to the Town of Brookhaven. Brookhaven National Laboratory, Brookhaven NY.

Herrera. 2006. Technology Evaluation and Engineering Report: WSDOT Ecology Embankment. Prepared for Washington Department of Transportation, by Herrera Environmental Consultants, Inc., Seattle, Washington.

Herrera. 2008. Effects of Trees on Stormwater Runoff. Prepared by Herrera Environmental Consultants. Prepared for Seattle Public Utilities. February 2008.

Herrera, 2009a. Water Year 2008 Data Report - High Point Phase I Block-Scale Monitoring. Prepared by Herrera Environmental Consultants for Seattle Public Utilities. April 2009.

Herrera. 2009b. Data Report 2006-2008: WSDOT Stormwater Management Program BMP Monitoring - SR 18 MP 18.51 Ecology Embankment. Prepared for Washington State Department of Transportation, by Herrera Environmental Consultants, Inc., Seattle, Washington.

Herrera. 2009c. Final Project Report: Compost-Amended Vegetated Filter Strip Performance Monitoring Study. Prepared for Washington State Department of Transportation, by Herrera Environmental Consultants, Inc., Seattle, Washington.

Herrera. 2009d. 2007-2008 Wet Season Report: WSDOT Stormwater Management Program Unimproved Embankment Monitoring, Herrera Environmental Consultants, Inc., Seattle, Washington.

Herrera. 2010. Woodland Park synthetic turf field stormwater drainage study. Prepared by Herrera Environmental Consultants for Seattle Public Utilities. June 2010.

Herrera. 2019. Environmental Monitoring Report Bobby Morris Playfield Renovation Pilot Program. Prepared by Herrera Environmental Consultants for Seattle Parks and Recreation. December 6, 2019.

Herrera. 2020. Rebecca Dugopolski and Neil Schaner, Herrera Environmental Consultants emailed memorandum to Sherell Ehlers and Mary Weber, Seattle Public Utilities. Rational for Proposed Edits to Rainwater Harvesting BMP On-site Approach Sizing. September 11, 2020.Holz, T.W. 2007. Deposition upon oral examination of Thomas

Holz. Puget Soundkeeper Alliance, et al. vs. State of Washington, et al. Cause No. 07-021, et al. taken December 13, 2007. Seattle, WA.

Horner, R.R. 1988. Biofiltration systems for storm runoff water quality control. Prepared for the Washington State Dept. of Ecology. Seattle, WA.

Horner, R.R. 2006. Initial Investigation of the Feasibility and Benefits of Low-Impact Site Design Practices (“LID”) for Ventura County. Report. Submitted to California Regional Water Quality Control Board, Los Angeles Region, by Natural Resources Defense Council in letter commenting on draft municipal regional stormwater permit. December 2006. Los Angeles, CA.

Horner, R.R. 2007. Initial Investigation of the Feasibility and Benefits of Low-Impact Site Design Practices (“LID”) for the San Francisco Bay Area. Report. Submitted to California Regional Water Quality Control Board, San Francisco Bay Region, by Natural Resources Defense Council in letter commenting on draft municipal regional stormwater permit. July 12, 2007. Oakland, CA.

Horner, R.R., and C.R. Horner. 1995. Design, Construction, and Evaluation of a Sand Filter Stormwater Treatment System, Part II. Performance Monitoring. Report to Alaska Marine Lines, Seattle, WA.

Horner, R.R., C. May, E. Livingston, D. Blaha, M. Scoggins, J. Tims, and J. Maxted. 2002a. Structural and non-structural BMPs for Protecting streams. Proceedings of the Seventh Biennial Stormwater Research and Watershed Management Conference. Southwest Florida Water Management District. p. 185-203. May 22-23, 2002. http://www.swfwmd.state.fl.us/documents/ (assessed June 17, 2008) Brooksville, FL.

Horner, R.R., L. Heungkook, and S.J. Burges. 2002b. Hydrologic monitoring of the Seattle ultra-urban stormwater management projects. Water Resource Technical Series Report No. 170. Department of Civil and Environmental Engineering, University of Washington. Seattle, WA.

Horner, R.R. and C. Chapman. 2007. NW 110th Street Natural Drainage System Performance Monitoring, with Summary of Viewlands and 2nd Avenue NW SEA Streets Monitoring. . Report. . Prepared for Seattle Public Utilities. . Department of Civil and Environmental Engineering, University of Washington. . September 2007. Seattle, WA.

Hruby, Thomas. 2014. Washington State Wetland Rating System for Western Washington. SEA Program, Washington State Department of Ecology Publication No. 14-06-029. October 2014 – Effective January 2015.

Hutchinson, Doug, and Dustin Atchison. 2014. Ballard Rain Gardens: The Other Side of the Story. Presentation at 2014 StormCon Conference, Portland, OR. August 3-7, 2014.

Jacobs, D.E., Cali, S., Welch, A., Catalin, B., Dixon, S.L., Evens, A., Mucha, A.P., Vahl, N., Erdal, S., and J. Bartlett. 2013. Lead and Other Heavy Metals in Dust Fall from Single-Family Housing Demolition. Public Health Reports, Volume 128, November-December 2013.

Kadlec, Robert H. and Robert L. Knight. 1996. Treatment Wetlands. CRC Press, Incorporated. Boca Raton, Florida.

Kalinosky, P., L. Baker, S. Hobbie, and C. Buyarske. 2012. Quantifying Nutrient Load Recovery through Targeted, Intensive Street Sweeping. Powerpoint presentation. Water Resources Conference Oct 17, 2012.

Kantrowitz, I. H. and W.M. Woodham. 1995. Efficiency of a stormwater-detention pond in reducing loads of chemical and physical constituents in urban streamflow, Pinellas County, Florida. USGS, Water-Resources Investigations Report 94-4217, Tallahassee, Florida.

Karr, J.R. 1991. Biological Integrity: A long-neglected aspect of water resource management. Ecological Applications, 1(1):66-84.

King County. 1998. Surface Water Design Manual. Seattle, WA.

King County. 1995. Evaluation of water quality ponds and swales. King County Surface Water Management. Seattle, WA.

King County. 1979. Storm Drainage Control—Requirements and Guidelines. Department of Public Works, Division of Hydraulics. Seattle, WA.

Kitsap County, City of Redmond, Department of Ecology, and Herrera. 2014. Results from Current Research on Pollutant Export from Bioretention Systems and Next Steps. Proceedings of the 2014 Washington State Municipal Stormwater Conference, November 5/6 2014. Puyallup, WA.

Kleindl, W. 1995. A benthic index of biotic integrity for Puget Sound lowland streams, Washington, USA. Master's Thesis, University of Washington. Seattle, WA.

Knight, R.L., R.W. Ruble, R.H. Kadlec, and S.C. Reed. 1994. Wetlands for wastewater treatment performance database. In G.A. Moshiri (ed.), Constructed wetlands for water quality improvement. Lewis Publishers, Boca Raton, Florida.

Konrad, C.P. and D.B. Booth. 2002. Hydrologic trends associated with urban development for selected streams in the Puget Sound Basin, western Washington. US Geological Survey, Water Resources Investigation Report 02-4040.

Kosti, K.F., S.J. Burges, and B.W. Jensen. 1995. Hydrologic response of residential-scale lawns on till containing various amounts of compost amendment. Water Resources Series Technical Report No. 147. Dept. of Civil Engineering, University of Washington. Seattle, WA.

Kulzer, L. 1989. Considerations for the Use of Wet Ponds for Water Quality Enhancement. Municipality of Metropolitan Seattle. Seattle, WA.

Kurahashi & Associates, Inc. 1997. Port of Seattle - Stormwater Treatment BMP Evaluation. Prepared for Port of Seattle, Pier 66. Prepared by Kurahashi & Associates, in association with AGI Technologies.

Law, N., L. DiBlasi, and U. Ghosh. 2008. Deriving Reliable Pollutant Removal Rates for Municipal Street Sweeping and Storm Drain Cleanout Programs in the Chesapeake Bay Basin. Center for Watershed Protection. September 2008.

Lawrence, A.I., J.J. Marsalek, B. Ellis, and B. Urbonas. 1996. Stormwater detention and BMPs. Journal of Hydraulic Research, 34:799-813.

Leif, B. 1999. Compost stormwater filter evaluation. Snohomish County Public Works, Surface Water Management Division. Everett, WA.

Litchfield, D.K. 1993. Constructed Wetlands for Wastewater Treatment at Amoco Oli Company's Madan, North Dakota Refinery. Pp.485-488. in: G.A. Moshiri (Ed.), Constructed Wetlands for Water Quality Improvement. Lewis Publishers. Boca Raton, Florida.

Litchfield, D.K. and D.D. Schatz. 1989. Constructed Wetlands for Wastewater Treatment at Amoco Oil Company's Madan, North Dakota Refinery. Chapter 18, pp. 233-237, in D.A. Hammer (Ed). Constructed Wetlands for Wastewater Treatment: Municipal, Industrial, and Agricultural. Lewis Publishers, Chelsea, Michigan.

Li, H., Sharkey, L., Hunt, W., and A. Davis. 2009. Mitigation of Impervious Surface Hydrology Using Bioretention in North Carolina and Maryland. Journal of Hydrologic Engineering.

Lucchettti, G. and R. Fuerstenberg. 1993. Relative fish use in urban and non-urban streams. Proceedings of the Conference on Wild Salmon, Vancouver, BC.

Maestre, A, and R. Pitt. 2005. The National Stormwater Quality Database, Version 1.1: A Compilation and Analysis of NPDES Stormwater Monitoring Information. University of Alabama, Tuscaloosa, AL, and Center for Watershed Protection, Ellicott City, MY. September 4, 2005.

Mar, B.W., R.R. Horner, J.F. Ferguson, D.E. Spyridakis, E.B. Welch. 1982. Summary – Highway Runoff Water Quality Study, 1977 – 1982. WA RD 39.16. September 1982.

Maryland Department of Environment. 1986. Stormwater Management Infiltration Practices in Maryland: A Departmental Summary. Sediment and Stormwater Administration.

Maryland Department of Environment. 1991. Stormwater Management Infiltration Practices in Maryland: A Second Survey. Sediment and Stormwater Administration.

Massman, J.W. 2003. Implementation of infiltration ponds research. Final Research Report, Research Project Agreement No. Y8265. Washington State Department of Transportation.

May, C.W. 1996. Assessment of cumulative effects of urbanization on small streams in the Puget Sound lowland ecoregion: Implications for salmonid resource management. Ph.D. dissertation, Department of Civil Engineering, University of Washington. Seattle, WA.

May, C. W., R. R. Horner, J. R. Karr, B. W. Mar & E. B. Welch. 1997. Effects of urbanization on small streams in the Puget Sound Lowland ecoregion. Watersh. protect. Techn. 2: 483–494.

McCrea, Rachel. Washington Department of Ecology Municipal Stormwater Specialist, NWRO. Personal communication July 2013.

McCullough, M.C., Spalding, S., and D. Sturdevant. 2001. Summary of Technical Literature Examining the Physiological Effects of Temperature on Salmonids. EPA-910-D-01-005, U.S. Environmental Protection Agency, Washington, DC.

McIntyre, J.K., Davis, J.W., Hinman, C., Macneale, K.H., Anulacion, N.L., and J.D. Stark. In Press. Soil bioretention protects juvenile salmon and their prey from the toxic impacts of urban stormwater runoff. Chemosphere. In Press.

McMahon, G. and T.F. Cuffney. 2000. Quantifying urban intensity in drainage basins for assessing stream ecological conditions. Journal of American Water Resources Association 36:1247-1262.

Medina, D., Monfils, J., and Z. Baccala. 2011. Green Infrastructure Benefits for Floodplain Management: A Case Study. Stormwater. November 2011.

Miller, I.M., Morgan, H., Mauger, G., Newton, T., Weldon, R., Schmidt, D., Welch, M., Grossman, E. 2018. Projected Sea Level Rise for Washington State – A 2018 Assessment. A collaboration of Washington Sea Grant, University of Washington Climate Impacts Group, University of Oregon, University of Washington, and US Geological Survey. Prepared for the Washington Coastal Resilience Project.

Minton, G.R. 2004. Short Course - Stormwater Treatment – How It Works. Shoreline, WA.

Minton, G.R. 2005. Stormwater Treatment: Biological, Chemical & Engineering Principles. Resource Planning Associates. Sheridan Books, Inc., Seattle, WA.

Mitsch, W. and J. Gosselink. 1986. Wetlands. Van Nostrand Reinhold.

Moretto, Robert. 2007. Environmental and health evaluation of the use of elastomer granulates (virgin and from used tyres) as filling in third generation artificial turf. EEDEMS as coordinator for ALIAPUR (tyre recycler) and Fieldturf Tarkett (artificial turf manufacturer/installer), and ADEME (Environmental French Agency).

National Research Council. 2009. Urban Stormwater Management in the United States. The National Academies Press, Washington DC.

Natural Resources Defense Council. 2006. Rooftops to Rivers, Green Strategies for Controlling Stormwater and Combined Sewer Overflows. http://www.nrdc.org/water/pollution/rooftops/rooftops.pdf

Newberry, G.P. and D.R. Yonge. 1996. The retardation of heavy metals in stormwater runoff by highway grass strips. Washington State Department of Transportation / US Department of Transportation.

Nevada Tahoe Conservation District. 2011. Effectiveness of Street Sweeping in Incline Village, NV. December, 2011.

Noller, B.N., P.H. Woods, and B.J. Ross. 1994. Case studies of wetland filtration of mine waste water in constructed and naturally occurring systems in Northern Australia. Water Sci. Tech. 29:257-266.

O’Brien. 2014. Oral testimony as recorded in Pollution Control Hearings Board, State of Washington – Findings of Fact, Conclusions of Law, and Order. PCHB No. 12-093c, PCHB No. 12-097c.

Oldcastle Infrastructure. 2017. Oldcastle PerkFilter System with ZPC Media. May 2017.

Oldcastle Infrastructure. 2018. BioPod Biofilter with StormMix Media. May 2018 with November 2018 Addendum.

Omaha. 2014. Omaha Regional Stormwater Design Manual Rev. 6. Chapter 8. City of Omaha, NE.

Owens, David W., P. Jopke, D.W. Hall, J. Balousek, and R. Roa. 2000. Soil Erosion from Two Small Construction Sites, Dane County, Wisconsin. USGS Fact Sheet FS-109-00. August 2000. Middleton, WI.

Pitt, R. 1979. Demonstration of Nonpoint Pollution Abatement through Improved Street Cleaning Practice. EPA 600/2-79-161.

Pitt, R. 1985. Characterizing and Controlling Urban Runoff through Street and Sewerage Cleaning. US Environmental Protection Agency, Storm and Combined Sewer Program, Risk Reduction Engineering Laboratory, Cincinnati, Ohio. EPA/600/S2-85/038. PB 85-186500.

Pitt, R.E. 1996. Groundwater contamination from stormwater infiltration. Ann Arbor Press, Boca Raton, Florida.

Pitt, R. 2013. The Role of Street Cleaning in Stormwater Management: Using WinSLAMM v10 to Meet Urban Stormwater Management Goals. New Jersey Department of Environmental Protection. PowerPoint presentation. January 24-25, 2013

Pollution Control Hearings Board (State of Washington). 2008. Order on Dispositive Motions (Phase I Municipal Stormwater Permits). PCHB No. 07-021 et.seq. April, 2008.

Portland. 2001. Ecoroof monitoring information. Bureau of Environmental Services. Portland, OR.

Portland. 2016. Stormwater Management Manual. City of Portland, OR. August 19, 2016

Pratt, C.J., Newmann, A.P., and P.C. Bond. 1999. Mineral oil bio-degradation within a permeable pavement: Long term observations. Water Science and Technology, 39, 103-109.

Prince George’s County Dept. of Environmental Resources, 1999. Low-impact development design strategies: an integrated design approach. Prince George's County, MD.

Prince George’s County Dept. of Environmental Resources. 2002. Low impact development (LID) integrated management practices guidebook. Prince George’s County, MD.

Puget Sound Partnership. 2010. 2009 State of the Sound Report. Olympia, Washington.

Reinelt, L.E., R.R. Horner, and A. Azous. 1998. Impacts of urbanization on palustrine (depressional freshwater) wetlands research and management in the Puget Sound region. Urban Ecosystems 2:219-236.

Reinelt, L.E. and B.L. Taylor. 2000. “Effects of Watershed Development on Hydrology” in Wetlands and Urbanization: Implications for the Future. New York: Lewis Publishers. Azous, A.L. and R.R. Horner (eds.).

Sands, K., and T. Chapman. 2011. Why Green Infrastructure and I/I Control Go Hand in Hand. Water World. Volume 27, Issue 2.

Sansalone, J., Berretta, C., and S. Raje. 2011. Quantifying Nutrient Loads Associated with Urban Particulate Matter (PM) and Biogenic/Litter Recovery Through Current MS4 Source Control and Maintenance Practices (Maintenance Matters!). University of Florida. May 2011.

San Antonio. 2016. Storm Water Design Criteria Manual. City of San Antonio, TX. January 2016.

San Francisco. 2016. San Francisco Stormwater Management Requirements and Design Guidelines. City of San Francisco, CA. May 2016

Schaap, M.G. and M. Th. Van Genuchten. 2005. A Modified Maulem-van Benuchten Forumlation for Improved Description of the Hyrdaulic Conductivity Near Saturation. Vadose Zone Journal. Published by Soil Science Society of America.

Scheller, Jerry. 2014. Piper's Creek GSI BMP Performance Modeling Technical Memo. September 2014.

Schaefer, MG. 2019. Assessment of 2-Hour, 6-Hour and 48-Hour Precipitation Time-Series for Non-Stationarity and Implications for Assessing Spillway Adequacy for Dams in Washington State. Prepared for Washington State Department of Ecology Dam Safety Program. MGS Engineering Consultants. October 25, 2019

Schiffer, D.M. 1989. Water Quality Variability in a Central Florida Wetland Receiving Highway Runoff, Water: Laws and Management Conference, American Water Resources Association, September 1989, Tampa, Florida.

Schueler, T.R. 1987. Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMPs. Metropolitan Washington Council of Governments, Washington, D.C.

Schueler, T.R. 1994. The importance of imperviousness. Watershed Protection Techniques 1(3)100-111.

Seattle. 2005. Environmentally Critical Areas: Best Available Science Review. Department of Planning and Development. August 2005.

Seattle. 2007. Environmentally Critical Areas Code Update: Best Available Science Review for Peat Settlement-prone Areas. Seattle Department of Planning and Development. August 2007.

Seattle. 2012a. Green Roof Performance Study, Final Report. Prepared by Cardno TEC for Seattle Public Utilities. June 2012.

Seattle. 2012b. Catchbasin StormFilter Performance Evaluation Report. March 2012.

Seattle. 2012c. Program Effectiveness Report: Street Sweeping for Water Quality. Seattle Public Utilities. March 2012.

Seattle. 2013a. Environmentally Critical Areas Code Update: Best Available Science Review for Fish and Wildlife Habitat Conservation Areas. Seattle Department of Planning and Development. December 2013.

Seattle. 2013c. StormFilter Hydrologic Performance and Sizing Study. June 2013.

Seattle. 2014. Ballard Roadside Raingardens. Phase 1 Hydrologic Monitoring Report, September 2012 through May 2013. January, 2014.

Seattle. 2015. Environmentally Critical Areas – Best Available Science Review (Supplemental Report). Exhibit B to the SPU 2015 Stormwater Code Bill Summary and Fiscal Note. February 12, 2015.

Seattle. 2020. Enclosure 4 - Sidewalk/Trail Compost-Amended Strip BMP Background and Techical Memorandum. October 23, 2020.

Seattle and Herrera. 2009. Seattle Street Sweeping Pilot Study - Monitoring Report. Prepared by Herrera Environmental Consultants for Seattle Public Utilities. April, 2009.

Selbig, W., and R. Bannerman. 2007. Evaluation of street sweeping as a stormwater-quality-management tool in three residential basins in Madison, Wisconsin: US Geological Survey Scientific Investigations Report 2007–5156.

Shaver, E., R.R. Horner, J. Skupien, C. May and G. Ridley. 2007. Fundamentals of Urban Runoff Management: Technical and Institutional Issues. Second Ed. North American Lake Management Society. Madison, WI.

Sheldon, D., T. Hruby, P. Johnson, K. Harper, A. McMillan, T. Granger, S. Stanley, and E. Stockdale. 2005. Wetlands in Washington State - Volume 1: A Synthesis of the Science. Washington State Department of Ecology. Publication #05-06-006. Olympia, WA.

Sidle, R.C. 1988. Bedload transport regime of a small forest stream. Water Resources Research 24(2):207-218.

Sinicrope, T.L., R. Langis, R.M. Gersberg, M.J. Busnardo, and J.B. Zedler. 1992. Metal removal by wetland mesocosms subjected to different hydroperiods. Ecol. Eng.1:309-322.

Soils for Salmon. 2012. Guidelines and Resources for Implementing Soil Quality and Depth BMP T5.13 in WDOE Stormwater Management Manual for Western Washington.

Stanley, D. W. 1996. Pollutant removal by a stormwater dry detention pond. Water Environment Research, 68:1076.

Tacoma. 2016. Stormwater Management Manual. City of Tacoma, WA. July 2016.

Tacoma-Pierce County Health Department/Pierce County Public Works Department. 1995. Pilot evaluation, subsurface stormwater disposal facilities, final report.

Tang, S-y. and X-w. Lu. 1993. The use of Eichhornia crassipes to cleanse oil refinery wastewater in China. Ecol. Eng., 2:243-251.

Terzakis S., M.S. Fountoulakis, I. Georgaki, D. Albantakis, I. Sabathianakis, A.D. Karathanasisz, N. Kalogerakis, and T. Manios. 2008. Constructed wetlands treating highway runoff in the central Mediterranean region. Chemosphere Vol. 72:2, Pp. 141-149.

Thom, R.M., A.B. Borde, K.O. Richter, and L.F. Hibler. 2001. Influence of urbanization on ecological processes in wetlands. Water Science and Application 2: 5-16.

Tian, Z., H. Zhao, K. T. Peter, M. Gonzalez, J Wetzel, C Wu, X. Hu, J. Prat., E. Mudrock, R. Hettinger, A. E. Cortina, R.G. Biswas, F. V. C. Kock, R. Soong, A. Jenne, B. Du, F. Hou, H. He, R. Lundeen, A. Gilbreath, R. Sutton, N. L. Scholz, J. W. Davis, M. C. Dodd, A.

Simpson, J.K. McIntyre, E. P. Kokoziej. 2020. A ubiquitous tire rubber-derived chemical induces acute mortality in coho salmon. Science. December 3, 2020.

Tomasek, M.D., G.E. Johnson, and P.J. Mulloy. 1987. Operational problems with a soil filtration system for treating stormwater. Lake and Reservoir Management: Volume III, Issue 1.

United States Geological Survey. 2009. Effects of Urbanization on Stream Ecosystems. http://water.usgs.gov/nawqa/urban/html/publications.html (assessed May 15, 2009)

Urbonas, Ben. 1999. Design of a Sand Filter for Stormwater Quality Enhancement. Water Environment Research, Vol. 71, No. 1 (Jan – Feb 1999), pp 102-113.

URS, 2010. Targeted Aggressive Street Sweeping Pilot Program Phase III Median Sweeping Study. Prepared for City of San Diego. Doc ID# CSD-RT-10-URS19-02. August, 2010.

URS, 2011. Targeted Aggressive Street Sweeping Pilot Program Phase IV Speed Efficiency Study. Prepared for City of Sand Diego. Doc ID# CSD-RT-11-URS28-02. May, 2011.

US EPA. 1983. Results of the nationwide urban runoff program. PB84-185552. Washington, D.C.

US EPA. 1997. Innovative Uses of Compost: Erosion Control, Turf Remediation, and Landscaping. US EPA Fact Sheet EPA 530-F-97-043.

US EPA. 1999. National Pollution Discharge Elimination System – Storm Water Phase II, Federal Register, Vol. 64, No. 235, December 9, 1999, Rules and Regulations.

US EPA. 2000. Vegetated roof cover, Philadelphia, Pennsylvania. EPA 841-B-00-005D. Washington, D.C.

US EPA. 2007. Developing Your Stormwater Pollution Prevention Plan: A Guide for Construction Sites. EPA 833-R-060-04. Washington, D.C.

US EPA. 2012. Green Infrastructure Permitting and Enforcement Series: Factsheet 2. Combined Sewer Overflows. EPA-832-F-12-013. Washington, D.C. 2012.

US EPA. 2014. Improving Community Resiliency with Green Infrastructure. EPA-830-F-14-001. Washington, D.C. 2014.

US EPA. 2015. What is Green Infrastructure? US EPA Green Infrastructure website, accessed July 2, 2015 at: http://water.epa.gov/infrastructure/greeninfrastructure/

Van Genuchten, M. Th. 1980. A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils. Soil Sci. Soc. Am. J. 44:892-898.

Vancouver. 2016. Best Management Practice ToolKit Volume II. Vancouver, BC. March 2016.

Walker, W. W. Jr. 1987. Phosphorus removal by urban runoff detention basins. Lake Reservoir Management, 3:314-328.

Walker, D.J. and S. Hurl. 2002. The reduction of heavy metals in a stormwater wetland. Ecol. Eng. 18:407-414.

Wanielista, M.P. and C.L. Cassagnol. 1981. Detention with effluent filtration for stormwater management. Published in Urban Stormwater Quality, Management, and Planning, Ben Chieyen, ed., 1982. Water Resources Publications, Littleton, CO.

Warner, J.W. T.K. Gates, R. Namvargolian, P. Miller, and G. Comes. 1994. Sediment and microbial fouling of experimental groundwater recharge trenches. Journal of Contaminant Hydrology, 15:321-344.

Weston Solutions. 2010. City of San Diego Targeted Aggressive Street Sweeping Pilot Effectiveness Assessment Final Report. Prepared for City of San Diego. June 2010

Whipple, W. Jr. 1979. Dual-purpose detention basins. Journal of the Water Resources Planning and Management Division, ASCE, 105:402-423.

WSU. 2014. Bioretention Facility Testing, Final Report. Memorandum of Agreement No. DA2009-39. Prepared for Seattle Public Utilities. March, 2014.

WSU and PSP. 2012. Washington State University and Puget Sound Partnership – Low Impact Development Technical Guidance Manual for Puget Sound. Olympia, WA.

Wu, J. S., R.E. Holman, and J.R. Dorney. 1996. Systematic evaluation of pollutant removal by urban wet detention ponds. Journal of Environmental Engineering, 122:983-988.

Xiao, Q., E.G. McPherson, J.R. Simpson, and S.L. Uston.1998. Rainfall Interception by Sacramento’s Urban Forest. Journal of Arboriculture 24(4): 235-244.

Yorke, T.H., and Herb, W.J. 1976. Urban-area sediment yield effects of construction site conditions and sediment control methods, Proceedings of the Third Federal Inter-Agency Sedimentation Conference, 1976, Denver, Colorado, March 22-25, 1976: Water Resources Council, Sedimentation Committee, p. 2-52 through 2-64

Yousef, Y. and L. Yu. 1992. Potential contamination of groundwater from Cu, Pb, and Zn in wet detention ponds receiving highway runoff. J. Environ. Science. Health, A27(4):1033-1044.

Zarriello, P., R. Berault, and P. Weisel. 2002. Potential Effects of Structural Controls and Street Sweeping on Stormwater Loads to the Lower Charles River, Massachusetts. US Geological Survey Water-Resources Investigations Report 02-4220.

Zawlocki, K.R., Ferguson, J.F., and Mar, B.W. 1981. A survey of trace organics in highway runoff in Seattle, Washington. M.S.E. Thesis. Department of Civil Engineering, University of Washington.

ABBREVIATIONS

AKART	All known, available and reasonable methods of prevention, control and treatment
API	American Petroleum Institute
ASCE	American Society of Civil Engineers
B-IBI	Benthic-Index of Biotic Integrity
BMPs	Best Management Practices
BOD	Biochemical Oxygen Demand
City	City of Seattle
ECA	Environmentally Critical Areas
Ecology	Washington State Department of Ecology
GSI	Green Stormwater Infrastructure
HCI	Habitat Comparison Index
HSPF	Hydrological Simulation Program-Fortran
KCRTS	King County Runoff Time Series
LID	Low Impact Development
mg/L	Milligrams per liter
MS4	Municipal Separate Storm Sewer System
NPDES	National Pollutant Discharge Elimination Program
PAHs	Polynuclear Aromatic Hydrocarbons
RCW	Revised Code of Washington
RSMP	Regional Stormwater Monitoring Program
SMC	Seattle Municipal Code
TSS	Total Suspended Solids/Sediment
USGS	United States Geological Survey
WAC	Washington Administrative Code
WSDOT	Washington State Department of Transportation
WWHM	Western Washington Hydrologic Model