Final

WHITE PAPER
for
Stormwater Management Program
Effectiveness Literature Review

Low Impact Development Techniques

April 2013

Prepared for:
Association of Washington Cities
and
Washington State Department of Ecology

Prepared by:
William J. Taylor
Taylor Aquatic Science and Policy
and
Cardno TEC, Inc.
2825 Eastlake Avenue East, Suite 300
Seattle, Washington 98102

EXECUTIVE SUMMARY

The upcoming National Pollutant Discharge Elimination System (NPDES) stormwater permits for Phase I and Phase II communities in the Puget Sound Basin include a provision for jurisdictions to participate in a Regional Stormwater Monitoring Program (RSMP) as part of compliance with the permit. Part of the monitoring program is to carry out "effectiveness studies" that will provide long term feedback to the jurisdictions on the effectiveness of various stormwater management measures under the permit.

One of the set of potential effectiveness studies will be to evaluate the performance of low impact development (LID) technologies, including permeable pavements, bioretention facilities, and green roofs. The intent of this white paper is to describe, through a review and synthesis of scientific literature, the existing understanding on the performance of these LIDs, and then identify areas where further effectiveness studies are either not needed or where additional specific studies may improve the implementation of these LIDs in the Puget Sound region.

A number of unifying scientific principles or means of analysis can be applied to these LIDs, including:

- All the LIDs are volume control-oriented technologies intended to reduce total flow through infiltration and evapotranspiration, with the added beneficial result of stormwater detention, reduced peak flows and increased lag times.
- Available volumetric storage (abstraction volume) together with the selected design storm duration - return interval, appears to be the key design element that will determine volumetric reduction performance of individual facilities. Water quality performance will largely follow this volumetric reduction sizing.
- Water quality improvement occurs for most parameters (e.g. total suspended solids, oils and grease, metals, nutrients, pathogens), but the potential for leaching of nutrientsand copper has been documented, and will be largely affected by soil media specification and the extent of use of compost or fertilization, especially for phosphorus and nitrogen. Facilities with underdrains will tend to exacerbate transport of these pollutants from LID facilities to receiving waters through bypassing local infiltration.
- Knowledge of site specific local subsurface exfiltration rates and groundwater levels, appears to be a key to successful programmatic design of LIDs. Volume reduction in LIDs is largely seen for small to medium storms, but increasingly less so for larger storms.
- Basin scale performance of the use of LIDs appears to depend on a high level of basin development and a high density of LID to affect a difference in receiving waters. This conclusion is based on modeling, and no basin scale studies have been conducted to document improvements in receiving waters as a result of the use of LIDs.
- Construction, operation, and maintenance of LID facilities have a significant effect on the performance of LIDs, necessitating attention to design specification, and care in construction and maintenance for facility success. Organizational development for the management of LIDs will be important for long term successful performance.

The literature review indicates substantial flow volume reduction and water quality improvements result from the use of LID technologies. Site specific volume reductions on the order of 50 to 90 percent are common for each of these technologies, with bioretention facilities appearing to show the highest degree of volume reduction, followed by permeable pavement and green roof facilities. Peak flow reduction and increased lag times coincidentally result from LID volume reduction. The critical design element to the ultimate volume reduction for any of these facilities is the design storage volume relative to the inflow volumes. Success of LID implementation will then depend on accurate sizing that takes site specific conditions into account.

Water quality improvement as a result of passage through LID facilities can be in the form of reduction in concentration of pollutants or reduction in load. For permeable pavements and bioretention facilities, most pollutants show a consistent decrease in concentration over inflowing concentrations, especially for the important parameters of total settleable solids, metals, oil, and polycyclic aromatic hydrocarbons. Nitrogen and phosphorus, however, are notably much more variable in concentration, with even increases in concentration being seen at the outlet of LIDs. Large increases have been related to decomposition and leaching of nitrogen and phosphorus from internal sources, especially for phosphorus, with a large portion of total phosphorus being in the biologically active soluble form. Green roofs also appear to raise concentrations of nutrients and copper from the use of rich soil media and contact with building materials. Nitrogen can accumulate in the form of nitrate, and discharge at levels similar to or higher than inflows. Soil media amendments to increase phosphorus sorption capacity, along with reducing the use of compost, appear promising to reduce phosphorus leaching from bioretention facilities. Nitrogen levels may be reduced by incorporating anaerobic zones into facilities. Copper may also originate from internal sources in bioretention facilities through soil amendments.

Pollutant loads are a product of both volume and concentration. Reduced volumes along with reduced concentrations contribute significantly to the reduction of pollutant loads over inflow loads. Frequently, however, reduced loads of phosphorus and nitrogen are largely due to reduction in flow volumes rather than concentrations.

Effects of high groundwater on bioretention performance and effects on groundwater quality were under-represented in the literature reviewed. Puget Sound region surficial soils and groundwater conditions are highly variable and heterogeneous; local groundwater mounding could occur if groundwater levels rise to near the elevation of LID facilities, thus reducing infiltration rates and detention storage, and affecting facility sizing. Similarly, increased nitrate, phosphorus and copper concentrations may affect local groundwater quality if the pollutant loads are large enough. Local Puget Sound infiltration and groundwater conditions will have a significant effect on how LID is designed and implemented in the region, and targeted additional study is needed especially for shallow groundwater.

Documentation of downstream hydrologic or ecological benefits on a basin scale as a result of the use of LIDs has not yet been conducted. Evaluation of basin scale effects of the use of LID has been limited to modeling, with only individual facility and development plat scales of implementation actually monitored on-site for performance, but not in receiving waters. Modeling of basin scale implementation indicates hydrologic benefits will be detectible for small

to medium storms, and only in basins where a large level of development, and a high enough density of LID use occurs. Water quality benefits in surface receiving waters might be expected to occur at the basin scale by the simple elimination of untreated stormwater discharges from many small and medium sized storms that are fully or first flush infiltrated by LID facilities.

Much of the literature documents general hydrologic and water quality performance of LIDs in the form of long term flow or concentration reduction percentages. These generalized types of percentage reduction studies should not be repeated without specific, locally relevant design- or management-related objectives. Studies should also be targeted to environmental conditions and criteria that are relevant to the Puget Sound region. Most of the literature reviewed reflected LID performance results for conditions outside the Puget Sound region. While the physical principles behind the performance analyses from these studies will be the same, local conditions that define the relevant mechanisms and magnitudes of LID performance, as well as receiving water criteria, need to be identified through the effectiveness studies carried out under the RSMP.

A range of scales of analysis of LID effectiveness are needed, from the individual facility scale to the organizational management scale. Effectiveness studies recommended here are focused on documenting and providing guidance on:

- the accuracy of sizing of LID designs for volumetric performance relevant to the Puget Sound region, including local exfiltration conditions unique to the region,
- soil media composition that avoids nutrient leaching while supporting plant community success,
- basin scale design and performance of LIDs through implementing a basin scale pilot project to document the basin scale performance and beneficial outcomes of LID use on receiving waters, and
- additional organizational development (in addition to that already required under the NPDES permits) for the management of LIDs by designating a local jurisdiction to implement and operate the basin-scale pilot project.

TABLE OF CONTENTS

ABBREVIATIONS AND ACRONYMS iii
1.0 Introduction and Problem Statement 1
1.1 Introduction 1
2.0 Literature Review 2
2.1 Synthesis and Overview of Common Flow and Water Quality Elements of Permeable Pavements, Bioretention, and Green Roofs, and Common Research Elements Found in the Literature Reviewed 2
2.1.1 Common Elements of "Volume Control" –Oriented LID Systems 2
2.1.2 Interpreting Flow Reduction Data from Volume Control-Oriented LIDs 2
2.1.3 Interpreting Pollutant Concentration or Load Reduction Rates in LID Facilities 4
2.1.4 Volume Reduction Contribution to Pollutant Load Reduction 4
2.1.5 Basin Scale Effects from the Wide-scale Use of LIDs 6
2.1.6 Effect of facility aging on long term performance 7
2.1.7 Lack of Documentation of Downstream Beneficial Effects on Flooding, Watershed Function or Receiving Water Hydrology or Ecology 7
2.1.8 Highly Variable Basis of Design and Sizing in the Literature Database Projects 8
2.1.9 Dearth of Publications in the Database from the Pacific Northwest 9
2.2 General Research Approach and Quality of Data Collection in the Literature in Evaluating LID Systems 9
2.3 Permeable Pavements Design and Effectiveness Overview 10
2.3.1 Hydrologic Findings from Pervious Pavement Study Results 10
2.3.2 Water Quality and Load Reduction from Permeable Pavement 14
2.4 Swales and Bioretention Facilities Design and Effectiveness Overview 16
2.4.1 Hydrologic Findings from Swales and Bioretention Facilities 17
2.4.2 Water Quality Findings from Swales and Bioretention Facilities 20
2.5 Green Roofs Facilities Design and Effectiveness Overview 27
2.5.1 Hydrologic Findings from Green Roof Facilities 27
2.5.2 Water Quality Findings from Green Roofs 29
2.5.3 Plant Composition and Density Effect on Performance of Green Roofs 31
2.6 Talking points 31
2.6.1 LID measures are not effective at reducing storm flows in retrofits and new developments. 31
2.6.2 LID measures are not effective at reducing pollutant loads in retrofits and new development. 34
2.6.3 LID measures are not feasible in areas with tight soils or shallow groundwater. 37

2.6.4 Recycled concrete cannot be used to provide storage under permeable pavement. 37
3.0 Conclusions and Recommendations 38
3.1 Effectiveness Study Recommendations 38
3.1.1 Internal Scale Effectiveness Studies 38
3.1.2 External Scale Effectiveness Studies 39
3.1.3 Basin Scale Effectiveness Studies 40
3.1.4 Organizational Scale Effectiveness Studies....40
4.0 References....41

List of Tables

Table 1. Summary of literature values for percent runoff and pollutant retention by permeable pavements, from Ahiablame et al. (2012). 12
Table 2. Summary of inflow and outflow concentration percentiles for permeable pavements from the International Stormwater Database (2012c)....15
Table 3. Summary of Flow Reduction for Filter Strips, Swales, and Bioretention from International BMP Stormwater Data Base (2011, 2012a)....17
Table 4. Summary of literature values for percent runoff and pollutant retention by bioretention systems, from Ahiablame et al. (2012)....22
Table 5. Summary of water quality inflow and outflow concentrations from the International Stormwater BMP Database (2012c). 23

List of Figures

Figure 1. Example flow response showing low or no flow for inflow volumes less than the BAV, followed by approximately a 1:1 ratio of outflow to inflow volume for inflow volumes greater than the BAV (Davis et al. 2012).... 3
Figure 2. Theoretical load reduction for coincident reductions in volume and concentrations.... 5

ABBREVIATIONS AND ACRONYMS

BAV	Bioretention Abstraction Volume
BMP	Best Management Practice
CGP	concrete grid pavers
CSO	combined sewer overflow
CWP	Center for Watershed Protection
Ecology	Washington State Department of Ecology
ISZ	internal storage zone
LID	Low Impact Development
mgL^{-1}	milligrams per liter
ugL^{-1}	micrograms per liter
NPDES	National Pollutant Discharge
OPO4-P	ortho-phosphorus
PC	pervious concrete
PICP	permeable interlocking concrete pavers
RSMP	Regional Stormwater Monitoring Program
SRP	soluble reactive form of phosphorus
SWG	Stormwater Work Group
TSS	Total Suspended Solids
USEPA	United States Environmental Protection Agency
WSU	Washington State University

1.0 INTRODUCTION AND PROBLEM STATEMENT

1.1 INTRODUCTION

As part of the National Pollutant Discharge Elimination System (NPDES) Stormwater Permit for Phase I and II communities scheduled to be in effect August 1, 2013, the permittees and the Washington State Department of Ecology (Ecology) are developing a coordinated "Regional Stormwater Monitoring Program" (RSMP) that will conduct the permit monitoring in lieu of monitoring typically conducted by each individual permittee (Ecology 2011). This monitoring will follow the guidance in the Stormwater Monitoring and Assessment Strategy for the Puget Sound Region (Puget Sound Stormwater Work Group, 2010). In anticipation of the "effectiveness studies" portion of the monitoring to be carried out by the RSMP, Ecology, together with the Stormwater Work Group (SWG), have sponsored preparation of synthesis white papers to be written on a variety of effectiveness study topics potentially to be addressed under the RSMP. This white paper covers a summary of the literature and recommended effectiveness studies for low impact development (LID) features: permeable pavements, bioretention, and green roofs.

This white paper represents a review and synthesis of relevant literature for these LID technologies that was identified in a literature database compiled by Brown and Caldwell and the Washington State Department of Transportation[1]. Regarding the database, it is recognized that not nearly all the available literature on these LIDs' design and performance features can be easily compiled in such a selected database. While much of the literature listed in the database was examined for applicability to the LID topic, many more unidentified reference sources exist, and many were obtained, especially more recent articles, to augment those listed in the database.

Additionally, some specific effectiveness questions drawn from plans for the RSMP (Ecology, 2011) were posed by the SWG to address from the literature in the database. These specific questions required original and targeted key word searches of academic databases to begin to identify potential information. Together, between the Ecology database and original academic database searches, the literature in this review provides considerable background for a synthesis and summary of the scientific principles and results on the effectiveness of the LIDs presented here.

The intent of this white paper is to provide a summary and synthesis of findings from the literature relevant to the question of mitigation of stormwater flow and water quality impacts by permeable pavements, bioretention (rain gardens) systems, and green roofs. The synthesis and literature summary was conducted, and a "talking points" narrative provided to address specific questions of interest to the SWG related to these LIDs. Additionally, recommended effectiveness studies are described to help refine future effectiveness studies to be undertaken within the RSMP. The intent of the synthesis and recommended effectiveness studies is to identify areas where, based on the literature, further studies may not be needed to evaluate the LIDs' performance, as well as areas where additional studies may be fruitful to better implement LID in local permittees' jurisdictions.

[1] http://www.ecy.wa.gov/programs/wq/psmonitoring/ effectivnessSubgrp.html

2.0 LITERATURE REVIEW

2.1 SYNTHESIS AND OVERVIEW OF COMMON FLOW AND WATER QUALITY ELEMENTS OF PERMEABLE PAVEMENTS, BIORETENTION, AND GREEN ROOFS, AND COMMON RESEARCH ELEMENTS FOUND IN THE LITERATURE REVIEWED

The scientific literature reviewed first and foremost affirms that LID stormwater control measures follow the first principles of the natural processes of hydrology, hydraulics, aquatic chemistry, soil physical properties, and interactions with various microbial organisms. The slight distinction from natural scale processes is that stormwater drainage is directed to these facilities on a human-designed scale that is tied to the scale of the LID facility, and with the intention of mitigating impacts of stormwater runoff on receiving waters. This section provides some unifying observations on the scientific analyses and principles of these LID features that are found in the literature as a basis of reporting on the research for these features.

2.1.1 Common Elements of "Volume Control" –Oriented LID Systems

A common theme of the three categories of LIDs (also known as best management practices [BMPs] or green stormwater infrastructure) addressed here is that they all represent designs that are an evolution of stormwater control measures from large centralized detention facilities that are more focused on large volume collection and slow release of flows primarily for *peak flow control*, to facilities such as permeable pavements, bioretention, and green roofs that are distributed on a more "micro-" scale relative to overall watershed processes, and focus more on *volume control* - i.e. a reduction in total flow (Davis et al. 2009, CWP 2008). These later control measures are intended to receive flows from comparatively smaller contributing drainage areas, have an available volume that acts as detention, and promote infiltration and evapotranspiration that together reduces the volume of flow that would otherwise reach receiving waters through pipes or channels (USEPA 2012a, Davis et al. 2009).

A consequence of volume reduction in LIDs also consistently seen in much of the literature is the reduction of peak flow rates and increased lag times to peak flow (Hood et al. 2007). The review and discussion included here is more focused on the effects of design on volume reduction and the associated hydrologic processes, with peak reductions and increased lag times largely being a positive consequence of volume control. The significance of peak reduction and greater lag time themselves plays a more important role in the overall effect of basin-wide use and distribution of LIDs on stream flows (Gilroy and McCuen 2009), and the associated ecological benefits.

2.1.2 Interpreting Flow Reduction Data from Volume Control-Oriented LIDs

Most of the literature reports runoff reduction as a percentage of total inflow for a given facility. The hydrologic runoff patterns from these LID systems, however, can be better interpreted through a recent analysis of hydrologic performance of bioretention facilities by Davis et al. (2012), the principal concepts of this analysis are applicable to all LID volume control-oriented designs such as permeable pavements, cisterns, green roofs, etc. This analysis recognizes bioretention abstraction volume (BAV) is the primary flow-controlling factor of these types of infiltrating facilities. The BAV is the initial short term storage volume available in the facility's surface pore space, soil, sand, gravel, stone fill material etc. As this storage space fills, no or

little runoff is expected from smaller rain events while the abstraction volume is less than filled. After the BAV is filled, however, runoff will tend to respond following a one-to-one overflow runoff relationship with the subsequent rain volume (or somewhat less than one-to-one, depending on the degree of lateral or deep exfiltration). Gilroy and McCuen (2009) note the same principle and its important effect on watershed performance of BMP volume design and spatial placement within a watershed.

The BAV at any one time between storms is not static, but will be dynamic, depending on the facility configuration, antecedent moisture conditions, storm size and intensity, and other site conditions (e.g., rate of subgrade infiltration). This variable storage condition results in slightly variable runoff volumes for a given storm volume as the BAV is fully filled (Davis et al. 2012). Facility runoff will tend toward this runoff pattern except to the degree subsurface exfiltration occurs. Long duration, low intensity storms that allow more subsurface exfiltration while surface runoff is occurring may also be less than the 1:1 ratio of runoff after filling of the BAV. The result is the percentage runoff for a given facility is not constant but becomes a function of the inflow volume of any one storm (similar to the problem of reporting water quality concentration reductions as a constant percentage of inflow concentrations - see below). Figure 1 provides an example runoff response seen by Davis et al. (2012) exhibiting this pattern.

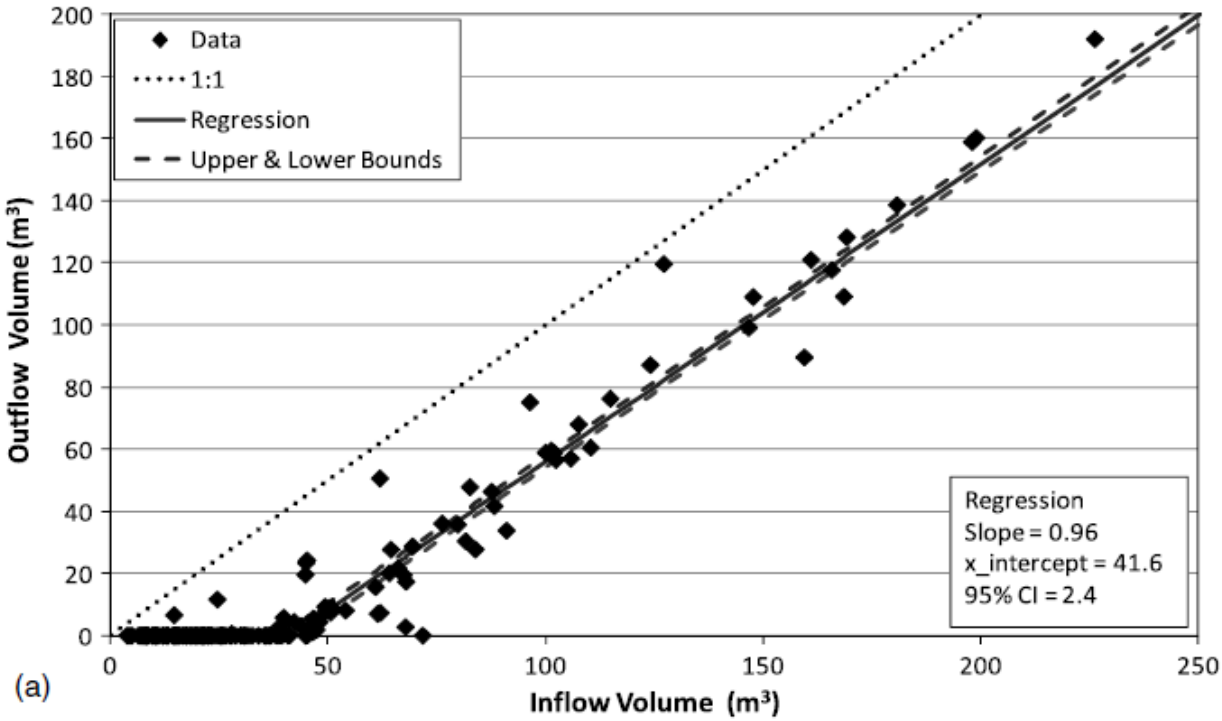

Figure 1. Example flow response showing low or no flow for inflow volumes less than the BAV, followed by approximately a 1:1 ratio of outflow to inflow volume for inflow volumes greater than the BAV (Davis et al. 2012).

Given that individualized control of runoff response at LID facilities depends so much on the abstraction volume for any one facility, the wide range in volume reductions observed in the literature for any one LID type is not surprising (cf. International BMP Stormwater Database

2012a). In fact, the reporting of volume reduction as a set percent of inflow volume becomes less informative of any one facility without a clear analysis of the storage volume relative to the contributing area and the distribution of storm sizes. When flow reduction is given as a percentage reduction for a site with a long record of storms, many small storms that had no outflow (100 percent reduction) are joined with large storms that may have had a large volume of outflow (small percentage reduction). The result is that a percentage volume reduction reported as a single number representation of a site does not represent the type of LID per se, but rather a weighted average flow reduction related to the BAV of that particular facility and the frequency distribution of storm sizes.

A recent analysis of bioretention BMPs by the International Stormwater BMP Database (2012a) of volume reduction versus the ratio of the BMP surface area to tributary area showed a range of roughly 20 to 100 percent volume reduction within a small range of four to six percent ratio of surface area to tributary area. These data likely illustrate the wide ranging combined effects of site specific BAV, subsurface exfiltration, whether an underdrain is included or not, the project target design storm used and other on-site and study-specific conditions that affect the ultimate volume reduction. Davis et al.'s (2012) analysis suggests the first three of these factors are the most influential on volume reduction, and can be used to better design and size an LID facility for more predictable volume reduction performance.

Keeping this analysis in mind, much of the volume reduction data presented in the literature is still provided as a percentage of rainfall or inflow, and some of that data will be presented here.

2.1.3 Interpreting Pollutant Concentration or Load Reduction Rates in LID Facilities

Similarly, pollutant concentrations in the outflows from BMPs are also frequently reported as a percentage of the inflow concentration or of the inflow load (the product of flow and concentration). This is still common, even when a constant percentage reduction in concentration or flow for any given storm event passing through an LID facility is not what is generally observed for either concentrations or load (Strecker 2001, Barrett 2005, Chapman and Horner 2010, Davis et al. 2012). This was originally identified by Schueler (1996) as "irreducible pollutant concentrations" discharging from BMPs.

Given this well-known observation, "removal rates" reported here from the literature (whether they be load or concentration reduction rates) should also be evaluated with this in mind. Alternatively, the International Stormwater Database (2012c) reports effluent concentrations independent of inflow concentrations as a way of characterizing the water quality performance of LID types, and some of these data will be presented here. Davis (2007) also notes the value of reporting effluent concentrations independent of inflow or percent removal.

2.1.4 Volume Reduction Contribution to Pollutant Load Reduction

Because pollutant loads are a product of volume and pollutant concentration, LID facilities will reduce much of pollutant loads as a combined result of flow reduction and associated water quality improvements (see water quality benefits discussion below). While some pollutant concentrations are reduced considerably in each of the LIDs addressed here (e.g. metals especially are removed near the surface of bioretention facilities [Li and Davis 2008]), others may remain at similar levels as inflowing concentrations (phosphorus and nitrogen in particular). Flow volume reductions alone will reduce pollutant loads as long as concentrations don't

increase significantly through the system. Davis (2007) notes in his study "[m]ass removals were always greater than concentration-based removals because of the attenuation of flow by the bioretention media, with some events demonstrating zero flow, and hence zero pollutant discharge." Relative to the irreducible concentration affect described above for concentration percent reduction, Line and Hunt (2009) note "[l]oad reduction efficiencies of most pollutants would likely have been greater if, to a certain extent, concentrations in inflow were greater." Similarly Passeport et al. (2009) note that ortho-phosphorus (OPO_4-P) concentrations flowing through two bioretention cells in the fall and winter periods "were increased by 17 percent and 53 percent; whereas thanks to high volume reductions OPO_4-P loads were decreased by 41 percent and 67 percent." Brown and Hunt (2011) note "[t]he primary reason for pollutant load reduction of total nitrogen and total phosphorus was significant runoff volume reduction." Figure 2 provides theoretical load reduction results for coincident levels of volume and concentration reduction.

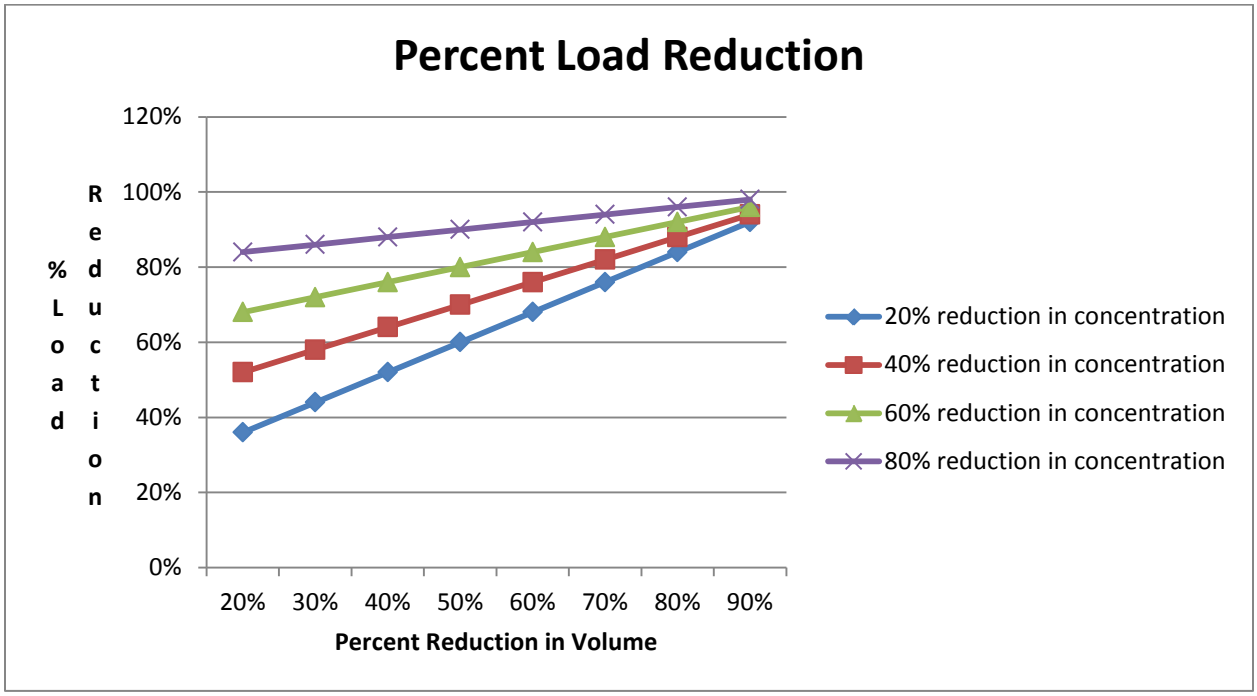

Figure 2. Theoretical load reduction for coincident reductions in volume and concentrations.

Additionally, because the initial runoff into pervious pavement systems is the first water to engage the available abstraction volume substrate materials, and this initial "first flush" runoff concentration can be higher for some parameters, such as particulates, than the remaining storm runoff concentrations, these initial higher concentrations may receive treatment removal at a higher rate than subsequent flows. Indeed, small storm event volumes may be captured entirely (with no resulting load), while later flows during large storms may bypass much of the detention system entirely and receive no treatment and no flow reduction at all. The elimination of discharges of untreated stormwater discharges of small and medium sized storms may provide a source of water quality impact mitigation in receiving waters as a basin scale effect, but has not been assessed in the literature.

2.1.5 Basin Scale Effects from the Wide-scale Use of LIDs

Most of the literature provided in the literature database on the LID facilities addressed here evaluates individual facility performance affecting hydrology and water quality. Some studies have begun to evaluate the use of LIDs on larger scales, from treatment trains or combined LIDs, to constructed pilot residential developments (Hinman 2009a, Bedan and Clausen 2009, Dietz and Clausen 2005, Zimmerman et al. 2010), to modeling of distributed use of LIDs on a basin scale and its effect on stream flow or load reduction (Damodaram et al. 2010,Carter and Jackson 2007, Scholz 2011, Zimmerman et al. 2010, Hurley and Forman 2011). Scale effects change from the local level to the basin-wide scale, with the determining factor being the percent impervious land use in the basin, density of LID, as well as the location of the LIDs in the basin. The higher the percent impervious area and the higher the density of LID use within that area, the more discernible the benefit of LIDs on downstream flows are expected to be.

The response of site development scale implementation of LIDs reflects a composited response of a high density of many individual facilities in a relatively small area. Maintenance (or restoration) of pre-developed flow rates was commonly seen among these projects, at least for the smaller range of storms. These projects showed an increase in number of small storms with no flow. Hydrologic changes from the reduced runoff from these developments, however, will be more realized in nearby first order receiving water stream channels (Gilroy and McCuen 2009). Together with a careful selection of the return-time storm to meet the intended objective, LID site design on the development scale can be further optimized through strategic placement of the facilities in the most effective locations on the site (Gilroy and McCuen 2009).

Watershed scale modeling of a widely distributed use of LID, however, finds that detectable effects on receiving waters are highly dependent on the overall level of impervious area in the basin, and the corresponding density of LID. Scholz (2011) found hydrologic response differences between conventional and LID build-out scenarios in a 211 square mile watershed were minimal at the watershed scale because total impervious cover was low (<7.5 percent), while differences were substantial in developed, smaller subwatersheds with high impervious cover. In this study the basin-wide conventional build-out scenario had a range of 29 to 36 percent increase in flow volumes, while LID build-out had a range of negative two to positive seven percent change.

Damodaram et al. (2010) found modeled performance of LID practices on a basin scale were effective for small events, but less so for flood events (similar to the performance of individual facilities). Control of larger events required inclusion of more traditional, peak-controlling, large centralized BMP facilities. Ackerman and Stein (2008) also found combined LIDs were more effective for smaller storms, but also saw LIDs operating in series may contribute to performance. Carter and Jackson (2007) found wide distribution of green roofs across a basin for volume control likewise would have minimal affect for storm events greater than the two-year, 24-hr event. Similar to Gilroy and McCuen (2009), however, spatial analysis to identify zoning with more flat roofed buildings (commercial, industrial, and institutional) had substantially greater affect than sloped-roof residential areas. In addition to the level of land use density of a basin for potential LID effectiveness, spatial discrimination in the use of LIDs on a basin scale is important in optimizing the use of LIDs in watersheds. Ahiablame et al. (2012) emphasize research is needed to identify the spatial and temporal performance characteristics of “scaled up” application of LID to a basin scale.

While some modeling of the basin scale use of LIDs on downstream hydrology has been conducted, virtually no documentation has been carried out on the ecological or geomorphological benefits of the use of LIDs in downstream receiving waters. Toland et al. (2012) monitored nutrient runoff concentrations from green roofs and compared those concentrations with nearby stream receiving water concentrations. The intention of that monitoring was to anticipate whether high nutrient concentrations might cause periphytic growth in the receiving waters. Carter et al. (2009) reviewed past literature looking for measured benefits of BMPs on downstream biota and conclude "much of the potential of BMP structures to mitigate effects of stormwater on stream biota remains unidentified at the watershed scale."

Modeling of potential hydrologic outcomes, including reduced flooding, was found in Damodaram et al. (2010), as well as in various other recent journal articles not listed in the database (Scholz 2011, Carter and Jackson 2007). Bedan and Clausen (2009) conducted a paired watershed study comparing quality and quantity of residential stormwater from a control, traditional, and LID watershed, but did not identify basin scale or ecological outcomes in the watershed.

Some authors are beginning to evaluate new metrics and field study designs to connect stormwater management performance with observable instream benefits (Carter et al. 2009, Walsh and Kunapo 2009). Clearly, with the growing requirements through the NPDES stormwater permit to implement LID technologies, and the plan to conduct effectiveness studies under the new permit, specific monitoring approaches that discern benefits of LID use at the basin scale are needed.

2.1.6 Effect of facility aging on long term performance

Most of the facility performance assessments were relatively short term in duration (six months to two years) and the age of the facility relatively young (less than eight years). Many of the literature reviewed noted rapid reductions in infiltration rate due to clogging soon after the beginning of facility operation, decreases in total suspended solids discharge within a short period of operation, sudden pulses or reductions in nutrient concentrations within the first few storms or years of operation, or the longer term effect of the establishment of vegetation on infiltration or interception and evaporation. Le Coustumer et al. (2009) found most bioretention facilities, for example, were oversized, so reduced infiltration rates with age did not reduce treatment performance. Le Coustumer et al. (2012) found hydraulic loading rates, sediment loading rates, and the long term development of root structures will affect the clogging rate of facilities, and so must be taken into account in facility sizing. Many of the literature sources recognized the need for long term monitoring to evaluate the effective lifespan of LID treatment performance, whether for water quantity or quality control.

2.1.7 Lack of Documentation of Downstream Beneficial Effects on Flooding, Watershed Function or Receiving Water Hydrology or Ecology

One clearly lacking discussion among all the papers reviewed was a lack of documentation of ecological benefits from the implementation of any of the LIDs discussed. Zimmerman et al. (2010) conducted monitoring of a small development-scale LID enhancement designed to diminish the effects of stormwater runoff on downstream flow and water quality. Only base flow improvement in small stream tributaries was discernible as a benefit. Jones and Hunt (2009) found that even small bioretention facilities decreased flow-through temperatures as well as

reducing flow volumes. Between reduced temperatures and reduced thermal loads, bioretention may be a benefit to instream cold water habitat for trout on the east coast.

Among the various modeling exercises reviewed, a common theme is the effect of LID use in a watershed on stream flows. Effects on stream flows was only discernible when a threshold of density of use was reached, and even then the effect on the largest storms diminished with increasing storm size. Additionally, many of the individual facility studies found small to medium sized storms were fully infiltrated and had no surface discharge. Consequently, water quality benefits in surface receiving waters might be expected to occur at the basin scale by the simple elimination or first flush infiltration of untreated stormwater discharges from many small and medium sized storms that are infiltrated by LID facilities. Conversely, infiltrated pollutants (e.g. nutrients) may also contribute to impacts to receiving waters if they are transported subsurface as groundwater flow to receiving waters. Neither of these potential effects on receiving water was evaluated in the literature reviewed.

To support documentation of receiving water benefits, Carter et al. (2009) propose study designs to discern watershed effects resulting from watershed-scale LID development, and report some initial findings of a paired watershed approach case study.

2.1.8 Highly Variable Basis of Design and Sizing in the Literature Database Projects

The range in design and sizing (and quite likely in the care of construction and maintenance) of the LID projects evaluated in the Stormwater Work Group's literature database being reviewed here was highly variable, with little ability to easily assess or compare the projects on more than a categorical basis (as is being done under the International Stormwater BMP Database). Barrett (2008) notes that (regarding the International Stormwater Database) "a popular misconception has been that the database contains well-designed BMPs and that the performance data represent what would be expected under current design guidelines." This comment applies equally to the results from the literature reviewed here. In combination with the simplification inherent in the reporting of percent reductions of concentrations or flows noted above, the reporting of more than general concepts in the performance of these systems for use in predicting the effectiveness of Puget Sound-based facilities would be equally inaccurate.

Hinman (2012) and Ecology (2012) provide an excellent existing basis for LID design in the Puget Sound Region. The recommendations provided in this report are intended to contribute to even more focused LID designs and sizing for use in the Puget Sound region. The need for more accurate sizing of facilities to more specifically match internal volumetric storage and surrounding site conditions that affect exfiltration and evapotranspiration, with expected retention performance for the targeted design storm event were noted in a number of articles. As noted above in the discussion of abstraction volume, the International Stormwater BMP Database (2012c) observed a wide range of study retention performance in bioretention facilities (20 to 80 percent) within a small range of bioretention to contributing area ratio (four to six percent). Since the areal hydraulic loading rate is a major design consideration for hydrologic retention, the wide range in retention performance suggests a wide range in volumetric design accuracy occurs across individual facilities.

2.1.9 Dearth of Publications in the Database from the Pacific Northwest

There is an obvious lack of published LID study projects in the peer-reviewed or grey literature listed in the database from the Pacific Northwest; only nine documents were listed for the combined rain garden, porous pavement, biofilter, LID categories. Among these included only Brattebo and Booth (2003) and Chapman and Horner (2010) from the peer reviewed literature, and Hinman (2009a, 2009b, 2012) as the only recent documents in the grey literature. A wide ranging survey of swales in Snohomish and King Counties is provided in Colwell et al. (2000). The overwhelming majority of the LID-related literature in the database is from the east coast, and some from the upper mid-West, Australia and Europe.

2.2 GENERAL RESEARCH APPROACH AND QUALITY OF DATA COLLECTION IN THE LITERATURE IN EVALUATING LID SYSTEMS

The studies and other literature presented in the literature database (and other acquired literature) on these LID systems (permeable pavements, bioretention, and green roofs) presented a common approach of building experimental columns, bench scale, unit scale or full scale systems with built-in monitoring systems for evaluating flow rates and/or collect water samples at inflow and outflow points within the system. The approaches involved measuring continuous flow rates over primary hydraulic control devices, which is the most robust means of getting accurate and precise flow rates in the field. Additionally, water samples were collected by automated water samplers, but precisely how and over what duration water samples were flow-weighted or time-paced was not always clear, nor were quality assurance and quality control measures clearly articulated (see below).

With these monitoring systems in place, the researchers aimed to provide a mass balance assessment of flow through the systems; that is, storm events or time-periods of inflow and outflows were measured, with the differential between the two (usually a loss of water) attributed to evaporation or infiltration to the ground either laterally or beneath the facility. Given the frequency of downloading and use of primary devices to measure flow, the flow quantities and water surface elevations reported appear to provide accurate and consistent results when reported. Some of the reported projects went to extraordinary means to try to assure the accuracy of flow data, such as laboratory-calibrated weir equations and redundant flow stage recorders (e.g. Collins et al. 2008). One study went so far as to excavate the project detention bed to visually inspect, reinstall, and reseal the subsurface flow collection system because “greater than expected rainfall retention” was observed in the first two years of monitoring (Fassman et al. 2010). Subsequent monitoring with the reinstalled system confirmed the accuracy of the first period of monitoring.

This being said, many of the papers reported equipment failures, submergence of flow measurement devices by flooding, unmeasured flows entering the system, or otherwise unreliable data that was not presented or used in the analyses. The International Stormwater BMP Database (2011) suggests “[e]ven a calibrated site with control structure may have an error of plus or minus 20 percent due to combined considerations of equipment sensitivity and multiple sources of potential error.” Nonetheless, the flow results from the literature appear to provide an overall dependable accounting of the total stormwater flows as they passed through the systems.

The water quality sampling quality control process, on the other hand, was not fully elaborated in the papers reviewed. Except for Bedan and Clausen (2009) and Hinman (2009a), no other papers of those reviewed referred to a quality system plan or a quality assurance quality control plan. Line and Hunt (2009) described blank and duplicate sample analysis. While the water quality sampling results provided data that appeared to have reasonable scales of magnitude and logical explanations for the changes in water quality as the flow passed through the systems, there was generally little detail provided of the quality assurance and quality control steps taken in the sampling procedures. Rossi et al. (2011) notes that in environmental applications, including stormwater monitoring, "Rarely described is how samples were taken." Similar to the moderately wide range in confidence for hydrologic results (even when all monitoring is done well), the water quality sampling process can be affected by an accumulation of errors resulting in 10 to 30 percent error (Rangarajan et al. 2012).

The Washington State Department of Transportation stormwater program has recognized the significance of cumulative sampling process error in the stormwater data generation process, and has developed a comprehensive "Quality Management System" designed to define stormwater monitoring procedures to be used through the entire data generation process (WSDOT 2011)). This level of detailed quality control planning is intended to reduce the cumulative effect of individual sources of error in the stormwater monitoring process. The lack of detailed sampling procedures for the water quality data generation process in most of the papers reviewed may add a pause for concern for both the accuracy and precision in the results of water quality samples collected in these studies.

2.3 PERMEABLE PAVEMENTS DESIGN AND EFFECTIVENESS OVERVIEW

Permeable pavements evaluated in the literature database comprise pervious concrete (PC), permeable interlocking concrete pavers (PICP) with small gravel filling the joining edge spaces, concrete grid pavers (CGP) with sand filling the grid voids, and pervious asphalt. Within each of these types of pervious paving surfaces, an underlying volume is excavated and filled with an aggregate stone base course material on top of the native soil subgrade, and a thinner layer of generally finer bedding material just beneath the permeable pavement itself. Various compositions of layer material size specifications and depths in the research plots were designed. A perforated drain pipe may also be included at an elevation in the detention volume to intercept and drain filling rain water to avoid submergence of the surface, and a geo-fabric placed above the subgrade to prevent upward migration of fine materials from the bare surface. Pervious asphalt may also involve only a "friction course" that is a shallow layer of pervious asphalt overlaying a conventional asphalt roadway (USEPA 2012b).

With this structural design of permeable pavements, the pavements themselves and the underlying basins act as both volumetric detention that slows the hydrologic flow, and facilitates evaporation and infiltration into the subgrade soils. Additionally, the various layers of material act as physical filtration and biologically activate surfaces that can filter contaminants or mediate contaminant transformation that affect water quality improvement.

2.3.1 Hydrologic Findings from Pervious Pavement Study Results

Numerous of the reviewed papers found consistent patterns and magnitudes of flow-through processes and infiltration rates on pervious pavement systems, and magnitudes of runoff reduction ranging commonly from 50 to 100 percent. When compared to side-by-side monitoring

of conventional asphalt, asphalt surfaces typically generated almost all the rainfall into runoff, with little time lag (Brattebo and Booth 2003, Fassman and Blackbourn 2010). Storm to storm runoff volumes from pervious pavement have been seen to generate no runoff from small or even most of the storms, followed by variable runoff that is proportional to larger storm event.

2.3.1.1 Pervious Pavement Volume Reductions

Keeping in mind the volume reduction analysis discussed previously, mean percent reductions in volume found by Collins et al. (2008) for PC, PICP, and CGP were 43 percent, 66 percent, and 63 percent respectively of the total rainfall during the study. Sansalone and Teng (2004) found volume reductions of 55 to 70 percent through a cementitious porous surface exfiltration reactor. Consistent with the abstraction volume concept of Davis et al. (2012), Fassman et al. (2010) found pervious pavement underdrain runoff percentage of the rainfall ranged from 29 percent for small storms (tenth percentile of storm size) to 63 percent for large storms (ninetieth percentile storm size). Ahiablame et al. (2012) after a thorough review of the literature suggested 50 percent to 93 percent reduction in volume was representative of pervious pavement systems (Table 1). The International Stormwater Database (2012b) determined that while the permeable pavement data category is relatively well represented in the database, it “is not well suited for volume analysis as an overall category due to variations in study designs associated with use of reference sites.”

Table 1. Summary of literature values for percent runoff and pollutant retention by permeable pavements, from Ahiablame et al. (2012).

Study	Location	Runoff	TSS	P/TP	NO3-N	NH4-N	TKN	Cu	Pb	Zn	FC
Legret et al. (1999)	Reze, France	--	58	--	--	--	--	--	84	73	--
Pagotto et al. (2000)	Nantes, France	--	87	--	--	--	--	20	74	--	--
Rushton (2001)	Florida, USA	50	>75	>75	--	>75	>75	>75	>75	>75	--
Hunt et al. (2006)	North Carolina, USA	75	--	--	--	--	--	--	--	--	--
Dierkes et al. (1999)	Lab Experiment, Germany	--	--	--	--	--	--	98	99	95	--
Fach and Geiger (2005)	Lab Experiment, Germany	--	--	--	--	--	--	>85	>85	>85	--
Dreelin et al. (2006)	Georgia, USA	93	--	10	--	--	--	--	--	80	--
Pezzaniti et al. (2009)	Lab Experiment, USA	--	94	--	--	--	--	--	--	--	--
Tota-Maharaj and Scholz (2010)	Edinburgh, Scotland	--	--	78	--	85	--	--	--	--	98-99
Meyers et al. (2011)	Adelaide, Australia	--	--	--	--	--	--	94-99	94-99	94-99	--

Definitions: TSS total suspended solids; P/TP phosphorus/ total phosphorus; NO3-N nitrate; NH4-N ammonia; TKN total Kjeldahl nitrogen; Cu copper; Pb lead; Zn zinc; FC fecal coliforms.
Source Ahiablame et al. 2012.

2.3.1.2 Surface Infiltration Rates in Pervious Pavements

Infiltration rates into pervious pavement surfaces were found to be variable but generally high in numerous studies (Abbott and Comino-Mateos 2003, Bean et al. 2007b, Brattebo and Booth 2003, Collins et al. 2008, Emerson et al. 2008, Hinman 2009b, Kwiatkowski et al. 2007, Illgen et al. 2007, Roseen et al. 2012). The range in surface infiltration rates at pervious pavement facilities ranged over many orders of magnitude (10^{-2} to 10^{4} cm hr^{-1}) and appeared to become less over time, especially quickly for new installation (Earles et al. 2009). However, in each case virtually all of the rainfall still fully infiltrated through the pervious surface and into the aggregate-filled basin area below. Some pervious surfaces even received and were able to infiltrate additional flow from adjacent impervious areas (Illgen et al. 2007).

Only in the facilities with the lowest infiltration rates and at the highest rainfall rates was surface runoff generated (Brattebo and Booth 2003), or where off-site fine materials significantly clogged a portion of the test area (Abbott and Comino-Mateos 2003, Bean et al. 2007b). Additionally, even where some surface areas became somewhat clogged and formed pooling on the surface of the permeable pavement test areas, the distribution of the pooling was very heterogeneous, and pooled areas were ultimately infiltrated in adjacent areas rather than generating surface runoff (Illgen et al. 2007).

One final major element of the characteristic of each study was the given age of the installed permeable pavement systems and its effect on accumulation of fine substrate on infiltration rates; either measured reductions in infiltration or perceived “clogging” of the porous media was observed in many of the projects. Overall, the systems were generally recent in their construction (less than five to seven years in operation). Regardless of, at times, large reductions in measured infiltration rates, the authors reported the remaining infiltration rates were still sufficient to infiltrate most of the largest storm intensities.

The benefit of infiltration for pervious pavement may be in their use over large otherwise impervious areas (e.g., parking lots and streets) where detention and infiltration can occur beneath the facility (i.e., do not require additional areas for these functions), and can receive inflows from adjacent areas. Bioretention systems, on the other hand, occur on the surface and require additional space, but receive flow from larger adjacent areas.

2.3.1.3 Storm Volume Loss by Evaporation and in Low Permeability Subgrade Soil

Overall reduction of total rainfall volume passing through the pervious pavement systems was seen consistently in the various pervious pavement studies. The reduction of water flowing through the underlying aggregate-filled basins was surprisingly large to some of the researchers, and many attributed the reduction to evaporation and infiltration into the underlying soil subgrade, even for “tight” (variously referred to as type C, glacial or clayey) soil subgrades that had low infiltration rates (Fassman and Blackbourn 2010, Roseen et al. 2012, Sansalone and Teng 2004). Fassman and Blackbourn (2010) recognized other studies have seen evaporation occurring as a means of reduction of rainfall volumes (even resulting in cooling effects on the pervious surface), and Collins et al. (2008) suggested evaporation was a source of total flow reduction in their study.

Regarding apparent high levels of infiltration in low permeability subgrade, more than one author suggested the underlying soils’ permeability may be heterogeneous, or may contain cracks and fissures allowing exfiltration through otherwise highly impervious soils. Tyner et al.

(2009) successfully applied construction treatments (trenching, ripping, and bore holes) to the underlying compacted clay subgrade to increase the infiltration rate. Similarly Brown and Hunt (2010) scarified the underlying soil surface to improve subgrade infiltration. Evidence of apparent infiltration in low infiltration sites for permeable pavements in the Northwest includes current performance at the Washington State University (WSU) Stormwater Research Program. Some projects have shown almost no outflow from the systems at the WSU LID research facility in Puyallup, WA where soils were expected to be highly impervious (Hinman, C. pers. comm.).

2.3.1.4 Related Peripheral, Permeable Pavement Questions Researched in the Database

Separate from flow and pollutant load reductions, however, literature was not identified from the database addressing the durability of pervious pavement (except cursory observations; cf. Brattebo and Booth 2003), especially for high speed, volume, or load roadways (see Liu et al. 2012 for a description of a high load bearing pervious pavement design used on high use roads); nor was of the use of alternate construction material (e.g., recycled concrete as aggregate base course material) found in the literature reviewed from the database or found easily in a separate academic database search. Each of these research questions are more roadway structural engineering questions that should be further researched through academic databases addressing roadway engineering. Among the permeable pavement designs, many of the designs are commonly used successfully in many different climates. Porous asphalt mixtures may need further refinement for more successful application in the Pacific Northwest (Hinman, C. pers. comm.).

2.3.1.5 Overall conclusions on hydrologic response of permeable pavement

The overall results from these literature reviewed from the database indicate both continued high surface infiltration rates and reduction of flow volumes, even as the permeable surface becomes partially clogged through age, and even when subgrade soils are expected to have low exfiltration rates.

The result of these studies reaffirm that pervious pavement infiltration systems respond to hydrologic flow following the same principles of hydrology within open watershed; i.e., they respond to the controlling factors of overall hydrologic abstraction (storage) volume, antecedent conditions, surface infiltration rate and processes, subsurface routing of flow (including detention storage), evaporation through surface area wetting and drying, and subgrade infiltration. While these factors will vary regionally, the unifying primary design consideration that distinguishes between facilities' performance (and that can be used for sizing) is the abstraction volume relative to the drainage contributing area and local rainfall intensity-duration pattern as described by Davis et al. (2012).

2.3.2 Water Quality and Load Reduction from Permeable Pavement

Various papers identified in the database addressed water quality improvement effectiveness as a result of passing through permeable pavement systems. Because infiltration through permeable pavements is essentially a filtration and infiltration process, numerous water quality parameters evaluated were improved through the passage through the permeable pavement systems. While filtration and infiltration mechanism are expected to be the primary removal processes, a number of processes can be active (Revitt et al. 2008), including:

- Adsorption
- Precipitation

- Settling and filtration
- Aerobic and anaerobic biodegradation
- Volatilization
- Photolysis
- Plant uptake

Substantial removal rates evaluated in field monitoring exercises were seen for total suspended solids (Bean et al. 2007a, Tota-Maharaj and Scholz 2010), phosphorus and nitrogen nutrient species (Bean et al. 2007a, Collins et al. 2010a, Tota-Maharaj and Scholz 2010), BOD and bacteria (Tota-Maharaj and Scholz 2010), metals (Bean et al. 2007a, Brattebo and Booth 2003), and PAHs and herbicides (Revitt et al. 2008). pH is typically slightly acidic in rainwater, and passage through permeable pavement materials (especially cementitious concrete) adds hardness to the infiltrate, and elevates pH and alkalinity in the exfiltrate (Brattebo and Booth 2003, Kuang and Sasalone 2011, Tota-Maharaj and Scholz 2010).

Additionally, biologically-mediated transformation of some pollutants was evident, especially nitrification of ammonia nitrogen to nitrate nitrogen. In some cases, however, this resulted in higher concentrations of nitrate-nitrogen exfiltrating from the basin system (Bean et al. 2007a, Collins et al. 2010a, Tota-Maharaj and Scholz 2010). Also as an exception, Brattebo and Booth (2003) detected increased concentrations of Zn in a permeable pavement system exfiltrate.

Overall, pollutant loads, if not actually calculated, were reduced substantially from all the systems evaluated due to the combined effects of consistently reduced volume and reduced concentrations. In addition to reduced runoff volumes, typical concentrations of measured pollutants are reduced from 50 percent to 95 percent (Tetra Tech 2010, USEPA 2012b). See Table 1 for data on flow pollutant reduction values for permeable pavements summarized by Ahiablame (2012) and Table 2 for inflow and outflow concentration quartiles for permeable pavements from the International Stormwater BMP Database (2011).

Table 2. Summary of inflow and outflow concentration percentiles for permeable pavements from the International Stormwater Database (2012c).

Permeable Pavement	Flow*	TSS mgL^{-1}	P/TP mgL^{-1}	NO3-N mgL^{-1}	NH4-N** mgL^{-1}	TKN mgL^{-1}	Total Cu mgL^{-1}	Total Pb mgL^{-1}	Zn mgL^{-1}	FC
25th percentile										
In	--	18.30	0.09	0.22	--	1.00	8.70	1.99	27.00	--
Out	--	7.08	0.05	0.33	--	0.46	4.84	0.93	9.00	--
Median										
In	--	65.30	0.18	0.42	--	1.28	13.07	4.30	57.60	--
Out	--	13.20	0.09	0.71	--	1.05	7.83	1.86	15.00	--
75th percentile										
In	--	186.70	0.29	0.79	--	2.50	27.00	9.98	131.40	--
Out	--	27.00	0.14	1.36	--	1.30	12.62	4.93	26.70	--

Definitions: TSS total suspended solids; P/TP phosphorus and total phosphorus; NO3-N nitrate; NH4-N ammonia; TKN total Kjeldahl nitrogen; Cu copper; Pb lead; Zn zinc; FC fecal coliforms.
*Flow analysis for porous pavement was deemed not appropriate due to irregular use of reference sites.
**Included with the TKN analysis result as the sum of free NH4 and organic nitrogen.

Infiltration of stormwater through permeable pavement systems did not appear to transport pollutants to a degree that would adversely affect ground water (Kwiatkowski 2007, Clark and

Pitt 2007, Diblasi et al. 2009). Potential for contamination will depend on concentrations, mobility, and soluble fractions of infiltrating source water (Clark and Pitt 2007).

Virtually all pollutants (except nutrients and chloride from road salt) become largely adsorbed or otherwise removed from infiltrating stormwater within the near surface, as long as the facility is properly sited. While the International BMP Stormwater Database (2012c) report nitrate levels appear to increase in the outflow from permeable pavement systems, the range of concentrations are not in the range that would negatively affect groundwater (Table 2).

Notwithstanding, the literature sources commenting on the potential for contamination of groundwater were few, and did not specifically address subsurface exfiltrating concentrations of the test facility, but rather surface outflow concentrations. In particular, subsurface samples were not commonly collected of the water exfiltrating from the system, and did not address the potential for extremely high concentrations of NO3-N originating from biofiltration media (see below for bioretention and talking points section).

Potential groundwater contamination will depend on exfiltrating mass loads and local hydrogeologic conditions (Wolf et al. 2007). More study of the local Puget Sound region conditions for potential groundwater contamination is an example of the effectiveness studies recommended in this report.

2.4 SWALES AND BIORETENTION FACILITIES DESIGN AND EFFECTIVENESS OVERVIEW

Bioretention LIDs including grass strips, grass swales, and constructed bioretention infiltration facilities (with rain gardens included as synonymous or a subset of bioretention) can be seen broadly as similar functional facilities in the literature, as they are vegetated soil facilities receiving stormwater inflow either as sheet flow or point inflows, with some degree of surface and subsurface filtration, and include plant communities. Grass strips are generally longitudinal in layout and receive sheet flow inputs, while swales are a low gradient vegetated dry or wet channel. Both are more commonly “non-engineered” designs utilizing existing vegetated ditches also frequently along roadsides or margins of developed land sites.

Bioretention facilities are more commonly “engineered” facilities receiving stormwater point inflows from adjacent impervious areas, and constructed with and without underdrains. The “engineered” quality includes more attention to storage volume of the facility relative to inflow drainage area, and specified layering of soil layer components. The configuration without an underdrain is more the form of “non-engineered” rain gardens as they are thought of in Washington State, where the facility is small and simply an excavated pit filled with top soil and plant material. As an example comparison of terminology, Bedan and Clausen (2009) refer to rain gardens in their study as “individual bioretention areas.”

As will be seen below, the presence of an underdrain in bioretention facilities can have an important effect on volume control and even water quality differences between facilities. Outflow from facilities with an underdrain is released via the drain and as overflow, and both are accounted for in monitoring studies as outflow. Flow from bioretention facilities without an underdrain exits either laterally or downward through the surrounding or subgrade soils, or as overflow when the facility fills completely.

The primary distinction between all these types of facilities is the degree of excavation and the design of layering of soil and subsurface materials (and thus the resulting degree of infiltration and subsurface storage volume). This ranges from grass strips and swales that may have little or no excavation of soil material or amendment of soil and plant materials, to designed bioretention facilities that have an excavated basin with specified soil mix fill layers and a planting plan (with or without an underdrain).

The result from this diversity of engineering of the soil and subsurface materials is a wide range in the degree of infiltration expected in each facility; from generally little or no infiltration in non-engineered swales and grass strips (where compaction has affected the infiltration capacity for example), to highly designed storage and infiltration capacities that can hold and infiltrate virtually all of the inflow volume. Each of these categories of LID responds to the concept of BAV from Davis (2012) previously described. Again, the variation in design and individual site conditions among these facilities can be substantial, generating wide variation in reported results in volume retention and water quality (International Stormwater Database 2011, International Stormwater Database 2012a).

Because the literature on bioretention was substantially greater, and the dynamics and variation in the hydrology and water quality results more complex, significantly more assessment is provided to this LID technology.

2.4.1 Hydrologic Findings from Swales and Bioretention Facilities

Hydrologic retention of grass strips and swales is generally less than for bioretention facilities as indicated by data from the International Stormwater BMP Database (2011). Table 3 provides a summary of data from the Database of the 25th, median, and 75th percentile flow reduction values for swales and bioretention facilities, including grass strips, grass swales, and bioretention features with and without an underdrain. Following are findings from the literature that affect performance of grass strips, swales and bioretention facilities.

Table 3. Summary of Flow Reduction for Filter Strips, Swales, and Bioretention from International BMP Stormwater Data Base (2011, 2012a).

Analysis Group	# of Studies	25th Pctl.	Median	75th Pctl.	Avg.
Bio-filter Grass Strip	16	18%	34%	54%	38%
Bio-filter Grass Swale (dry)	13	35%	42%	65%	48%
Bioretention (all studies)	20	42%	66%	98%	66%
Bioretention (no underdrain)	6	85%	99%	100%	89%
Bioretention (with underdrain)	14	33%	52%	73%	56%

2.4.1.1 Grass Strips

Grass strips are commonly identified as part of road side studies where sheet flow passes through an initial grass strip along the shoulder. Regardless of their location, unless amended with additional porous soil, vegetation in grass strips promotes reduced velocities within the strip rather than infiltration (Minton 2011).

Soil compaction and incomplete vegetation cover were identified as significant influences on low volume reduction (5 to 15 percent) of a grass strip studied by Winston et al. (2012). Drought is likely a significant factor affecting poor vegetation cover on roadside runoff areas of the Pacific Northwest (Colwell et al. 2000). Conversely, the high volume reduction (85 percent) seen by

Hunt et al. (2010) was attributed to the high filter strip area to watershed ratio, relative flat slope, and surface soil amendment included in the site. Between these, inflow volume was reduced by 49 percent for a grass strip planted with a thin top soil layer overlain by Burmuda sod (Line and Hunt 2009). See Table 3 for a summary of flow reduction values by grass strips.

2.4.1.2 Swales

Swales are categorized as dry or wet swales, depending on whether perpetual water stands in the swale or not. In either form, swale facilities are more intended to maintain vegetation that slows velocities during runoff, thereby promoting a water quality function through settling and surface adsorption rather than infiltration (Ahiablame et al. 2012, Colwell et al. 2000, Minton 2011). The Center for Watershed Protection (CWP) (2008) indicates a runoff reduction range from a literature review of 40 to 60 percent for dry swales, and zero for wet swales.

Deletic and Fletcher (2006) found deposition of sediments within the channel appeared to cause clogging of soil and a decrease in infiltration rates, leading to decreased infiltration in swales especially at the head of the swale treatment reach where deposition will be greatest. Ahiablame et al. (2012) do not report a summary of flow rate reductions for swales from their literature review. See Table 3 for a summary of flow reduction values by grass swales.

2.4.1.3 Bioretention Facilities

Bioretention facilities, whether large or small, with or without an underdrain, show the highest runoff reductions among this group of LIDs (Ahiablame et al. 2012, International Stormwater BMP Database 2011 2012a). Table 3 and 4 provide summaries of flow reductions by the International Stormwater BMP Database (2012a) and Ahiablame (2012). As discussed before, these values composite into one number the variability of individual storm flow reductions from small storms (high reduction) to large storms (low reduction). The distribution of the storm sizes used in the analysis of flow reduction will also affect the outcome (i.e, if storm size distribution was skewed to smaller or larger storms than is normally seen in the local weather patterns).

Notable within the International Stormwater BMP Database (2012a) results for flow reduction distribution for bioretention facilities is the difference in reduction between facilities with and without an underdrain (Table 3). The outflows monitored for facilities with an underdrain included both flow from the underdrain and overflows exiting through surface outlets which occurred when the facility was fully saturated. Because one of the original and most important goals of the use of LID is to support infiltration and stream base flows, some researchers recommend non-use of underdrains unless subsurface infiltration rates and downstream conditions suggest otherwise (Jones and Hunt 2009, Dietz 2007).

Consistent with the principles of available BAV described by Davis et al. (2012), numerous of the bioretention facilities reported no outflow for small storms (e.g. Chapman and Horner 2010, Davis 2008, Diblasi et al. 2009). Peak flows are typically reduced for small and medium in virtually all studies reporting on peak flow response when flow does occur. However, when saturation of the bioretention facility occurs during large storms, runoff response will tend to approach unmitigated peak flows of the contributing area as predicted in Davis et al. (2012).

In addition to the importance of design volume in reducing total volume and peak flows for a given storm event, Gilroy and McCuen (2009) found the spatial location of bioretention or other LID facilities within the contributing catchment had an effect on the volume reduction and peak

reduction for one- to two-year frequency design storms. Placement of facilities to prioritize receiving runoff from impermeable areas over permeable areas results in substantial increases in infiltration and optimization of available volume. In addition to hydrologic performance "[k]nowledge of the most effective location and quantity of BMPs can influence the cost, maintenance, aesthetics, and safety of a development design."

Some seasonality of flow reduction was also observed, with less reduction during the winter wet season than the summer. The effect of the wet season was presumably from the combined effects of antecedent moisture conditions in the facility (i.e. reduced abstraction volume available for the next storm), less evaporation, and influence of higher local ground water. The effects of ground water intrusion to the project were not identified significantly among the literature reviewed except for Line and Hunt (2009) that found an overall increase in flow exiting the facility, and suggest the "data indicate probable water influx into the outflow underdrains." Emerson and Traver (2008) found seasonal infiltration rates can be explained by the temperature variation in viscosity.

Asleson et al. (2009) developed a visual assessment procedure to evaluate performance of twelve rain gardens, with four apparently "failing" based on the presence of ponded water, hydric soils, emergent vegetation, or failing vegetation. The remaining eight were evaluated for saturated hydraulic conductivity of the soil surface at several locations of each, with a mean range of three to 72 cm hr^{-1}.

The distribution of infiltration rates within bioretention facilities may be heterogeneous, with less near inflow points or flow paths within the facility and more in the remaining perimeter of the surface area (as was similarly suggested for permeable pavements, Pitt et al. 2008). This concept of heterogeneous infiltration rates within a basin took the most extreme example in Carpenter et al. (2010) where high infiltration-rate soil mixtures promoted development of "preferential flow paths" (i.e. short circuited paths) directly to the underdrain and circumventing a significant portion of the retention cell volume. An effective visual assessment of large numbers of bioretention facilities may be a cost effective programmatic alternative to more costly flow monitoring.

Brown and Hunt (2011) also discovered the potential for bioretention facilities to become clogged with fines thereby significantly affecting their infiltration rates. Granite fines passing through a geotextile from construction of the asphalt parking lot subbase reduced the drawdown rate to approximately 0.25 to 1.3 cm hr^{-1}. The resulting increased frequency of overflow produced minimal reduction of peak flow control at the facility. Similar to the clogging impacts described for permeable pavements, bioretention facilities can be susceptible to clogging from nearby significant run-on sources of fine materials, but the overall infiltration capacity can remain sufficient to infiltrate runoff (Gilbert Jenkins et al. 2010). Emerson and Traver (2008) also found no degradation of infiltration rate over a period of six years, although they recognize there may be an initial rapid decrease in infiltration rate soon after construction. Hatt et al. (2009) found enhanced infiltration from root growth and senescence in bioretention areas will counter compaction and clogging.

Greater media depth in bioretention facilities provides greater contact with subsurface soils thereby increasing exfiltration. Notwithstanding the clogged surface conditions encountered by Brown and Hunt (2011), they still found greater exfiltration in a media depth of 0.9 meters over

0.6 meters. Exfiltration overall was greater than expected in most bioretention facilities, even in "tight" soils (e.g. Chapman and Horner 2010, Sansalone and Teng 2004). The data from the International Stormwater BMP Database (2012a, see Table 3) indicating greater bioretention volume reduction in facilities without an underdrain as opposed to with an underdrain would tend to support this.

2.4.2 Water Quality Findings from Swales and Bioretention Facilities

The literature provided in the database shows wide ranging but generally large (greater than 50 percent) reduction in the concentrations of multiple water quality parameters in swales and bioretention facilities. Total suspended solids (TSS), nutrients, and metals all show relatively dependable reductions at least in load if less so in concentration, with some notable exceptions from the literature reviewed. High outflow phosphorus values in some projects appear to skew the range outflow concentrations seen in the International Stormwater BMP Database (2012c).

Characteristics of grass strips, swales and bioretention facilities will be described together here but largely focused on bioretention facilities. Water quality performance of strips and swales will be based more on a physical particulate settling process (Minton 2011), while bioretention facilities have a more complex combination of settling, filtration, and internal processes that affect the ultimate effluent water quality conditions. Davis et al. (2009) provide an excellent overview of the water quality performance, mechanisms and challenges of bioretention technology. Tables 4 and 5 provide summaries of water quality retention, and inflow and outflow quartiles for various parameters (Ahiablame et al. 2012, International Stormwater Database 2012c).

Most of the pollutant parameters evaluated in the literature have a considerable fraction that is associated with particulate matter; only chloride from road salt is largely conservative and ionized as it passes through LID facilities. Otherwise concentration reduction at individual facilities appears to be highly correlated with TSS reduction (Chapman and Horner 2010, Diblasi et al. 2009). Chapman and Horner (2010) suggest that because TSS reduction is associated with successful volume reduction, volume reduction could be the most important design aspect of water quality mitigation design. Potential impacts to groundwater quality will be similar to that described for permeable pavements, except nutrient and copper leaching from bioretention media has become an identified concern (see below and "Talking Points" section for further discussion).

Wide ranges in outflow concentrations (even negative reduction rates) found in the literature are often associated with nutrients (nitrogen and phosphorus) and copper, or are otherwise related to a site specific design condition that did not meet infiltration or volume storage design parameters, resulting in a greater degree of overflow events than expected for the facility. More importantly, soil media nutrient content (and at times application of fertilizer) is appearing to be a major influence on nutrient effluent concentration. Hatt et al. (2009a) provide a comment on the effects of soil composition on water quality response of bioretention systems that summarizes observations made in other sources regarding irreducible (background) concentrations and internal sources of nutrient:

> "For pollutants whose primary removal processes are physical (sediment, heavy metals), this background [irreducible] concentration is determined by the amount of media particles washed out of the systems and should therefore decrease as the system

> matures. Background concentrations for nutrients, on the other hand, will clearly be a function of the sorption capacity of the filter media and the processing capacity of the biological community (i.e. plant and microbial uptake, denitrification rates, etc.)."

Herrera (2012) collected outflow samples from a bioretention facility in Redmond, WA that showed nitrate nitrogen well over an order of magnitude concentration higher than groundwater standards. The maximum concentration from this study (over 125 mgL^{-1} nitrate plus nitrite as nitrogen) was the highest reported value of all the literature reviewed here, and higher than all values reported for all LID categories by the International Stormwater BMP Database (2012c). (Phosphorus and copper are other contaminants found by Herrera (2012) at high concentrations that may originate from bioretention media and need to be evaluated for contamination of and movement in groundwater.) Such high levels could obviously affect local groundwater conditions.

Collins et al. (2010b) and Roy-Poirier et al. (2010a) provide in-depth reviews of performance and cycling processes in bioretention facilities for nitrogen and phosphorus, respectively. Interest is developing for the inclusion of design modifications and media amendments to enhance denitrification, and phosphorus and nitrogen retention (Lucas and Greenway 2011, O'Neil and Davis 2012 a, b, Ergas et al. 2010, Collins et al. 2010b, Stander and Borst 2010).

Non-conventional water quality parameters are less studied in the LID literature. Diblasi et al. (2009) found that polycyclic aromatic hydrocarbons were rapidly adsorbed and transported only a few centimeters beneath the surface in a bioretention facility, and did not pose a hazardous waste threat to either solid waste disposal of surface sediments or to groundwater; use of special sorbents is unnecessary for PAHs in bioretention facilities.

Keeping in mind the earlier discussions of percent reduction of concentration being a function of inflow concentrations (i.e. lower inflow concentrations resulting in lower percent removals), and the contribution of flow reduction to reduced loads reported, following are patterns observed on water quality from LIDs seen in the literature. Table 4 provides a summary of loading reductions presented by Ahiablame et al. (2012), and Table 5 provides the inflow and outflow concentration quartiles for concentrations seen in grass strips, grass swales and bioretention facilities in the International Stormwater BMP Database (2012c).

Table 4. Summary of literature values for percent runoff and pollutant retention by bioretention systems, from Ahiablame et al. (2012).

Study	Location	Runoff	TSS	P/TP	NO3-N	NH4-N	TKN	TN	Cu	Pb	Zn	FC	O/G
Davis et al. (2001)	Lab Experiment, USA	--	--	60-80	24	60-80	60-80	--	>90	>90	>90	--	--
Davis et al. (2003)	Lab Experiment, USA	--	--	>65	>15	--	>52	>49	>43	>70	>64	--	--
Hsieh and Davis (2005)	Lab Experiment, USA	--	--	4-99	1-43	2-49	--	--	--	66-98	--	--	>96
Glass and Bissouma (2005)	Washington, DC USA		98	-3	--	-65	--	--	75	71	80	--	--
Sun and Davis (2007)	Lab Experiment, USA	--	--	--	--	--	--	--	88-97	88-97	88-97	--	--
Davis et al. (2006)	Maryland, USA	--	--	70-85	<20	--	55-65	--	--	--	--	--	--
Dietz and Clausen (2005)	Connecticut, USA	--	--	--	67	82	26	51	--	--	--	--	--
Hong et al., (2006)	Lab Experiment, USA	--	--	--	--	--	--	--	--	--	--	--	83-97
Hunt et al. (2006)	North Carolina, USA	--	--	--	13-75	--	--	--	99	81	98	--	--
Roseen et al. (2006)	New Hampshire, USA	--	96	--	27	--	--	--	--	--	99	--	--
Davis (2007)	Maryland, USA	--	47	76	83	--	--	--	57	83	62	--	--
Rusciano and Obropta (2007)	Lab Experiment, USA	--	92	--	--	--	--		--	--	--	92	--
Hunt et al. (2008)	North Carolina, USA	--	60	31	--	73	44	32	54	31	77	71	--
Zhang et al. (2010)	Lab Experiment, USA	--	--	--	--	--	--	--	--	--	--	>82	--
Chapman and Horner (2010)	Washington, USA	48 - 74	87-93	67-83	63-82	--	--	--	80-90	86-93	80-90	--	92-96
DeBusk and Wynn (2011)	Virginia, USA	97	99	99	--	--	--	99	--	--	--	--	--
Zang et al. (2011)	Lab Experiment, USA	--	--	--	--	--	--	--	--	--	--	72-97	--

Definitions: TSS total suspended solids; P/TP phosphorus/total phosphorus; NO3-N nitrate; NH4-N ammonia; TKN total Kjeldahl nitrogen; Cu copper; Pb lead; Zn zinc; FC fecal coliforms.

Table 5. Summary of water quality inflow and outflow concentrations from the International Stormwater BMP Database (2012c).

	TSS mgL^{-1}	P/TP mgL^{-1}	P/diss mgL^{-1}	NO3+2-N mgL^{-1}	NH4-N* mgL^{-1}	TKN mgL^{-1}	Total Cu ugL^{-1}	Total Pb ugL^{-1}	Total Zn ugL^{-1}	FC
Grass Strips										
25th percentile										
In	19.30	0.08	0.06	0.20	--	0.75	11.00	3.20	53.0	--
Out	10.00	0.10	0.18	0.14	--	0.75	4.80	0.72	11.0	--
Median										
In	43.10	0.14	0.08	0.41	--	1.29	24.52	8.83	103.3	--
Out	19.10	0.18	0.25	0.27	--	1.09	7.30	1.96	24.3	--
75th percentile										
In	88.00	0.26	0.14	0.92	--	2.00	51.00	29.00	210.0	--
Out	35.00	0.35	0.38	0.61	--	1.64	12.00	4.60	52.5	--
Grass Swales (dry)										
25th percentile										
In	8.00	0.06	0.03	0.11	--	0.31	5.02	1.65	19.1	1400
Out	5.12	0.12	0.05	0.13	--	0.29	3.57	1.08	15.5	1900
Median										
In	21.70	0.11	0.06	0.30	--	0.72	10.86	3.93	36.2	4720
Out	13.60	0.19	0.07	0.25	--	0.62	6.54	2.02	22.9	5000
75th percentile										
In	56.00	0.24	0.09	0.62	--	1.48	27.00	18.20	136.0	20300
Out	33.00	0.32	0.26	0.47	--	1.10	13.20	6.27	50.0	18500
Bioretention Facilities										
25th percentile										
In	18.30	0.06	--	0.16	--	0.54	8.35	2.06	46.3	--
Out	3.80	0.05	--	0.11	--	0.32	3.98	2.50	4.8	--
Median										
In	37.50	0.11	--	0.26	--	0.94	17.00	3.76	73.8	--
Out	8.30	0.09	--	0.22	--	0.60	7.67	2.53	18.3	--
75th percentile										
In	87.80	0.22	--	0.41	--	1.58	38.50	7.00	153.8	--
Out	16.00	0.20	--	0.39	--	1.25	12.00	5.00	36.0	--

Definitions: TSS total suspended solids; P/TP phosphorus and total phosphorus; NO3-N nitrate; NH4-N ammonia; TKN total Kjeldahl nitrogen; Cu copper; Pb lead; Zn zinc; FC fecal coliforms

*Included with the TKN analysis result as the sum of free NH4 and organic nitrogen.

** Only one study reported in the source, so not reported here.

2.4.2.1 Total Suspended Solids

Reduction in TSS appears to be one of the most consistently improved water quality parameters in LID bioretention treatment. Performance of TSS removal will depend again on appropriate volumetric sizing of the facility (thus increasing the volume and number of storms that are infiltrated and treated), and whether overflow volumes pass through the facility to an outlet, or are bypassed around the facility (Brown and Hunt 2011).

Exceptions to successful TSS removal (other than undersized facility volume) were generally due to erosive events within the facilities, such as head cuts, channelization scour, compaction or poor vegetative cover in filter strips, or inflow of clogging fine sediments (Winston et al. 2012). Hatt et al. (2009a) conducted a rare pollutograph sampling scheme with results suggesting that higher media infiltration rates may lead to higher effluent concentrations of particulates (and their associated pollutants). Initial wash out of particulates (and their associated pollutants) may occur mostly during the first storm events and decrease rapidly with aging of the facility (Roy-Poirier et al. 2010b).

2.4.2.2 Phosphorus

Phosphorus is a common limiting nutrient for sensitive lakes, and stormwater treatment for phosphorus is required for development in such watersheds in Washington State (Ecology 2012). Both phosphorus and nitrogen were inconsistent in their concentration reductions due apparently to sources internal to the bioretention facilities. Some internal sources of phosphorus, especially total phosphorus, were attributed to erosive events contributing TSS. More importantly, phosphorus leaching (especially soluble phosphorus) appeared to originate from fill media and surface mulch sources, especially with high organic or compost constituents, or from other decomposing organic sources such as grass clippings remaining in the facility (Davis et al. 2009, Passeport et al. 2009, Hatt et al. 2009a). Roy-Poirier et al. (2010a) and Dietz (2007) identified numerous cases of phosphorus export. Dietz (2007) suggests use of an underdrain in the facility may exacerbate the problem. A decrease over time as the facility ages was seen in one case (Dietz and Clausen 2005).

Hatt et al. (2009a) saw large increases in dissolved phosphorus (0.006 mgL^{-1}inflow concentration to over 0.100 milligrams per liter [$mg\ L^{-1}$]) through each of three different soil compositions with increases as a function of increased flow rate. They note phosphorus can be successfully removed from bioretention media, but the media must be appropriately specified with low phosphorus content. Chapman and Horner (2010) saw an almost three fold increase in average event mean concentrations in soluble reactive phosphorus at the outlet over the inlet (0.013 mgL^{-1} to 0.036 mgL^{-1}) in their Seattle-based bioretention project.

Roy-Poirier et al. (2010a) analyze in detail the multiple processes involved in phosphorus dynamics in bioretentions systems, including dissolution and precipitation, sorption and desorption, vegetative uptake, mineralization and immobilization, filtration and mobilization, and sedimentation. These authors suggest that more research and models of phosphorus dynamics in bioretention facilities is needed.

Some of the literature on bioretention has begun to report a phosphorus index of the soil mix to indicate the relative risk of phosphorus loss from the soil (Line and Hunt 2009), although definition and use of a phosphorus index is inconsistent (Sharpley et al. 2012). Clearly, media

phosphorus content, its form, and the physico-chemical soil dynamics of potential leaching processes require additional understanding to prevent unexpected leaching of a nutrient that can have impacts on receiving waters.

2.4.2.3 Nitrogen

Nitrogen is a common limiting nutrient in marine nearshore waters, and nitrate (NO_3) is a pollutant of concern in potable groundwater. Nitrogen parameters showed the widest range of concentration reduction, and even extremely large (20x) increases in effluent concentrations at times, possibly resulting from mulch decomposition (Brown and Hunt 2011) or other internal soil media sources (Deitz 2007). Locally, Herrera (2012) in a study evaluating effluent quality from a bioretention facility for the city of Redmond, WA, found initially elevated NO_3 levels at more than two orders of magnitude higher than inflowing concentrations approximately (1 mgL^{-1}). Outflow concentrations decreased to below groundwater standards (10 mgL^{-1}) over the subsequent six months, suggesting decreasing leaching from an internal compost source. The nitrate levels observed in this study were the highest of all the literature reviewed for this report.

The general nitrogen dynamic seen in much of the literature is nitrification of ammonia nitrogen to NOx - N (nitrate plus nitrite nitrogen) resulting in lower ammonia concentrations and higher NOx-N levels. These dissolved nitrogen species, however, are mobile through ground water infiltration, have little opportunity for sorption or denitrification of NOx-N to N2 gas, the later requiring anaerobic conditions. Seasonal patterns in nitrogen export are observed in this process, with some denitrification occurring during warmer periods if anaerobic conditions are present. Challenges to N removal will remain in facilities subject to drying (Hatt et al. 2009 a,b), and tradeoffs in design for N removal may require compromises in hydrologic performance (Collins et al. 2010b). Ahiablame et al.(2012) reports a wide range in load reduction in NOx-N (Table 4), and the International BMP Stormwater Database (2012c) reports a lower frequency distribution in the outflow concentration of bioretention facilities than for the inflow (Table 5).

Some designs have begun to include a stagnant “internal storage zone” (ISZ) to promote anaerobic conditions to support denitrification to nitrogen gas (Passeport et al. 2009). Collins et al. (2010b) note design for an ISZ may require tradeoffs with hydrologic detention of facilities. Additionally, nitrification is the only process that permanently removes nitrogen from a bioretention system, and apparent retention of nitrogen through load calculations may only indicate accumulation within the system with later delayed release of soluble NOx-N forms. Deep exfiltration from the system may otherwise remove nitrogen to groundwater.

Assessment of the sensitivity of Puget Sound ground water and receiving waters relative to the magnitude of loading is needed to evaluate whether the current levels of nitrogen loading in stormwater or leaching from bioretention media pose a concern to receiving waters. Puget Sound area surficial soils and ground water are highly variable due to the geologic influence of the last glacial retreat. Clark and Pitt (2007) note the need to assess the relative concentration, mobility, and soluble fraction of pollutants of concern in their potential effect on ground water. Nitrate is considered low in stormwater concentrations relative to the potential for contamination of ground water. However, the observation of very high nitrate concentrations originating from the bioretention media (Herrera 2012) suggests evaluation of media N content is important to the potential for groundwater contamination. The maturity of compost used in biofiltration media will have a significant effect on this potential internal source of contaminanty (Lenhart 2007).

2.4.2.4 Metals

Davis et al.'s (2009) summary of literature found heavy metals, both dissolved and particulate-bound, are very efficiently removed in bioretention facilities, and that most of the removal occurs in the upper layers of the media (Li and Davis 2008). However, some indication are that low levels of metals are associated with the fill media itself and, much like internal sources of nutrients, may be transported out with the outflow (Hatt et al. 2009 a, b). Trowsdale and Simcock (2011) found median concentrations of dissolved copper higher in the outlet than in the inlet. They suggest dissolved copper may be coming from slow release fungicides used in the plant material potting soil or used on plants. Additionally, accumulated particulate copper from inflowing sediments may release as dissolved at later times. Zinc median concentration values of total and dissolved Zn were substantially reduced from inflow concentrations by an order of magnitude, but median outflow levels were still three times higher than local receiving water guidelines. Chapman and Horner (2010) recognize that in urban environments, stormwater flows may constitute a vast majority of urban stream flows. As a result, minimum levels of dissolved metals in even LID-treated stormwater flows may not be sufficiently reduced for protection of aquatic biota in urban environments.

2.4.2.5 Oil and Grease

Oil and grease (including motor oils) can obviously be a substantial contaminant in road surface storm runoff. Like metals, oil and grease is consistently removed through bioretention facilities (Davis et al. 2009). Chapman and Horner (2010) found consistently low minimum outflow concentrations of motor oil after treatment through their project facility. Additionally, bacteria in the facility mulch can be a natural source of biodegradation of oils and grease.

2.4.2.6 Bacteria

Closure of shell fish areas and elevated stream concentrations can be important issues in Puget Sound. Bacteria are another pollutant that has been seen associated with particulate material, and so has been effectively reduced in bioretention facilities where TSS is reduced. Hathaway (2009) found a bioretention LID facility and wetlands among a number of LID and proprietary systems tested performed the best in reducing indicator bacteria, with greater than 50 percent reduction in concentrations. Zhang et al. (2010) note biological sorption is the primary mechanism for removal of bacteria, and sorption capacity may vary in different media. Addition of iron oxide substrate augmented sorption sites within the media improved sorption. Dietz (2007) suggests evaluation of bacteria reduction in biofiltration systems is in need of additional research.

2.4.2.7 Temperature and pH

Reduction of the thermal load of stormwater can be expected through media infiltration and deep exfiltration in bioretention systems. Jones and Hunt (2009) found water temperatures reached equilibrium with soil temperatures within 60 cm depth of media in one bioretention facility without increasing soil temperatures, while another nearby facility with a larger proportional contributing area saw increases in soil temperatures. Outflow temperatures were lower than inflow temperatures, and may contribute to improving instream thermal conditions for trout. These results also suggest temperature mitigation may influence facility sizing if temperatures in receiving waters are a concern. In addition, pH has been seen to be well

buffered by exposure to hardness elements in bioretention fill media. Low pH rainfall water typically is seen to approach more neutral conditions, with a corresponding increase in hardness at the outlet (Chapman and Horner 2010, Dietz 2007).

2.5 GREEN ROOFS FACILITIES DESIGN AND EFFECTIVENESS OVERVIEW

Green roof designs include two categories of roof: “extensive” roofs that are thin layer of soil (five to 20 cm) planted with shallow rooted plants, and “intensive” roofs that are constructed with a deep layer of soil (one to two meters), and planted with deep rooting plants including shrubs and trees. This discussion will focus on the performance of extensive green roof designs, as the latter is much less prevalent.

Green roofs are distinctly different from the other categories of LID addressed above as they don’t receive stormwater runoff onto the facility, only direct rainfall (uncommonly some facilities may include additional “run-on” from adjacent roofs). As a result, the hydrologic loading rate is much less than for permeable pavements or bioretention facilities. Correspondingly, the rainfall input also does not have the stormwater pollutant load associated with the impervious surface inflows of the other facilities. Additionally, the underlying roof is positively expected to be an impermeable barrier, and so lateral or deep infiltration losses are non-existent; all hydrologic losses are via evaporation or transpiration by plants.

The soil media composition and underlying layered system of water proof barrier and filter layers differ between commercial providers of green roofs. However, the overall system of layers and soil media, and especially the media depth and composition, will be the largest determinant of the hydrologic and water quality response of the green roof. Water quality response in green roofs appears to be the most wide ranging, and thought to largely add pollutants especially phosphorus and metals.

Additionally, while grass strips, swale and bioretention facilities include plant materials, green roof plant communities are more integrally dependent on the shallow soil depth, composition, and local climatological conditions for long term survival. Plant material density and composition appears to have a large contributing effect on hydrologic and water quality performance of green roofs.

2.5.1 Hydrologic Findings from Green Roof Facilities

Green roof soil and plant community systems act as a sponge into which rainfall soaks and accumulates. The system is a natural hydrologic system to the extent it still responds to rainfall, evaporation, storage, conveyance, transpiration, and runoff. As with the other LID facilities, green roofs’ retention capacity and peak runoff pattern is a function of the media and interception volume, the added dimension of slope and geometry (Cardno TEC 2012), an underlying drainage layer, and local rainfall intensity-duration patterns, with retention the greatest for small storms, and less for larger storms.

Within these factors, the antecedent moisture condition of the soil media (i.e., the bioretention abstraction volume) and storm size determines the retention capacity on a storm-by-storm basis (Cardno TEC 2012, Stovin 2009, Stovin et al. 2012, Zimmerman et al. 2010), and the loss of accumulated water volume is exclusively via evaporation and transpiration. Uhl and Scheidt (2008) summarize by stating “layer depth dominates the retention effect clearly compared to

other construction details," but given a depth, peak flow reduction and retention are predominately influenced by "evapotranspiration and sequence of rainy and dry periods."

The volume retention values found in the literature are wide ranging. Ahiablame et al. (2012) found a range from their literature review of thirteen projects of 23 to 100 percent. Gregoire and Clausen (2011) report a range of 34 to 69 percent from thirteen different studies, with a mean of 56 percent; the CWP (2008) reports a range of 45 to 60 percent. Seasonal differences in retention are frequently seen and can be highly pronounced in some regions (Cardno TEC 2012, Schroll et al. 2011). The International Stormwater BMP Database (2011) does not provide a summary of green roof volume reductions due to excessive complications of irrigation and other factors in the data collected (Jane Clary, Wright Water Engineers, personal communication).

Stovin et al. (2012) found the storm-to-storm individual retention values, and even peak to peak lag times and peak reduction values highly variable (possibly more so than what is reported in swales and bioretention facilities because of the reduced media volume and added element of roof slope to the factors affecting runoff). These authors found regression analysis was unable to predict runoff volumes, and only by using first principles of hydrologic processes involving antecedent drying period, evapotranspiration rates, and media field saturation capacity were they able to predict storm retention values on a storm-by-storm basis.

Otherwise, these authors note, the high variability of natural rain events and variable conditions of detention storage make peak-to-peak lag times "arguably meaningless" by themselves (although peak flow reduction and lag times may be important in their basin-wide effect on receiving waters). Instead these authors propose modeling based on substrate moisture flux conditions will support more accurate green roof sizing based on local rainfall intensity-duration return periods that meet the hydrologic goals of the design (She and Pang 2010). Use of this approach in design and sizing could well result in a more accurate prediction of volume retention in newly installed facilities.

Locally, Cardno TEC (2012) conducted three years of continuous hydrologic mass balance monitoring on three different green roofs within the City of Seattle, with the intent to collect data sets suitable to calibrate a green roof hydrologic model for reducing downstream combined sewer overflow (CSO) events. Results of this monitoring confirm and reinforce the patterns seen in the literature, and the authors further elaborate on those patterns for responses of green roofs in the Pacific Northwest. From these three monitored roofs, individual storm retention rates range from seven to 100 percent across all seasons and roofs, and peak reductions ranged between negative 15 to 65 percent across all storms and roofs. Specifically, these findings found for retention, peak reduction, and lag time:

- The dependence of retention, lag time and peak flow reduction response on green roof geometry, slope, and flow path timing, combined with local seasonal rainfall patterns,
- Extreme seasonality of response in a dry summer, wet winter climate,
- The importance of antecedent wet weather conditions on subsequent storm runoff patterns,
- Rapid recovery (drying out) of the soil profile between storms even during extended wet periods, allowing for substantial peak flow reduction year around,

- Large differences in plant community success between green roofs apparently affecting runoff,
- Differences in summer irrigation practices also affect runoff patterns.

In addition to the overall effects of media depth, geometry, slope, aspect, and flow path affecting runoff response, indications also suggest flow path short circuiting or infiltration to the under drain layer may occur before complete saturation of the soil profile occurs, reducing the detention effect of an already shallow soil profile (Cardno TEC 2012, Buccola and Spolek 2011, She and Pang 2010). This affect is analogous to the heterogeneous infiltration process (or "preferential flow path") seen in bioretention facilities. As well, short circuiting to the underdrain layer will have the effect of hastening runoff similar to the underdrains in bioretention facilities. Each of these processes likely occurs in green roofs facilities, and will be averaged into the hydrologic responses seen in monitoring results.

Finally, plant material above ground biomass can constitute a dense and interactive component of the hydrologic processes on green roofs in the form of interception storage and subsequent evaporation as well as transpiration (Nagase and Dunnett 2012). Given the dependence of green roof retention exclusively on evapotranspiration processes, the success of green roof plant communities appears to be an important component to their hydrologic retention performance.

2.5.2 Water Quality Findings from Green Roofs

The literature on green roof water quality recognizes a wide range in potential water quality concentrations and loads from green roofs, especially in nutrients. This may not be surprising given that the influent water is rainwater (rather than stormwater runoff as in the other LIDs), and the growing media and construction materials contain a composition of organic matter, inorganic soil and construction products all of which can leach into the passing flow. Green roof runoff is then better compared not to stormwater but to runoff from conventional roofs. Nutrients and metals, especially copper, are the water quality parameters most evaluated for green roofs and will be the focus of the discussion here.

In many of the studies reviewed, green roofs frequently showed higher concentrations of numerous parameters than conventional roofs. For example, in addition to the literature reviewed here, the International Stormwater BMP Database (2012c) indicates higher outflowing concentrations than inflowing for total and dissolved phosphorus, total and dissolved nitrogen, and total and dissolved copper all on the order of three- to-five fold. The total suspended solids distribution did show lower concentrations in the outflow distribution than the "inflow". (Green roof data from that Database is not presented here as many of the parameters were not summarized, or results were from relatively few studies). While some concentrations can be elevated, the overall volume reduction from green roofs compared to conventional roofs often results in load reductions compared to conventional roofs.

Numerous authors note the runoff of nutrients, and phosphorus in particular, is highly tied to fertilization of the soil with compost or fertilizer, or to additional fertilization applied during the growing season. While numerous authors suggest concentrations and loads of nutrient export may diminish over time (Berndtsson 2010, Rowe 2011, Hathaway et al. 2008), a major water quality challenge in the use of green roofs is the matching of soil composition and fertility with a

plant community requiring little or no fertilization for success (Dietz 2007, Toland et al. 2012, Berndtsson 2010, Rowe 2011). Additionally, the broader question of the significance of these levels of nutrient concentrations from green roofs (or LIDs in general) on receiving waters has not been substantively addressed. Toland et al. (2012) made initial comparisons of green roof nutrient runoff concentrations to instream concentrations and found higher concentrations than nearby receiving waters.

2.5.2.1 Phosphorus

Of the contaminants examined in the green roof literature, phosphorus is consistently identified as increasing in concentration in the outflow of green roofs over rainfall inputs, and usually over conventional roof concentrations. Recent studies of phosphorus production from green roofs demonstrates a wide range (three orders of magnitude), but also that the biologically more active dissolve form represents a large proportion (60 to 80 percent) of the total phosphorus being produced from the roof (Berndtsson 2010, Vander Linden and Stone 2009, Toland et al. 2012).

The dissolved soluble reactive form of phosphorus (SRP) is highly biologically active and can contribute to eutrophication of streams through periphyton growth. Concentrations of SRP in the recent literature ranged over three orders of magnitude, reflecting the solubility of compost or fertilizer additions to the soil media. Beck et al. (2011) saw ranges of phosphate-phosphorus of 7.7 to 19.8 mgL^{-1} in their experimental units, while Gregoire and Clausen (2011) saw much lower values in the range of 0.003 to 0.079 mgL^{-1} phosphate to P, attributing the lower levels to the use of slow release fertilizers. Hathaway et al. (2008) report a range of total phosphorus concentration in green roof runoff from 0.6 to 1.4 mgL^{-1}, with these levels being 1 mgL^{-1} and 0.8 mgL^{-1} higher than rainfall and control conventional roofs, respectively. Similarly Toland et al. (2012) found SRP concentrations in green roof runoff in the range of 1.57 to 1.82 mgL^{-1}, and Vijayaraghavan et al. (2012) found a phosphate range of 20 to 66 mgL^{-1} in green roof test assembly runoff. Soil media in these later three studies were fertilized with 15 to 22 percent composted cow manure or organic compost. In contrast, Vander Linden and Stone (2009) saw SRP concentrations range from 0.008 to 0.098 mgL^{-1} even with 14 percent compost and fertilization.

2.5.2.2 Nitrogen

Discharge of nitrogen from green roofs appears highly variable in the literature (Berndtsson 2010). Some results find total nitrogen concentrations similar to rainfall concentrations, while others find substantial release from green roof soils. Again soil composition, fertilization and the age of the green roofs may have an effect. Nitrate - nitrogen was reported as the highest proportion of total nitrogen found by Toland et al. (2012) and in past studies they reviewed. Toland et al. (2012) reported nitrate - nitrogen similar across various media compositions, even with compost amendment. Ranges in nitrogen reported in recent literature include: 0.300 to 4 mgL^{-1} total nitrogen (Toland et al. 2012), 0.3 to 7.3 mgL^{-1} nitrate - nitrogen (Vijayaraghavan et al. 2012), 10 to 79 mgL^{-1} total nitrogen (Beck et al. 2011), and 0.49 mgL^{-1} geometric mean total nitrogen (Gregoire and Clausen 2011).

Processes contributing to nitrogen release from green roofs appear to be not clearly understood, but concentrations are often in ranges that suggest potential ecological impacts to receiving waters, as in the case of phosphorus.

2.5.2.3 Metals

While typically found in lower concentrations than found in stormwater runoff, metals concentrations in runoff from green roofs are found to be similar to that in precipitation (Berndtsson 2010). Copper appears to be an exception, however, as numerous authors mention the presence of copper-bearing additives or construction material, or otherwise the soil itself as contributing copper to the flow through green roof systems (Alsup et al. 2011, Gregoire and Clausen 2011, Rowe 2011, Vijayaraghavan et al. 2012). As noted above, the International Stormwater BMP Database (2012c) reports median green roof outflow values from their database of 0.009 mgL^{-1} and 0.012 mgL^{-1} dissolved and total copper, respectively.

2.5.3 Plant Composition and Density Effect on Performance of Green Roofs

Plant community composition and density appear to play a significant role in runoff retention and pollutant runoff from green roofs. Green roof vegetation will affect the amount of water loss to the atmosphere through interception, retention, and transpiration (the only way water is lost from green roofs). Additionally, potential runoff pollutants present in the soil such as nutrients and metals may be sequestered through plant uptake. Finally, plant composition selection that is more successful without intensive maintenance through irrigation and fertilization will reduce the influence of human intervention on hydrologic or water quality.

Green roof growing environments have been observed to resemble highly marginal growing environments, with a shallow substrate depth, and high exposure to sunlight, wind, desiccation, and freezing conditions. Under these conditions, a more purposeful selection of plant material can greatly enhance survival and improve the performance of green roofs. A number of authors reviewed here noted this difficult environment, calling for selection of more regionally appropriate plant choices (Schroll et al. 2011, Nagase and Dunnett 2012, Sutton et al. 2012). Nagase and Dunnett (2012) found grass species were most effective in reducing stormwater runoff in their controlled experiments with *Sedum* spp. being the least effective, even less than for bare soil. Sutton et al. (2012) note that prairie-based green roofs (i.e., primarily grasses) may be best suited for plant success on green roofs, and that maritime grass communities exist that could provide a template for coastal green roofs.

2.6 TALKING POINTS

Following are “talking points” addressing effectiveness null hypotheses and study questions posed as part of the RSMP (Ecology 2011) to help jurisdictions identify where the literature has adequately addressed a particular issue, and where additional studies are still warranted. Each of the following section headers are null hypotheses that were to be addressed by the literature review.

2.6.1 LID measures are not effective at reducing storm flows in retrofits and new developments.

<u>Which LID measures are most effective at reducing flow from developed areas?</u>

Of the three LID technologies evaluated, the literature shows each can provide a considerable degree of flow reduction, primarily depending on the accuracy of sizing of the facility’s storage volume and the degree of exfiltration to meet a desired level of retention (i.e. depending on the design storm size - return frequency). Permeable pavements and bioretention facilities have a large storage volume and large potential for exfiltration, so they can be designed to receive

more flow than just the rainfall on the surface of the facility. Green roofs are limited to storage and flow reduction for direct rainfall on the roof. To this extent, the permeable pavements and bioretention facilities will affect a greater volume of reduction.

While much of the literature shows substantial reduction, the subset of literature for bioretention evaluated by the International Stormwater BMP Database (2012c) specifically shows there can be a wide range in reduction (20 to 80 percent) within a small range of facility to contributing area ratio (four to six percent). This means that within this set of data (which is a much smaller set than in the published literature), some factors related to the installation are affecting runoff reduction more than the size of the contributing area.

The primary factor affecting flow reduction in these facilities is not the areal ratio of the facility to the area contributing runoff, but the available "bioretention abstraction volume" in the facility media (Davis et al. 2010). This is the volume of inflow designed for storage before flow out of the facility occurs. Also very important to the degree of flow reduction in a given facility is the degree to which infiltrated water exfiltrates to the surrounding soils and sub-grade (which reduces flows), and whether an underdrain is present (which increases flows).

Thus, "which LID is most effective" is not inherent to the LID, but rather depends on the degree of accuracy in the facility abstraction volume sizing relative to a targeted design storm duration - return period desired. Knowledge of the degree of local exfiltration and, to a lesser degree, evapotranspiration will play into design of the abstraction volume. (For green roofs, no exfiltration is possible, so the response of the design will be related to storage volume and evapotranspiration only.) After a rain event fills the available storage, any additional rainfall will flow out of the facility.

An additional significant question to the sizing issue in implementing LIDs is "what design storm return-interval size is best in targeting LID storage sizing?" The answer to this question will more specifically affect the performance of the LIDs, and will have a direct bearing on the success of basin-scale implementation of LIDs, as discussed below.

<u>Will installing porous pavements in alleys and road rights-of-way with rain gardens substantially reduce runoff?</u>

Both porous pavements and rain gardens substantially reduce runoff, assuming the volumetric storage design is conducted accurately. As with any runoff-contributing impervious area, routing the runoff through facilities that infiltrate stormwater will reduce runoff.

One important possible consideration for alleys is an assessment of the local subsurface conditions. Assuming alley ways are in more densely developed areas, the subsurface fill material may have preferential pathways near building foundation structures, which may be a concern for seepage into buildings.

<u>Does amending landscapes with compost significantly reduce flows during small and medium storms?</u>

As noted previously, the degree of attenuation of storm water by any media will depend on the extent of storage in the media compared to the storm size. Some layer of compost will attenuate some degree of runoff. But once saturated, any additional rainfall will produce runoff.

More significant to this question, however, is "what is the nutrient (phosphorus and nitrogen) and other contaminant (especially copper, herbicides, pesticides) content of the compost?" Much of the literature points to high nutrient content (as through the use of mulch, compost amendment or fertilization) as the major contributor to nutrient and other contaminant leaching from LID facilities (Davis et al. 2009, Dietz 2007, Roy-Poirier 2010, Brown and Hunt 2011, Carpenter and Hallam, 2010, Hatt et al. 2009a, b, Herrera 2012, Lenhart 2007, Li and Davis, 2009). These publications indicate media composition is highly influential and complex in its effect on LID performance, and involves media infiltration capacity, texture, organic content, nutrient content, aerobic and anaerobic zones, the presence of toxic substances and sorption equilibrium dynamics to mention only a few issues. More research is needed in this area, including addressing compost source quality and potential solid waste disposal of expended media.

<u>Is LID more effective than traditional BMPs for improving hydrology at the basin scale?, and, Will a developed basin with a high density of LID measures have measureable differences in hydrology and pollutant loads compared to a similar basin with a low density of LID measures?</u>

The effectiveness of either LIDs or BMPs at the basin scale will depend on the magnitude of storage provided by either relative to the size of the design storm duration, return-time selected. In each case, once the available storage is reached with the maximum design storm, any additional rainfall will produce direct runoff. Additionally, however, traditional BMPs are peak-control oriented, with little reduction of volume, while LIDs are volume-control oriented, with peak reduction happening as a beneficial consequence. .

The difference is LID storage capacity appears to be smaller than traditional BMP storage, and so expresses volume and peak reduction primarily under a high density of use for a highly developed basin, and for only the small to medium range of storm sizes (generally up to the 24-hour, 2-year storm). This conclusion is based on modeling of basin scale effects, and no large scale implementation has provided empirical observation. A combined use of LID and traditional BMPs that affect both the volume-control benefit of LID, and the peak-control benefit of BMPs for large storms has been recommended (Damodaram et al. 2010).

Related questions to these are: at what level of basin development and LID implementation results in observable benefits to receiving waters over what would have been seen without LID? Indications suggest there are break points for level of development and level of LID implementation where benefits should be observable, but these break points will require empirical observation rather than results from modeling.

<u>How well can a calibrated and verified stormwater model (e.g., SUSTAIN and EPA SWMM5) function as a replacement for a control in a paired watershed study design?</u>

It can be assumed some degree of additional error will be incurred in using a model rather than collected data during the treatment phase of the paired watershed study; a model will only be better if the quality of data collected during the pre-treatment phase (and therefore used for model calibration) is significantly better than the quality of data collected during the treatment phase.

Use of a calibrated model as the measure of the control watershed in a paired study design will depend on two main factors: the quality and duration of pre-treatment calibration data the model is built on, and the magnitude of difference in the signal between the control and the treatment

watersheds resulting from the treatment. If the signal from the treatment watershed is on the order of the error in the model, it will be difficult to discern the signal as statistically significant.

One other factor to be considered is whether much land use change occurs in the control watershed. If much change has occurred, it may actually be more appropriate to use the model prediction of the control watershed – i.e. the hydrology of a changed control watershed will not have been calibrated against the treatment watershed.

2.6.2 LID measures are not effective at reducing pollutant loads in retrofits and new development.

Does the installation of bioretention, bioinfiltration, biofiltration, rain gardens, and other LID measures have a measurable effect on water quality?, and,

Which LID measures are most effective at improving water quality from developed areas?, and,

Can compost mixes and plant species be tailored to enhance removal of specific pollutants (i.e. phosphorus, metals, bacteria)?

Water quality affects receiving waters through both concentrations and loads. As a result, concentrations and loads from LIDs are separate issues for many of the parameters. Additionally, water quality will also be affected by the facility sizing since under-sizing a facility will result in less first flush treatment through infiltration, and more volume by-passing the facility entirely once it is saturated. Whether the presence of elevated concentrations of nutrients in LID outflows is of a magnitude relevant to impacts in receiving waters is unclear, and is an issue to be addressed more in the basin-scale application of LIDs and their benefits on receiving waters.

Concentrations

For improvement of runoff concentrations, permeable pavements and bioretention facilities show improvement in most parameters. One significant departure is in nutrient concentrations, especially nitrogen from permeable pavements, and both phosphorus and nitrogen, and to a lesser extent copper, from bioretention facilities. The highest concentrations of nutrients from facilities can be associated with particulate matter originating from within the facility, which also may decrease over time.

Green roofs have shown high leaching of phosphorus and heavy metals due to the use of highly processed soil media, use of fertilizers, and exposure to building materials on the building surfaces. The CWP (2008) assigns volume reduction credits to green roofs, but no water quality credits.

The nitrogen concentrations in outflows from permeable pavements appear to be from the lack of a removal process for nitrogen within the detention systems of permeable pavements. Inflowing and outflowing nitrogen concentrations appear to be similar, simply showing the conversion of ammonia and organic nitrogen to nitrate, thus increasing the nitrate concentrations in the outflows.

Bioretention facilities have shown wide ranges in nutrient concentrations associated with the use of compost or other soil media fertilization. Nitrogen again does not have a significant method of removal within bioretention facilities, except where saturated anoxic zones are designed into the facility to promote denitrification. These designs compromise storage capacity

however. Especially with the common use of “mulch” in the top layer of bioretention, large concentrations of nitrogen have been observed.

Increases in phosphorus concentrations through leaching from bioretention media is a commonly recognized issue. Phosphorus concentrations are primarily reduced by solids removal, precipitation and sorption, and concentrations can be reduced through the passage through bioretention media; removal or addition of phosphorus is largely a question of the level of compost or other nutrient augmentation in the media. There is some thought in the literature that increases in phosphorus may diminish over time, especially initially, but substantiation of the reduction over time is not well documented. The increases in phosphorus may simply be related to resuspension of particulate matter and initial settling of the media within the facility. Decomposition and desorption may still result in continued release of phosphorus later, however, and sorption capacity may decrease over the life of the facility.

Pollutant Loads

Pollutant loads are the product of volume and concentration, and so load reduction can be affected by volume as much as concentration. In some case related to nutrients, load reduction at all was the result of volume reduction as concentrations actually increased. Nutrient loads are more significant to lake and marine shoreline receiving waters where eutrophication processes are the integrated effect of total nutrient loads rather than high instantaneous concentrations.

Media Amendments and Plant Use Affecting Pollutant Removal

Plant composition and density can affect removal of pollutants through roots stabilizing the soil media and facilitation of infiltration, as well as nutrient uptake. Success of plant communities are expected generally to improve pollutant removal through maintaining hydraulic conductivity to increase treatment and reduce volume runoff (Le Coustumer et al. 2012), but plant success should be tied to appropriate matching of plants with the local climate that minimizes maintenance and fertilization. Phosphorus uptake rates are more well known for crops and trees in the forest industry, and the rate of phosphorus uptake by plants typically used in bioretention is not well documented (Roy-Poirier et al. 2010).

Addition of phosphorus sorption amendments may well be a useful development in the evolution of media specifications for bioretention. Clay amendments and aluminum and iron based water treatment residuals all have shown improvements in phosphorus retention. Contact time in bioretention flow-through appears to have an influence on performance of these water treatment residuals (O’neil and Davis 2012a) and existing facilities can be retrofitted through incorporating water treatment residuals by surface application and rototilling (O’neil and Davis 2012b).

Use of amendments for nitrate removal includes addition of a low nutrient source of organic matter (e.g. newspaper) together with an anoxic zone to promote denitrification. Amendment of iron oxide-coated sand was also evaluated for removal of E. coli, showing this amendment enhanced capture and promoted microorganism predation of the bacteria for substantial removal.

<u>Does bioretention treat runoff sufficiently to allow for infiltration without violating groundwater standards?</u>

The literature reviewed from the database indicates stormwater pollutants are largely at low enough concentrations and are removed within the near-surface depths that there are not

concerns for groundwater contamination (Diblasi et al.,2009, Kwiatkowski et al. 2007, Brown and Hunt 2010, Weiss et al. 2008) . The main possible exception could be nitrate concentrations where high stormwater influent concentrations and high infiltration may focus nitrate into a localized zone of groundwater. None of the literature reviewed evaluated the potential of contamination from extreme nitrate concentrations originating from within bioretention soils.

The literature sources commenting on the potential for contamination of groundwater were few and subsurface samples were not commonly collected of the exfiltrating water from the system. Herrera (2012) collected samples from a facility in Redmond, WA that showed well over an order of magnitude concentration higher than groundwater standards for nitrate nitrogen. The maximum concentration from this study (over 125 mgL^{-1} nitrate plus nitrite as nitrogen) was the highest reported value of all the literature reviewed here, and higher than all values reported for all LID categories by the International Stormwater BMP Database (2012c).

Potential groundwater contamination will depend on exfiltrating mass loads and local hydrogeologic conditions. More study of the local Puget Sound region conditions for potential groundwater contamination is an example of the effectiveness studies recommended in this report.

<u>What type and frequency of maintenance is needed to ensure the long-term performance of bioretention facilities?</u>

Long term monitoring of the performance of bioretention facility performance (more than seven to eight years) is largely unrepresented in the literature simply due to the recent advent of these systems. However, the primary issues in long-term maintenance of bioretention facilities appear to be:

1. the long term continuation of infiltration rates that support the design storm event sizing,
2. the long term media nutrient (especially phosphorus) adsorption capacity, and
3. the long term media fertility for sustaining plant growth. Each of these issues can be addressed in the initial media composition specification and sizing of the facility, and can be easily monitored through visual inspection over the course of the life of the facility. A broad scale program to conduct visual monitoring by facility owners should be conducted for all facilities, and landscaping activities and fertilization minimized.

<u>Is LID more effective than traditional BMPs for improving water quality at the basin scale?, and,</u>

<u>Will a developed basin with a high density of LID measures have measureable differences in pollutant loads compared to a similar basin with a low density of LID measures?</u>

These questions are related to the response on whether LIDs will have a measureable effect on stormwater volume. Load reduction will largely follow volume reduction for most pollutants, and the volume reduction from LIDs will be greater for small to medium storms. BMPs can then be used for peak control of larger storms.

As with volume reduction, water quality improvement on a basin scale will likely be discernible in receiving waters depending on the magnitude of development in the basin, and the density of LID applied to the development. The modeling of basin scale use of LIDs suggests both the

level of development and the level of LID density both need to be high for benefits to be seen in receiving waters.

2.6.3 LID measures are not feasible in areas with tight soils or shallow groundwater.

What, if any, LID measures are feasible in areas with tight soils?

Many of the literature sources reviewed for bioretention noted substantial infiltration of stormwater volumes into presumed low permeability or "tight" subgrade soils. In each of the cases more infiltration occurred than thought would be present. Many of these authors suggested heterogeneous subgrades allow infiltration through the underlying subgrade, or through cracks in the soil. The literature is not sufficient to answer this question for local Puget Sound region conditions, and effectiveness studies to evaluate the local exfiltration rates of tight soils is recommended in this report.

What, if any LID measures are feasible in areas with shallow ground water?

Shallow ground water will interfere with the subsurface storage capacity and infiltration rate of designed permeable pavement or bioretention facilities. Any of the ground-based LID measures will be technically feasible in areas with shallow ground water depending on the facility sizing and frequency and extent of submersion of storage volume of the facility. The resulting performance will be as if the storage volume and infiltration rates were reduced by the level of the groundwater filling the storage or causing mounding, resulting in greater overflow of the facility (Machusick, et al. 2011).

To account for shallow ground water, a facility would need to be sized to accommodate the loss of storage and decreased infiltration rates due to mounding. The facility may not be feasible if space is not available to size a facility affected by groundwater. The Puget Sound region surficial geology is highly heterogeneous, and evaluation of local conditions will be critical to proper identification of shallow groundwater conditions and the resulting effect on facility sizing. Affectiveness studies related to local groundwater and exfiltration conditions are recommended in this report.

Is permeable pavement feasible over the long-term for applications on high speed roads?

This question is more of a roadway structural engineering question, and can be researched through engineering database searches. Pervious asphalt as a surface "friction course" layer has been used substantially on freeways in some regions, and these pervious asphalt layers have shown hydrologic and water quality benefits (Klenzendorf et al. 2012, Fassman 2012). In the literature review, permeable pavers were thought to be applicable only to low velocity and light load use.

2.6.4 Recycled concrete cannot be used to provide storage under permeable pavement.

Can recycled concrete be used as storage under permeable pavement?

This question is more of a roadway structural engineering question, and can be researched through engineering database searches. Concrete has been evaluated for impacts on water quality, showing largely an increase in pH and addition of alkalinity to the effluent (Kuang and Sansalone 2011).

3.0 CONCLUSIONS AND RECOMMENDATIONS

3.1 EFFECTIVENESS STUDY RECOMMENDATIONS

In making effectiveness study recommendations there will necessarily be a prioritization among the range of possible topics needing study, and in the level of intensity of study of those topics. If budget were no object, a wide selection of possible study topics and high levels of effort could be recommended. Various authors in the literature reviewed recognized that identification and prioritization of the flow and pollutant reduction needs relevant to a region must precede and inform research priorities and design criteria. Assumptions on those local priorities for the Puget Sound region are incorporated in the study recommendations below. The recommendations here, informed by the literature, emphasize more pragmatic and locally relevant effectiveness studies that will support increasing implementation of LIDs in the Puget Sound region.

There are four scales of LID effectiveness evaluation studies recommended to improve the use of LIDs in the Puget Sound basin. Each of these studies may be nested within another as they are related, but each will still have distinct objectives:

1. Internal scale studies to characterize internal conditions that will narrow design criteria and specifications internal to the technology,
2. External scale studies to characterize local site environmental conditions that contribute to the technology performance,
3. Basin scale studies to identify measureable effects of high density use of LIDs on a large basin scale, and
4. Organizational, institutional scale study conducted with a pilot jurisdiction designated to manage and learn from implementing an intensive, basin scale use of LIDs.

The long term tracking of maintenance and performance of LIDs by local agencies and institutions, and the management of those LIDs will clearly be an important component in the use and success of these systems. The ultimate performance of LIDs, on any scale, will involve not just the largely passive performance of the technologies themselves, but also the active and integrally important role of construction, operation, and maintenance of facilities carried out by local jurisdictions and site owners.

It is evident from the literature that the long term performance of LIDs will be highly dependent on organized active management. Because of the relative inexperience in the regular use of LIDs, there will be a learning period and associated paradigm shift in public works culture to incorporate the broad scale use of LIDs. A variety of institutional challenges and potential solutions exist in implementing LIDs (Roy et al. 2008), but active participation of an institution in implementing a watershed scale use of LIDs will begin to address these, as well as summarize and integrate the learning from the first three levels of effectiveness studies. Documenting the public works cultural and organizational transition to a more intensive use of LIDs will be of significant value in conveying learned lessons to other jurisdictions.

3.1.1 Internal Scale Effectiveness Studies

The literature points to two important areas of investigation of the internal design and performance of LID facilities: more accurate sizing for retention of specified volumes at specified storm event-return time design storms; and specification of media composition that retains

leachable constituents (especially phosphorus) while supporting plant community growth. Much of the literature indicates load reduction is best targeted through volume reduction. Except for primarily phosphorus and copper, concentration and load reductions will follow successful volume reductions. Below are three suggestions for internal effectiveness studies to fill information gaps in our knowledge about LID facility performance.

3.1.1.1 Recommended Internal Effectiveness Study I-1

Measure actual bioretention abstraction volumes available in bioretention facilities following the Ecology design approach. Results of these effectiveness studies (together with Effectiveness Study E-1) will provide feedback to the bioretention design process so desired storm retention sizing and the best use of site space can be jointly optimized. These studies should also be carried out with explicit measurement of under drains in retention, when present.

3.1.1.2 Recommended Internal Effectiveness Study I-2

Conduct soil media composition and leaching studies together with nutrient sorption amendments and identification of a plant pallet most appropriate for growth success. Media studies should be conducted especially related to phosphorus and copper content and their leaching potential. Results of this effectiveness study will narrow the range of appropriate media composition and viable amendments for use in bioretention and green roof facilities to prevent high concentrations of phosphorus in the runoff while encouraging success of low maintenance planting plans.

3.1.1.3 Recommended Internal Effectiveness Study I-3

Conduct visual assessment of permeable pavements and bioretention facilities over many facilities and a long duration of time. This effectiveness study can be developed as an institutional inspection program to evaluate the aging of infiltrating surfaces for assessment of ware and infiltration capacity.

3.1.2 External Scale Effectiveness Studies

Much of the literature on LIDs emphasized the role of local conditions external to the LID design. This was largely emphasized in the lateral and sub-grade soil conditions affecting exfiltration around permeable pavement and bioretention facilities, but also the seasonal meteorological patterns (rainfall distribution, insolation, humidity, and wind, all determining evapotranspiration) which affect all three categories of LID performance, but especially affecting green roofs. Below are two suggestions for external effectiveness studies to fill information gaps in our knowledge about LID facility performance.

3.1.2.1 Recommended External Effectiveness Study E-1

Together with effectiveness study I-1, conduct detailed subsurface investigations of exfiltration conditions around bioretention facilities that will affect exfiltration rate and potential for groundwater contamination, especially where shallow, low infiltration sub-grades exist. Results of this effectiveness study will combine more detailed knowledge of local exfiltration conditions with the observed initial storage volume of the facility for use as feedback in the design of facility infiltration capacity.

3.1.2.2 Recommended External Effectiveness Study E-2

Together with effectiveness study I-1, conduct meteorological monitoring to evaluate the magnitude of effect of local meteorological conditions on LID retention performance. Results of this effectiveness study will provide information on the contributing scale of effect of the local meteorology, compared to storage and exfiltration, on LID volume retention.

3.1.3 Basin Scale Effectiveness Studies

No evaluation of implementation of LIDs on a scale broader than pilot residential plat scale was found in the literature except by modeling. A number of authors identified scaling up and spatial/temporal effects will likely play a significant role in the performance of, and ecological benefits of, a basin-wide application of LIDs. Below is one suggestion for watershed scale effectiveness studies to fill information gaps in our knowledge about LID facility performance.

3.1.3.1 Recommended Basin Effectiveness Study B-1

Select an area for a paired watershed (or similar) study that is of substantial enough size that multiple land uses are present, increasing development is expected to occur, and a receiving water stream is in early stages of impact from increasing land use. Results from a basin scale effectiveness study will provide insights to identify at what level of development within a basin LIDs begin to make a discernible difference on impacts on receiving waters, and the magnitude of LID density required to manifest that difference. Benefits (or impacts avoided) will include hydrologic measures such as low flow and overall flow durations, channel geometry, and biological measures such as benthic community compositions or fish habitat.

3.1.4 Organizational Scale Effectiveness Studies

Various authors noted that performance of LIDs in their studies was likely affected by management actions, whether planned or incidental to the facility. These were largely construction related or landscape management actions such as errors in construction installation, stockpiling of excavated soils near permeable pavement surfaces, fertilization of plant materials in bioretention or green roof facilities, plant potting media including copper based fungicides, or remnants of grass clippings. These incidents are correctable outcomes in the use of LIDs that can be avoided through organizational development. The Washington State NPDES permits currently contain a substantial number of organizational actions and reporting requirements (Ecology 2012). Below is one suggestion for an organizational scale effectiveness study to further support organizational development in the management of broad scale implementation of stormwater LIDs.

3.1.4.1 Recommended Organizational Effectiveness Study O-1

In conjunction with the watershed-scale study effectiveness study, select a pilot organization to develop organizational structures to implement a basin scale effectiveness study. Results of this effectiveness study will identify and document organizational structures and actions taken to improve the success of the watershed-scale implementation of LIDs. Activities should range from establishment of institutional mandates, to internal organizational education, public education, and development of an asset management framework designed specifically for management of LIDs, as similarly described in the NPDES permit. Applying an organizational effectiveness study to a basin scale LID implementation project would not only provide focus to a localized intensive implementation project, but also connect results of the project to benefits observed in receiving water for an additional level of public education.

4.0 REFERENCES

Abbott, C.L., and L. Comino-Mateos. 2003. In-situ hydraulic performance of a permeable pavement sustainable urban drainage system. The Journal, v.17 no3., 187 – 190.

Ackerman, D. and E.D. Stein. 2008. Evaluating the effectiveness of best management practices using dynamic modeling. J. Environ. Eng. 134(8): 628 – 639.

Ahiablame, L.M., B.A. Engel, I. Chaubey. 2012. Effectiveness of low impact development practices: literature review and suggestions for future research. Water Air Soil Poll. 223: 4253 – 4273.

Alsup, S.E., S.D. Ebbs, L.L. Battaglia, and W.A. Retzlaff. 2011. Heavy metals in leachate from simulated green roof systems. Ecol. Eng. 37: 1709 – 1717.

Asleson,B.C. R.S. Nestingen, J.S. Gulliver, R.M. Hozalski, and J.L. Nieber. 2009. Performance assessment of rain gardens. JAWRA 45(4): 1019 – 1031.

Barrett, M.E. 2005. Performance comparison of structural stormwater best management practices. Water Environ. Res. 77(1): 78-86.

Barrett, M.E. 2008. Comparison of BMP performance using the international BMP database. J. Irr. Drain Eng. 134: 556 – 561.

Bean, E.Z., W.F. Hunt, and D.A. Bidelspach. 2007a. Evaluation of four permeable pavement sites in Eastern North Carolina for runoff reduction and water quality impacts. J. Irr. Drain. Eng. 133 (3), 583-592.

Bean, E.Z., W.F. Hunt, and D.A. Bidelspach. 2007b. Field survey of permeable pavement surface infiltration rates. J. Irrig. Drain. Eng. 133 (3), 249-255.

Beck, D.A., G.R. Johnson, and G.A. Spolek. 2011. Amending greenroof soil with biochar to affect runoff water quantity and quality. Environ. Poll. 159: 2111 – 2118.

Bedan, E.S., and J.C. Clausen. 2009. Stormwater runoff quality and quantity from traditional and low impact development watersheds. JAWRA 45(4): 998 – 1008.

Berndtsson, J. C. 2010. Green roof performance towards management of runoff water quantity and quality: a review. Ecol. Eng. 36: 351 – 360.

Brattebo, B.O. and D.B. Booth. 2003. Long-term stormwater quantity and quality performance of permeable pavement systems. Water Res. 37: 4369 – 4376.

Brown, R.A. and W.F. Hunt. 2010. Impacts of construction activity on bioretention performance. J. Hydrol. Eng. 15(6): 386 – 394.

Brown, R.A. and W.F. Hunt. 2011. Impacts of media depth on effluent water quality and hydrologic performance of undersized bioretention cells. J. Irrig. Drain Eng. 137: 132 – 143.

Buccola, N., and G. Spolek. 2011. A pilot-scale evaluation of greenroof runoff retention, detention, and quality. Water Air Soil Pollut. 216: 83 – 92.

Cardno TEC. 2012. Green roof performance study. Seattle Public Utilities, Seattle, WA.

Carpenter, D.D., and L. Hallam. 2010. Influence of planting soil mix characteristics on bioretention cell design and performance. J. Hydrol. Eng. 15(6): 404 – 416.

Carter, T. and C.R. Jackson. 2007. Vegetated roofs for stormwater management at multiple scales. Landscape Urban Plan. 80: 84 – 94.

Carter, T., C.R. Jackson, A. Rosemond, C. Pringle, D. Radcliffe, W. Tollner, J. Maerz, D. Leigh, and A. Trice. 2009. Beyond the urban gradient: barriers and opportunities for timely studies of urbanization effects on aquatic ecosystems. J.N. Am. Benthol. Soc. 28(4): 1038 – 1050.

Center for Watershed Protection (CWP). 2008. Runoff reduction method technical memo. Center for Watershed Protection, Ellicott City, MD.

Chapman, C., and R.R. Horner. 2010. Performance assessment of a street-drainage bioretention system. Water Environ. Res. 82(2): 109 – 119.

Clark, S.E., and R. Pitt. 2007. Influencing factors and a proposed evaluation methodology for predicting groundwater contamination potential from stormwater infiltration activities. Water Environ. Res. 79(1): 29 – 36.

Collins, K.A., W.F. Hunt, and J.M. Hathaway. 2008. Hydrologic comparison of four types of permeable pavement and standard asphalt in Eastern North Carolina. J. Hydrol. Eng. 13 (12), 1146 – 1157.

Collins, K.A., W. F. Hunt, and J.M. Hathaway. 2010a. Side-by-side comparison of nitrogen species removal for four types of permeable pavement and standard asphalt in Eastern North Carolina. J. Hydrol. Eng. 15 (6), 512-521.

Collins, K.A., T.J. Lawrence, E.K. Stander, R.J. Jontos, S.S. Kaushal, T.A. Newcomer, N.B. Grim, M.L. Cole Ekberg. 2010b. Opportunities and challenges for managing nitrogen in urban stormwater: a review and synthesis. Ecol. Eng. 36: 1507 – 1519.

Colwell, S., R.R. Horner, D.B. Booth, and D. Gilvydis. 2000. A survey of ditches along county roads for their potential to affect storm runoff water quality. Center for Urban Water Resources Management, University of Washington, Seattle, WA.

Damodaram, C., M.H. Giacomoni, C.P. Khedum, H. Holmes, A. Ryan, W. Saour, and E.M. Zechman. 2010. Simulation of combined best management practices and low impact development for sustainable stormwater management. JAWRA 46(5): 907-918

Davis, A.P. 2007. Field performance of bioretention: water quality. Environ. Eng. Sci. 24(8): 1048 – 1064.

Davis, A.P. 2008. Field performance of bioretention: hydrology impacts. J. Hydrol. Eng. 13(2): 90 – 95.

Davis, A.P., W.F. Hunt, R.G. Traver, and M. Clar. 2009. Bioretention technology: Overview of current practice and future needs. J. Environ. Eng. 135(3): 109 – 117.

Davis, A.P., M. Shokouhian, H. Sharma, and C. Minami, 2001. Laboratory study of biological retention for urban stormwater management. Water Env. Res. 73(1): 5 – 14.

Davis, A.P., M. Shokouhian, H. Sharma, and C. Minami, 2006. Water quality improvement through bioretention media: nitrogen and phosphorus removal. Water Env. Res. 78: 284 – 293.

Davis, A.P., M. Shokouhian, H. Sharma, C. Minami, and D. Winogradoff. 2003. Water quality improvement through bioretention: lead, copper, and zinc removal. Water Env. Res. 75: 73 – 82.

Davis, A.P., R.G. Traver, W.F. Hunt, R. Lee, R.A. Brown, J.M. Olszewski. 2012. Hydrologic Performance of bioretention storm-water control measures. J. Hydrol. Eng. 17(5): 604-614.

Deletic, A., and T.D. Fletcher. 2006. Performance of grass filters used for stormwater treatment – a field and modeling study. J. Hydrol. 317: 261-275.

DeBusk, K.M. and K.M. Wynn. 2011. Storm-water bioretention for runoff quality and quantity mitigation. J. Env. Eng. 137: 800 – 808.Diblasi, C.J., H. Li, A.P. Davis and U. Ghosh. 2009. Removal and fate of polycyclic aromatic hydrocarbon pollutants in an urban stormwater bioretention facility. Environ. Sci. Technol. 43: 494 – 502.

Dietz, M.E. 2007. Low impact development practices: a review of current research and recommendations for future directions. Water Air Soil Pollut. 186: 351 – 363.

Dietz, M.E. and J.C. Clausen. 2005. A field evaluation of rain garden flow and pollutant treatment. Water Air Soil Pollut. 167(1-4): 123 – 138.

Dierkes, C., A. Holte, W.F. Geiger. 1999. Heavy metal retention within a porous pavement structure. Proc. 8th International Conference on Urban Storm Drainage, August 30 – September 3, Sydney, Australia.

Dreelin, E. A., L. Fowler and C. Ronald Carroll. 2006. A test of porous pavement effectiveness on clay soils during natural storm events. Water Res. 40: 799 - 805.

Earles, T.A., J. Keyes, and E. Wong. 2009. Monitoring of a pervious pavement/ bioswale infiltration system In Colorado, 2006 – 2008. StormCon, 2009.

Emerson, C.H. and R.G. Traver. 2008. Multiyear and seasonal variation of infiltration from storm-water best management practices. J. Irrig. Drain. Eng. 134 (5), 599-605.

Ergas, S.J., S. Sengupta, R. Siegel, A. Pandit, Y. Yao, and X. Yuan. 2010. Performance of nitrogen-removing bioretention systems for control of agricultural runoff. J. Environ. Eng. 136(10): 1105 – 1112.

Fach, S. and W. Geiger. 2005. Effective pollutant retention capacity of permeable pavements for infiltrated road runoffs determined by laboratory tests. Water Sci. Tech. 51: 37 - 45.

Fassman, E.A. 2012. Stormwater BMP treatment performance variability for sediment and heavy metals. Separat. and Purif. Tech. 84: 95 – 103.

Fassman, E. A. and S. Blackbourn. 2010. Urban runoff mitigation by a permeable pavement system over impermeable soils. J. Hydrol. Eng. 15(6): 475 – 485.

Gilbert Jenkins, J.K., B.M. Wadzuk, and A.L. Welker. 2010. Fines accumulation and distribution in a storm-water rain garden nine years postconstruction. J. Irrig. Drain Eng. 136(12): 862 – 869.

Gilroy, K.L. and R.H. McCuen. 2009. Spatio-temporal effects of low impact development practices. J. Hydrol. 367: 228 – 236.

Glass, C., and S. Bissouma. 2005. Evaluation of a parking lot bioretention cell for removal of stormwater pollutants. Ecosystems and sustainable development V (81, pp. 699 – 708). Southampton: WIT Press.

Gregoire, B. and J.C. Clausen. 2011. Effect of a modular extensive green roof on stormwater runoff and water quality. Ecol. Eng. 37: 963 – 969.

Hathaway, A.M., W.F. Hunt, and G.D. Jennings. 2008. A field study of green roof hydrologic and water quality performance. Trans. ASABE 51(1): 37 – 44.

Hathaway, J.M., W.F. Hunt, and S. Jadlocki. 2009. Indicator bacteria removal in storm-water best management practices in Charlotte, N.C. 135(12): 1275 – 1285.

Hatt, B.E., T.D. Fletcher, and A. Deletic. 2009a. Hydrologic and pollutant removal performance of stormwater biofiltration systems at the field scale. J. Hydrol. 365: 310 – 321.

Hatt, B.E., T.D. Fletcher, and A. Deletic. 2009b Pollutant removal performance of field-scale stormwater biofiltration systems. Water Sci. Tech. 59(8): 1567 – 1576.

Herrera Environmental Consultants. 2012. Pollutant export from bioretention soil mix. Prepared for the City of Redmond, WA. Seattle, WA.

Hinman, C. 2009a Flow Control and Water Quality Treatment Performance of a Residential Low Impact Development Pilot Project in Western Washington. Water Environment Research Foundation.

Hinman, C. 2009b. Bioretention soil mix review and recommendations for Western Washington. Technical memorandum. Puget Sound Partnership, Tacoma, WA.

Hinman, C. 2012. Low impact Development Technical Guidance Manual for Puget Sound. Puget Sound Partnership, Tacoma, WA.

Hong, E., E.A. Seagren, and A.P. Davis. 2006. Sustainable oil and grease removal from synthetic storm water runoff using bench-scale bioretention studies. Water Env. Res. 78(2): 141 – 155.

Hood, M.J., J.C. Clausen, and G.S. Warner. 2007. Comparison of stormwater lag times for low impact and traditional residential development. JAWRA 43(4): 1036 – 1046.

Hsieh, C. and A.P. Davis. 2005. Evaluation and optimization of bioretention media for treatment of urban storm water runoff. J. Env. Eng. 131(11): 1521 – 1531.

Hunt, W.F., S. Stephens, and D. Mayers. 2002. Permeable pavement effectiveness in Eastern North Carolina. In Proceedings of 9th International Conference on Urban Drainage, ASCE, Portland, OR.

Hunt, W. F., J. M Hathaway, R. J. Winston, and S. J. Jadlocki. 2010. Runoff Volume Reduction by a Level Spreader–Vegetated Filter Strip System in Suburban Charlotte, N.C. Journal of Hydrologic Engineering; Jun2010, Vol. 15 Issue 6, p499-503, 5p, 2 Color Photographs, 1 Diagram, 3 Charts.

Hunt, W. F., A. R. Jarrett, and J. T. Smith. 2006. Evaluating Bioretention Hydrology and Nutrient Removal at Three Field Sites in North Carolina. Journal of Irrigation & Drainage Engineering; Nov/Dec2006, Vol. 132 Issue 6, p600-608, 9p, 5 Black and White Photographs, 1 Diagram, 6 Charts, 1 Graph, 1 Map.

Hunt, W. F., J. T. Smith, S. J. Jadlocki., J. M. Hathaway, and P. R. Eubanks. 2008. Pollutant Removal and Peak Flow Mitigation by a Bioretention Cell in Urban Charlotte, N.C. Journal of Environmental Engineering; May2008, Vol. 134 Issue 5, p403-408, 6p, 1 Color Photograph, 4 Charts, 1 Graph

Hurley, S.E., and R.T.T. Forman. 2011. Stormwater ponds and biofilters for large urban sites: modeled arrangements that achieve the phosphorus reduction target for Boston's Charles River, USA. Ecol. Eng. 37: 850 – 863.

Illgen, M., K. Harting, T.G. Schmitt, and A. Welker. 2007. Runoff and infiltration characteristics of pavement structures – review of an extensive monitoring program. Water Sci. Tech. 56 (10), 133 – 140.

International BMP Stormwater Database. 2011. Technical summary: volume reduction. International stormwater database at www.bmpdatabase.org.

International BMP Stormwater Database. 2012a. Addendum 1 to volume reduction technical summary (January 2011). Expanded analysis of volume reduction in bioretention BMPs. International stormwater database at www.bmpdatabase.org.

International BMP Stormwater Database. 2012b. Narrative overview of BMP database study characteristics. International stormwater database at www.bmpdatabase.org.

International BMP Stormwater Database. 2012c. Pollutant category summary statistical addendum: TSS, bacteria, nutrients, and metals. International stormwater database at www.bmpdatabase.org.

Jones, M.P. and W.F. Hunt. 2009. Bioretention impact on runoff temperature in trout sensitive waters.

Legret, M., V. Colandini, and C. Le Marc. 1999. Effects of a porous pavement with reservoir structure on runoff water: water quality and fate of heavy metals. Water Sci. Tech. 39(2): 111 – 117.

Klenzendorf, J.B., B.J Eck, R.J. Charbeneau, M.E. Barrett. 2012. Quantifying the behavior of porous asphalt overlays with respect to drainage hydraulics and runoff water quality. Environ. Eng. Geosci. 18(1): 99 – 111.

Kuang, X., and J. Sansalone. 2011. Cementitious porous pavement in stormwater quality control: pH and alkalinity elevation. Water Sci. Tech. 63(12): 2992 – 2998.

Kwiatkowski, M., A.L. Welker, R.G. Traver, M. Vanacore, and T. Ladd. 2007. Evaluation of an infiltration best management practice utilizing pervious concrete. JAWRA 43 (5): 1208-1222.

Le Coustumer, S., T.D. Fletcher, A. Deletic, S. Barraud, and J.F. Lewis. 2009. Hydraulic performance of biofilter systems for stormwater management: influences of design and operation. J. Hydrol. 376: 16 – 23.

Le Coustumer, S., T.D. Fletcher, A. Deletic, S. Barraud, and P. Poelsma. 2012. The influence of design parameters on clogging of stormwater biofilters: A large-scale column study. Water Res. 46: 6743 – 6752.

Lenhart, J.H. Compost as a soil amendment for water quality treatment facilities. Presented at the 2nd Annual Low Impact Development Conference, Wilmington N.C.

Li, H., and A.P. Davis. 2008. Heavy metal capture and accumulation in bioretention media. Environ. Sci. Technol. 42(14): 5247 – 5253.

Li, H. and A.P. Davis. 2009. Water quality improvement through reductions of pollutant loads using bioretention. J. Environ. Eng. 135 (8): 567 – 576.

Line, D.E. and W.F. Hunt. 2009. Performance of a bioretention area and a level spreader-grass filter strip at two highway sites in North Carolina. J. Irrig. Drain Eng. 135(2): 217-224.

Liu, Chung-Ming, Jui-Wen Chen, Jen-Hui Tsai, Wei-Shian Lin, M.-T.Yen, Ting-Hao Chen. 2012. Experimental studies of the dilution of vehicle exhaust pollutants by environment-protecting pervious pavement. J. Air Waste Man. Assoc. 62(1): 92-102.

Lucas, W.C. and M. Greenway. 2011. Phosphorus retention by bioretention mesocosms using media formulated for phosphorus sorption: response to accelerated loads. J. Irrig. Drain Eng. 137: 144 – 153.

Machusick, P.G., A. Welker, R. Traver. 2011. Groundwater mounding at a storm-water infiltration BMP. J. Irrig. Drain Eng. 137: 154 – 160.

Meyers, B., S. Beecham, and J.A. Leeuwen. 2011. Water quality with storage in permeable pavement basecourse. Water Man. 164(7): 361 – 372.

Minton, G.R. 2011. Stormwater Treatment – Biological, Chemical, and Engineering Principles, Resource Planning Associates, Seattle, WA.

Nagase, A. and N. Dunnett. 2012. Amount of water runoff from different vegetation types on extensive green roofs: effects of plant species, diversity, and plant structure. Landscape and Urban Planning 104: 356 – 363.

O'Neil, S.W. and A.P. Davis. 2012a. Water treatment residual as a bioretention amendment for phosphorus. I: evaluation studies. J. Environ. Eng. 138(3): 318 – 327.

O'Neil, S.W. and A.P. Davis. 2012b. Water treatment residual as a bioretention amendment for phosphorus. II: long term column studies. J. Environ. Eng. 138(3): 328 – 336.

Pagotto, C., M. Legret, and P. Le Cloirec. 2000. Comparison of the hydraulic behavior and the quality of highway runoff water according to the type of pavement. Water Res. 34(18): 4446 – 4454.

Passeport, E., W.F. Hunt, D.E. Line, R.A. Smith, and R.A. Brown. 2009. Field study of the ability of two grassed bioretention cells to reduce storm-water runoff pollution. J. Irrig. Drain Eng. 135(4): 505 - 510.

Pezzaniti, D. S. Beecham, and J. Kandasamy. 2009. Influence of clogging on the effective life of permeable pavements. Water Man. 162(3): 211 – 220.

Pitt, R., S. Chen, S.E. Clark, J. Swenson, and C.K. Ong. 2008. Compaction's impacts on urban storm-water infiltration. J. Irrig. Drain Eng. 134(5): 652 – 658.

Puget Sound Stormwater Work Group. 2010. Draft Stormwater Monitoring and Assessment Strategy for the Puget Sound Region, Volume 1: Scientific Framework and Volume 2: Implementation Plan. 83 pp.

Rangarajan, S., D.J. Sample, M. Boone, J. Lee, A. Muneer, K. Narayanaswamy, and M. Hochstedler. 2012. Urban wet weather flows. Water Environ. Res. 84(10): 861 – 970.

Revitt, D.M., L. Scholes and B.E. Ellis. 2008. A pollutant removal prediction tool for stormwater derived diffuse pollution. Water Sci. Tech. 57 (8): 1257 – 1264.

Roseen, R.M., T.P. Ballestero, J.J. Houle, J.F. Briggsand K.M. Houle. 2012. Water quality and hydrologic performance of a porous asphalt pavement as a storm-water treatment strategy in a cold climate. J. Environ. Eng. 138 (1): 81 – 89.

Roseen, R.M., T.P. Ballestero, J.J. Houle, P. Avelleneda, R. Wildey and J. Briggs. 2006. Stormwater low-impact development, conventional structural, and manufactured treatment strategies for parking lot runoff. Transportation Research Record: Journal of the the Transportation Research Board of the National Academies, 1984, 135 – 147.

Rossi, L., L. Rumley, C. Ort, P. Minkkinen, D.A. Barry, and N. Chevre. 2011. Sampling helper a web-based tool to assess the reliability of sampling strategies in sewers and receiving waters. Water Sci. Tech. 63 (12): 2975 – 2982.

Rowe, D.B. 2011. Green roofs as a means of pollution abatement. Environ. Pollut. 159: 2100 – 2110.

Roy, A.H., S.J. Wenger, T.D. Fletcher, C.J. Walsh, A.R. Ladson, W.D. Shuster, H.W. Thurston, R.R. Brown. 2008. Impediments and solutions to sustainable, watershed-scale urban stormwater management: Lessons from Australia and the United States. Environ. Manage. 42: 344 – 359.

Roy-Poirier, A., P. Champagne, and Y. Filion. 2010a. Bioretention processes for phosphorus pollution control. Environ. Rev. 18: 159 – 173.

Roy-Poirier, A., P. Champagne, and Y. Filion. 2010b. Review of bioretention systems research and design: past, present, and future. J. Environ. Eng. 136(9): 878-889.

Rusciano, G.M. and C.C. Obropta. 2007. Bioretention column study: fecal coliform and total suspended solids reductions. T. ASABE 50(4): 1261 – 1269.

Rushton, B. 2001. Low-impact parking lot design reduces runoff and pollutant loads. J. Water Res. Plan. Man. 127(3): 172 – 179.

Sansalone, J. and Z. Teng. 2004. In situ partial exfiltration of ranfall runoff. I: Quality and quantity attenuation. J. Environ. Eng. 130 (9): 990 – 1007.

Schueler, T.R. 1996. Irreducible pollutant concentrations discharged from urban BMPs. Watersh. Prot. Tech. 2(2): 369-372.

Sharpley, A. D. Beegle, C. Bolster, L. Good, B. Joern, Q. Ketterings, J. Lory, R. Mikkelsen, D. Osmond, and P. Vadas. 2012. Phosphorus indices: why we need to take stock of how we are doing. J. Environ. Qual. 41: 1711 – 1719.

She, N., and J. Pang. 2010. Physically based green roof model. J. Hydrol. Eng. 15(6): 458 – 464.

Scholz, A. 2011. Consequences of changing climate and land use to 100 year flooding in the Lamprey River watershed of New Hampshire. University of New Hampshire, Durham, NH.

Schroll, E., J. Lambrinos, T. Righetti, and D. Sandrock. 2011. The role of vegetation in regulating stormwater runoff from green roofs in a winter rainfall climate. Ecol. Eng. 37: 595 – 600.

Stander, E.K. and M. Borst. 2010. Hydraulic test of a bioretention media carbon amendment. J. Hydrol. Eng. 15: 531 – 536.

Strecker, E.W., Quigley, M.M., Urbonas, B.R., Jones, J.E., and Clary, J.K. 2001. Determining urban storm water BMP effectiveness. J. Water Resour. Plann. Manage. 127(3): 144 – 149.

Stovin, V. 2009. The potential of green roofs to manage urban stormwater. Water Environ. J. 24: 192 – 199.

Stovin, V., G. Vesuviano, and H. Kasmin. 2012. The hydrologic performance of a green roof test bed under UK climatic conditions. J. Hydrol. 414-415: 148 – 161.

Sun, X.L., and A.P. Davis. 2007. Heavy metal fates in laboratory bioretention systems. Chemosphere 66(9): 1601 – 1609.

Sutton, R.K., J.A. Harrington, L. Skabelund, P. MacDonagh, R.R. Coffman, and G. Kock. 2012. Prairie-based green roofs: literature, templates, and analogs. J. Green Build. 7(1): 143 – 172.

Tetra Tech. 2010. Stormwater best management practices (BMP) performance analysis. USEPA, Region 1, Boston MA.

Toland, D.C., B.E. Haggard, and M.E. Boyer. 2012. Evaluation of nutrient concentrations in runoff water from green roofs, conventional roofs, and urban streams. Trans. ASABE 55(1): 99 – 106.

Tota-Maharaj, K., and M. Scholz. 2010. Efficiency of permeable pavement systems for the removal of urban runoff pollutants under varying environmental conditions. Env. Prog. Sust. Energy 29 (3): 358-369).

Trowsdale, S.A and R. Simcock. 2011. Urban stormwater treatment using bioretention. J. Hydrol. 397: 167 – 174.

Tyner, J.S., W.C. Wright, and P.A. Dobbs. 2009. Increasing exfiltration from pervious concrete and temperature monitoring. J. Environ. Man. 90: 2636 -2641.

Uhl, M., and L. Scheidt. 2008. Green roof storm water retention – monitoring results. In: 11th International Conference on Urban Drainage, Edinburgh, Scotland, UK, 31/8 – 5/9.

United States Environmental Protection Agency (USEPA). 2012a. Low impact development web page. Downloaded from http://water.epa.gov/polwaste/ green/index.cfm

United States Environmental Protection Agency (USEPA). 2012b. Menu of stormwater BMPs, porous asphalt pavement. Downloaded from http://cfpub.epa.gov/npdes/stormwater/menuofbmps.

Vanderlinden, K. and M. Stone. 2009. Treatment performance of an extensive vegetated roof in Waterloo, Ontario. Water Qual. Res. J. Can. 44(1): 26 – 32.

Vijayaraghavan, K., U.M. Joshi, and R. Balasubramanian. 2012. A field study to evaluate runoff quality from green roofs. Water Res. 46: 1337 – 1345.S

Walsh, C.J. and J. Kunapo. 2009. Retention capacity: a metric to link stream ecology and stormwater management. J. Hydrol. Eng. 14: 399 – 406.

Washington State Department of Ecology (Ecology). 2011. Draft Phase I Municipal Stormwater Permit. Olympia, WA

Washington State Department of Ecology (Ecology). 2012. Stormwater Management Manual for Western Washington. Publication No. 12-10-130. Olympia, WA.

Washington State Department of Transportation. 2011. Stormwater monitoring quality management plan. Environmental Services Office, Stormwater and Watersheds Program. Olympia, WA.

Weiss, P,T., G. LeFevre, and J.S, Gulliver. 2008. Contamination of soil and groundwater practices due to stormwater infiltration practices, a literature review. University of Minnesota Stormwater Assessment Project. Project Report No. 515.

Winston, R.J., W.F. Hunt, S.G. Kennedy, J.D. Wright, and M.S. Lauffer. 2012. Field evaluation of storm-water control measures for highway runoff treatment. J. Environ. Eng. 138: 101-111.

Wolf, L., J. Klinger, and H. Hoetzl. Quantifying mass fluxes from urban drainage systems to the urban soil-aquifer system. J. Soils Sed. 7: 85 – 95.

Zhang, L., E.A. Seagren, A.P. Davis, and J.S. Karns. 2010. The capture and destruction of Escherichia coli from simulated urban runoff using conventional bioretention media and iron oxide-coated sand. Water Environ. Res. 82(8): 701 – 714.

Zhang, L., E.A. Seagren, A.P. Davis, and J.S. Karns. 2011. Long term sustainability of *Escherichia coli* removal in conventional bioretention media. J. Env. Eng. 137(8): 669 – 677.

Zimmerman, M.J., M.C. Waldron, J.R Barbaro, and J.R. Sorenson. 2010. Effects of low-impact-development (LID) practices on streamflow, runoff quantity, and runoff quality in the Ipswich River Basin, Massachusetts – A summary of field and modeling studies. U.S. Geological Survey Circular 1361, 40 p.