Synthesis of Findings of Effectiveness Study Literature Review

In 2012 the Stormwater Work Group (SWG) commissioned a series of “synthesis papers” to evaluate the findings of an earlier literature review and summarize the state of research and understanding of stormwater management approaches. The white papers with key findings from these projects are posted below, arranged by management program effectiveness topic area. Many of the findings should be helpful in developing, modifying and operating effective local stormwater programs. The papers’ authors also propose ideas for getting helpful answers to the questions that had been posed by permittees and others as being important to answer to improve stormwater management programs.

The SWG has been working since 2010 to develop a list of effectiveness topics and questions to be addressed by studies that will be conducted by the new Regional Stormwater Monitoring Program (RSMP) and implemented through the municipal stormwater NPDES permits. In September 2011 the workgroup submitted a ranked list of 22 topics to Ecology. These papers were used to help the workgroup update the September 2011 list. The new list was finalized In June 2013. The SWG hosted two workshops in early 2014 to discuss proposals for the RSMP studies. A final set of ten proposals is now under consideration by the SWG.

- Low Impact Development
- Public Education and Outreach
- Source Control
- Operation and Maintenance
- Traditional BMPs
    - Retrofit
    - Filter Strips

BMP Effectiveness Literature Review, 2011

Introduction

This database contains the results of a literature review on the effectiveness of various stormwater best management practices (BMPs). The literature review is intended to help the Puget Sound Stormwater Work Group (SWG) develop recommendations for BMP effectiveness studies in the next municipal separate storm sewer system (MS4) permits. The literature review should help the SWG identify BMP effectiveness studies that complement rather than duplicate previous studies. In addition, the literature review may facilitate the design of effectiveness studies by making it easier to find potentially relevant studies and take advantage of their "lessons learned."

The literature review was funded by the Puget Sound Partnership, the City of Everett, and Pierce County. Pierce County retained Brown and Caldwell (BC) to assist with the project (Pierce County Work Order D082-01). The scope of the literature review was limited to the budget specified in the Pierce County work order. Washington State Department of Transportation (WSDOT) staff performed the literature searches and helped obtain the relevant documents for review. The SWG Effectiveness sub-group provided direction and oversight.

Approach

BC prepared a draft keyword list and a draft template for an Excel database to summarize the literature review results and sent it to the SWG Effectiveness sub-group for review. Shortly thereafter, the SWG obtained a list of approximately 180 effectiveness questions submitted by the Phase II permittees and questionnaire respondents. BC reviewed the questions and revised the keywords list accordingly. BC sent the revised list to the SWG Effectiveness sub-group for review and made additional changes based on their feedback.

WSDOT research staff used the revised keyword list to search the "Environment Complete" database. This database includes more than 1,000 academic journals, magazines, books, and monographs. WSDOT identified about 450 potentially relevant documents and provided BC with abstracts for these documents.

BC's initial review found fewer than expected abstracts for catch basin cleaning and street sweeping studies, possibly because some of the key studies were published before many of the journals in the "Environment Complete" database began digital indexing. We also noted that the database did not cover conference proceedings for some of the key water resources organizations. To address these potential gaps, WSDOT performed a series of follow-up searches as outlined below.

WSDOT used the "Ulrich" periodicals directory to perform a focused search for relevant articles that pre-date the "Environment Complete" digital indexing. The search focused on periodicals deemed likely to contain documents relevant to our stormwater keywords (e.g., Journal of American Water Resources Assn., Water Environment Research, Water Resources Research, Water & Environment Journal, Water Environment & Technology, Water Science & Technology, and Journal of Water Resources Planning and Management). WSDOT also searched the federal government documents database, "Gov.doc," for additional materials relevant to BMP effectiveness.

WSDOT was unable to find a comprehensive, searchable database for water resources conference proceedings. Therefore, WSDOT staff contacted several key organizations (e.g., AWRA, Oregon ACWA, StormCon, WEF, and CASQA) but was unable to obtain searchable databases for their respective conference proceedings. WSDOT's follow-up searches identified a number of documents potentially relevant to stormwater BMP effectiveness. WSDOT provided the citations and other available information to BC.

BC reviewed the results of the initial and follow-up searches, and found that about 335 of the documents appeared to be directly relevant to the BMP effectiveness questions compiled by the Washington State Department of Ecology (Ecology) and the SWG.

Based on the literature search results and feedback from the SWG Effectiveness sub-group, BC refined the database structure and sent a prototype to the SWG Effectiveness sub-group for review and comment.

Database Format

The results of the literature review are summarized in the accompanying Excel workbook. As noted above, it is designed to allow users to identify documents that may be relevant to their questions on BMP effectiveness. This workbook contains the worksheets described below:

- **Read Me:** Documentation.
- **Literature Database:** This sheet summarizes the results of the literature review. It is structured so that users can filter the records to identify those relevant to a specific BMP or other key attribute. It also lists the Internet address for obtaining the document online (if available). Clicking on the document title will bring the user to the summary of that document, which is on the Literature Summaries sheet.
- **Literature Summaries:** This sheet contains brief summaries of each document in the database. Each summary contains a "back" button that takes the user back to the corresponding record on the Literature Database sheet.
- **Data Dictionary:** This worksheet provides definitions for the BMPs and other key attributes in the database. The BMP definitions are based primarily on the definitions used for the International BMP Database. You can click on any attribute in the Literature Database and be directed to the corresponding definition.
- **Key Words:** This worksheet provides the revised keyword list used to perform the literature search.
- **Data Entry Template:** This sheet contains a blank form for adding documents to the database.

General Procedure

1. Use the filters in the Literature Summaries sheet to identify the documents that may be pertinent to a National Pollutant Discharge Elimination System (NPDES) permit area, BMP type, pollutant, or other key attribute of interest. To facilitate filtering by BMP type, documents pertinent to more than one BMP are listed multiple times (once per BMP type).
2. Click on the document title to view a summary of the document.
3. If the summary indicates that the document is relevant to the user’s needs, click on the Internet address for that document. (Note: Some documents are not readily available on the Internet, and some require payment to obtain the full report.)
4. After obtaining the relevant articles, users may wish to review the literature cited in those articles in order to identify additional relevant documents.
5. Use the Data Entry Template to add additional relevant studies (e.g., from conference proceedings), and/or update the database as new studies are completed.

Limitations

The scope of the literature review was limited to the budget specified in the Pierce County work order. The literature search focused on using the keyword list to search journals, magazines, and other sources with digital indexes. The budget did not allow for a thorough search of conference proceedings and university and municipal Web sites; outreach to individual researchers; or identification of planned or ongoing research. Therefore, the database should not be considered comprehensive.

The literature review focused on documents that appeared relevant to the BMP effectiveness questions compiled by Ecology and the SWG Effectiveness sub-group. The literature search identified a number of indirectly relevant documents that were not included in the database due to cost limitations.

Contact Karen Dinicola, Project Manager, at 360-407-6550 for more information.

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

List of Tables

List of Figures

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.

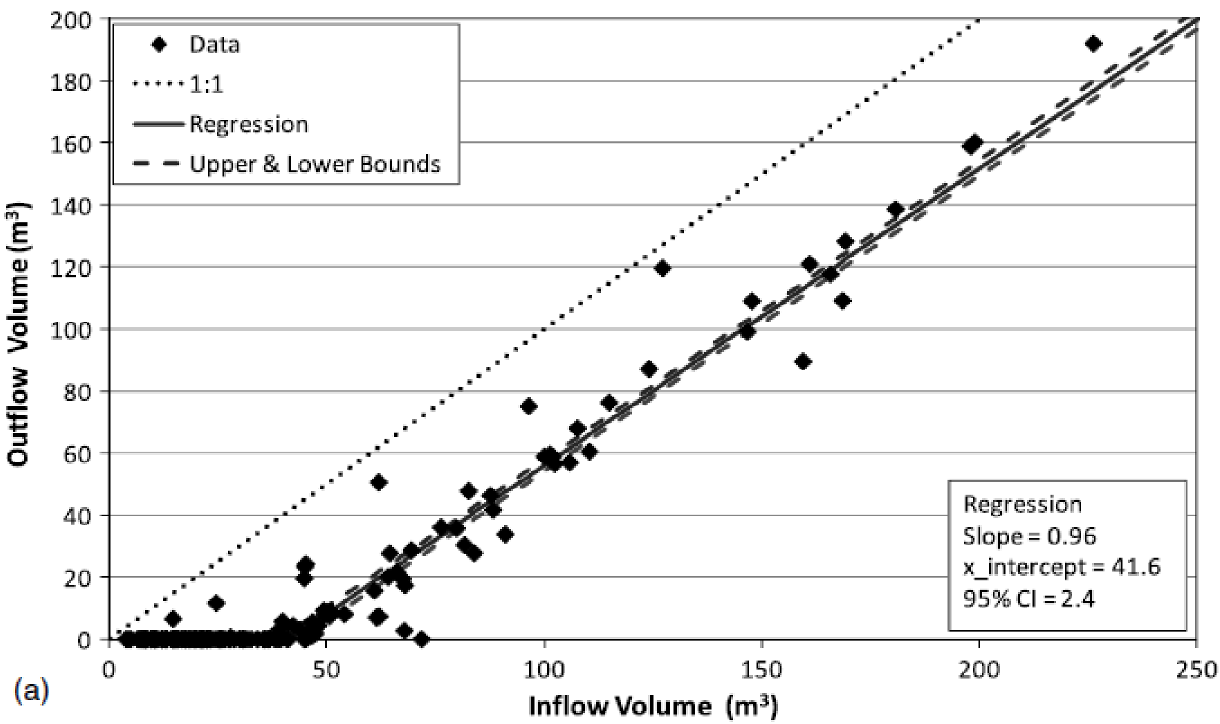

Figure 1. Example flow response showing low or no flow for inflow volumes less than the BAV, followed by approximately a 1:1 ratio of outflow to inflow volume for inflow volumes greater than the BAV (Davis et al. 2012).

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.

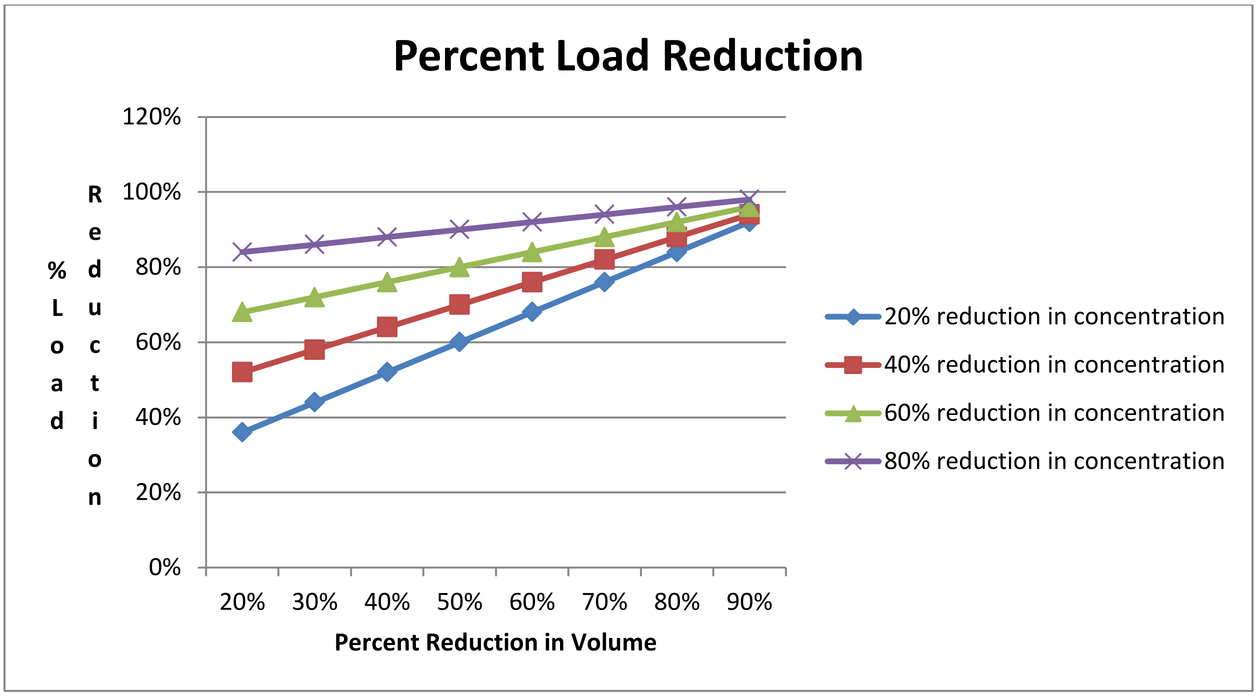

Figure 2. Theoretical load reduction for coincident reductions in volume and concentrations.

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.

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?

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.

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?

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.

<u>What, if any, LID measures are feasible in areas with tight soils?</u>

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.

<u>What, if any LID measures are feasible in areas with shallow ground water?</u>

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.

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

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.

<u>Can recycled concrete be used as storage under permeable pavement?</u>

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.

Effectiveness of Public Education and Outreach Programs for Reducing Impacts of Stormwater on Rivers and Streams

Prepared by
Leska S. Fore
Statistical Design
Seattle, WA

Prepared for
The Stormwater Work Group, Puget Sound Ecosystem Monitoring Program,
Washington Department of Ecology, and
The Association of Washington Cities

April 12, 2013

Produced by *Earthright Insight*, www.earthrightinsight.com

Table of Contents

Effectiveness of Public Education and Outreach Programs for Reducing Impacts of Stormwater on Rivers and Streams

Key Findings

- Many people in Puget Sound are very aware of stormwater issues and how they relate to the health of Puget Sound. Many are willing to do more and pay more to protect the Sound.
- Public education and behavior change programs work: behaviors can be changed and pollutants can be reduced.
- Increased awareness of an issue does not necessarily lead to a positive change in behavior; nonetheless, awareness may be a prerequisite for a successful behavior change program.
- Behavior change programs are more successful when they target specific behaviors and audiences.
- Studies are more likely to measure whether behavior has changed rather than whether the health of the water body has improved.
- The Puget Sound Partnership and King County have developed and tested indexes to identify target audiences and measure behavior change at a regional and local scale.

Context for this Document

The Washington Municipal Stormwater Permits for Phase 1 and 2 jurisdictions require an education and outreach program that targets specific audiences to change polluting behaviors associated with, for example, yard care, storage of chemicals, pet waste, auto maintenance, and prevention of illicit discharges (Department of Ecology, 2012a,b).

The Stormwater Work Group (SWG) is a group of stakeholders representing local, state, and federal governments, environmental and business organizations, tribes, and agriculture. The goal of the Work Group is to reduce the harm caused by stormwater to the Puget Sound ecosystem. The SWG's Regional Stormwater Monitoring Program (RSMP) will be implemented through municipal stormwater permits.

During 2011-2012, the Stormwater Work Group identified 22 questions about the effectiveness of various stormwater management practices for reducing the impact of stormwater on water resources. To answer these questions, the Stormwater Work Group commissioned a series of literature reviews to evaluate which of those questions have already been answered. The purpose of this document is to provide just enough context in order to answer and evaluate the questions asked by the SWG. This document addresses 4 of the 22 effectiveness monitoring questions related to public education and outreach (See Appendix 1 for complete list of questions).

This document includes:

1) A description of how social marketing principles are used in public education and outreach;
2) Results from local surveys and research to answer the specific questions from the Stormwater Work Group about whether public education can reduce pollutants in stormwater, increase awareness about stormwater issues, and change negative behaviors;

3) Recommendations for future effectiveness studies; and

4) Descriptions of other groups working to change public behavior to reduce the impacts of stormwater in Puget Sound.

Model for Behavior Change

In recent years, the ideas of social marketing have changed how public education is implemented (Allred et al., 2011). Social marketing has had a profound impact on social issues in the areas of public health, injury prevention, and the environment (Lee and Kotler, 2008). The guiding principles of social marketing are 1) allocate resources to change a specific behavior, 2) conduct activities aimed at the target audience, 3) test for the response of the audience, and 4) ultimately measure indicators in the environment to test for change (Figure 1). In California, stormwater permits are written using the framework of community based social marketing.

Many nonpoint sources of pollution in stormwater derive from common human behaviors; thus, there exists a huge opportunity to reduce stormwater pollution if a large number of people make even a small change in their behavior. Earlier models of public education were based on the idea that if people knew more about the issues, they would make rational decisions that are good for the environment.

The new idea is to change behavior by identifying the barriers to change and working to remove the barriers. Behavior change campaigns tailored specifically to people that are performing negative behavior are more effective than a scattershot approach to everyone. Research has shifted aware from understanding the problem, toward identifying which behaviors cause the biggest problems, and which people are doing them. Social marketing emphasizes the value of knowing your target audience, that is, what is important to people whose behavior you want to change (Ryan, 2009). This conceptual model is the foundation for many of the documents reviewed here.

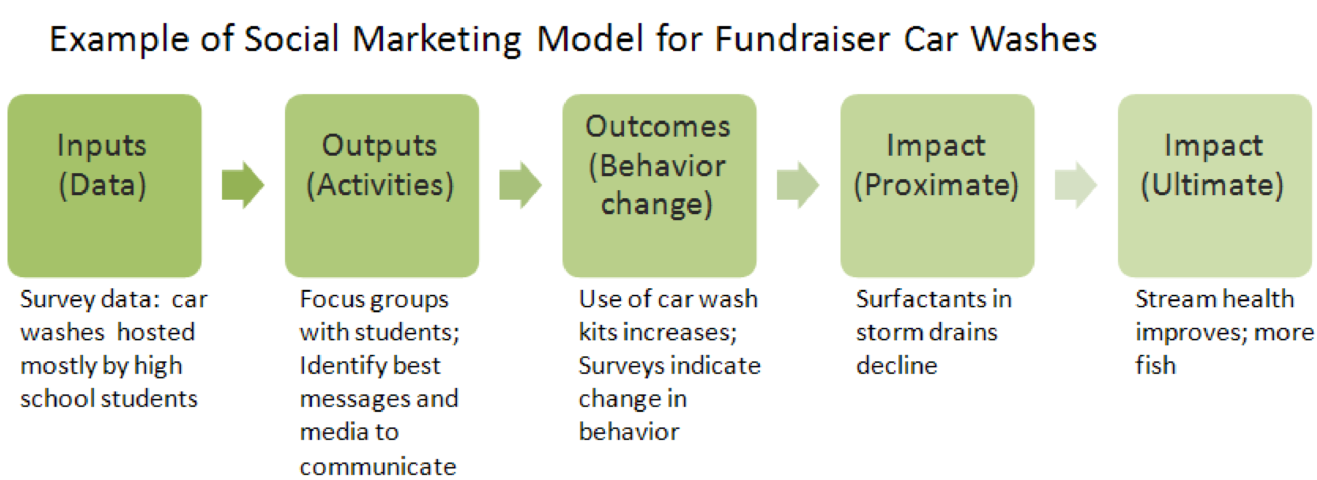

Figure 1. Social marketing model with example activities for fundraiser car washes.

Testing for Effectiveness of Behavior Change

There are multiple points in a (simple) model of behavior change where we can test for the effectiveness of public education and outreach programs (Figure 1). As an example, fundraiser car washes can result in hundreds of gallons of untreated water going in to storm drains. At the output step, we can evaluate whether planned activities were successful, specifically, did people read or hear the message and understand it. At the outcome step, changes in behavior are typically reported. Surveys are often used and people are asked to about their behavior. One caveat here is that self-reported data can be overly optimistic (Taylor and Wong, 2002). At the other end of the model, detecting a change in stream health can be challenging because of the many influences in a watershed. For this reason, intermediate outcomes are often best because they avoid self reporting bias and provide an objective measure of effectiveness. Intermediate outcomes include counting the number of car washes that use kits to prevent waste water from going down the drain.

Prioritizing Behaviors for Change

For a single identified problem, this approach is straightforward although not necessarily simple. For a multidimensional problem like stormwater, a larger frame may be needed to first select among the various behaviors that affect stormwater. A project in Ontario to reduce phosphorus in agricultural waterways provides an example of a simple, structured approach to prioritize behaviors (Lura Consulting, 2010). For this study, at the input step, a literature review identified all sources of phosphorus related to local farming practices. An expert panel shortened the list according to how widespread the negative activity was and the amount of impact a change in behavior was likely to have. At the output step, focus groups of farmers prioritized the list of behaviors according to potential barriers and benefits. Finally, they created a graphic plot with impact on streams as one axis and probability of behavior change as the other. The highest scoring behaviors were targeted with additional education programs.

The WRIA 8 Salmon Recovery Council used a similar approach to prioritize public behaviors for change programs by first developing a rough ranking of the behaviors most important to salmon recovery and next ranking behaviors according to how easy they are to change (Sage Enviro, 2009a). From this matrix they developed specific behavior change activities for target audiences.

Worth noting here is that the list of possible behaviors developed for WRIA 8 salmon recovery was more inclusive and more tightly connected to the ultimate desired outcome of healthy watersheds than a list of possible behaviors typically derived from stormwater permits. The regulatory framework of the Clean Water Act has historically focused on water quality parameters such as nutrients and bacteria. In contrast, the Endangered Species Act has a greater focus on habitat. Within the context of Chinook recovery, WRIA 8 stakeholders identified key outcomes related to landscape design of shorelines, native plantings, and removal of invasive plants, along with outcomes more typically associated with stormwater management (Sage Enviro, 2009b).

The questions developed by the Stormwater Work Group for this project reflect the historic emphasis on water quality measures even though the Clean Water Act's goals emphasize protection of the "chemical, physical and biological integrity" of rivers and streams. Thus, behaviors related to habitat management might also be considered for public education.

Answering Questions from the Stormwater Work Group

The questions about effectiveness monitoring developed by the Stormwater Work Group represent a successful process to work as a group to make regional decisions about stormwater management based on the best available science and the professional expertise of group members.

This document is organized to align with the questions posed by the Stormwater Work Group. Each of the four general questions is addressed first and followed by responses to the more specific questions in each section. For the more specific questions, I document whether the question has been answered already, whether it is the right question to ask, and how we might ask a better question. Under each question I review related journal articles and local, unpublished reports prepared by regional consultants and stormwater professionals that address the topic of the question.

3. Does public education decrease pollutants in stormwater?

This is a great question that has not been well answered. Two studies documented a reduction in nutrients as a result of lawn owners changing their behavior (see question 3.b. below). Another study showed that bacteria declined significantly in a Kitsap County stream as a result of an education campaign (see question 9.b. below). In WRIA 8, stakeholders are designing studies to connect human behavior with changes in stream condition at a watershed scale, but results are not yet available.

In general, the effectiveness of public education campaigns is typically measured in terms of behavior change rather than the ultimate impact of the project on stream health. In the language of social marketing, measures of effectiveness are typically done for *outputs* rather than *outcome* (see Figure 1). When testing for the effectiveness of an education program, change in behavior is typically measured. Measures are usually based on surveys where people self-report their behavior. Taylor and Wong (2002) caution that self-reporting can be overly optimistic and that direct measures of behavior are more reliable.

It is both difficult to measure and to compare the relative effectiveness of nonstructural best management practices (BMPs) such as public education, city planning, and regulatory ordinances. Taylor et al. (2007) note that there is very little published guidance for measuring the effectiveness of nonstructural BMPs.

A recent assessment of stormwater needs for Puget Sound municipalities found there was not enough information available to evaluate the effectiveness of public education programs at the level of the stream (Bissonnette and Parametrix, 2010). Measuring the effectiveness of public education is an emerging field of research with great opportunities to make an impact.

a. Are fecal coliform levels in stormwater reduced after <u>pet waste</u> education?

This is a good question about outcomes and I found no studies that tested for a decline in fecal bacteria as a result of pet waste education.

Regional surveys of behaviors indicate that dog owners dispose of waste properly most of the time. A survey of 2000 Puget Sound residents found that 87% of dog owners usually or always pick up dog waste and 45% usually or always put it in the trash (PSP, 2012b). A similar survey in King County found an increase in proper dog waste disposal from 52% in 2008 to 74% in 2011 (Tarnai, 2011). From a survey of Kitsap County residents, about half of dog owners pick up waste every time while walking (54%) and others pick up most of the time (19%). Answers to these questions did not change from 2008 to 2011 (CEC, 2011a). A seven-city survey in Puget Sound found that 90% of dog owners reported they always pick up dog waste (Klima and Buttenob, 2009). Results from these surveys indicate that residents of more urban areas were more likely to dispose of dog waste properly than residents of rural or suburbanizing areas.

b. Are nutrient levels in stormwater reduced after <u>natural yard</u> care education?

Two studies compared nutrient levels in stormwater drains after phosphorus fertilizers were restricted. In a before/after study design, Lehman et al. (2009) documented the effects of public education programs and a city ordinance banning lawn fertilizer in Ann Arbor, MI near the Huron River. Within one year of the ban, they documented a 28% decrease in phosphorus loading measured at stormwater drains. Results were based on weekly samples from May to September. A similar study in Minnesota used paired watersheds to test whether restricting the use of fertilizers containing phosphorus reduced phosphorus in stormwater (Vlach et al., 2010). For watersheds with fertilizer restrictions, the study documented a significant reduction (25%) of phosphorus as measured by stormwater concentrations in the catch basin. Data comparison was complicated because concentrations had to be adjusted for flow, impervious cover and watershed size.

A related study in Ontario looked at phosphorus reduction in an agricultural setting (Lura Consulting, 2010). This study is a very good example of community-based social marketing techniques and includes an excellent example of how to prioritize behaviors for change. Scientific experts identified sources of phosphorus and their relative impact. Farmers with the most potential for reducing phosphorus use (the target audience) were identified and they developed a list of possible behaviors to reduce phosphorus. The list of behaviors was ranked according to the potential impact on phosphorus reduction and the probability of the preferred behavior being adopted. Unfortunately, the effectiveness of the program, which included education, workshops and individual contact, has not been reported.

Here in Puget Sound, a survey of 2000 residents found that 51% report that they never or seldom use fertilizer (PSP, 2012b). In Kitsap County, self-reported chemical fertilizer use declined dramatically from 52% in 2008 to 21% in 2011; use of Weed and Feed also declined from 54% to 40% (CEC, 2011a). In King County, a similar survey found an even more dramatic decline in reported use of chemical lawn fertilizer with 84% of respondents saying they never use chemical lawn fertilizer compared to 11% in 2005 (Tarnai, 2011). Changes in behavior indicate that education and social marketing programs were effective in King and Kitsap Counties.

c. Are pesticide concentrations and number of hits reduced in an urban stream after general awareness?

This is a good question about outcomes. I found no studies that directly tested the link between changes in pesticide concentrations and public education. However, a recent report tested for changes in pesticide concentrations in urban and agricultural watersheds and found significant decreasing trends for some pesticides in Thornton Creek, an urban creek in King County. Although the study did not relate observed changes in pesticide use to public education efforts, outreach and behavior change programs are ongoing in Seattle.

A regional survey of 2000 Puget Sound residents found that a majority of yard or garden owners seldom or never use pesticides (78%) or weed killer (65%; PSP, 2012b). A survey of Kitsap County residents found a dramatic decline in pesticide use from 74% in 2008 to 16% in 2011; clearly, whatever methods are being used in Kitsap County are effective (CEC, 2011a). A seven-city survey of 700 residents found that nearly all (97%) respondents reported that they applied insecticide and weed killer at the recommended rates, but did not ask how often they were applied or how many used them (Klima and Buttenob, 2009).

On a related note, Washington State Department of Agriculture planned to mail surveys about pesticide use to 15,000 Puget Sound residents in February 2013 to evaluate how they are used.

d. Does establishing a spill hotline result in reduced stormwater pollutants?

This is a good question about outcomes; I found no studies that related a spill hotline to concentrations of stormwater pollutants.

A 2009 survey of residents in seven cities of Puget Sound found that 34% did not know who to call to report illicit discharges (Klima and Buttenob, 2009). To determine what type of information is needed, Kitsap County funded a study to interview focus groups (N = 21 people) about their use of a Stormwater Hotline (CEC and GRG, 2008). They showed them examples of educational materials and asked them to rate what types of information would be most effective. When asked what would make them change their behavior of not reporting spills, they said the most compelling messages were related to children safety or public health.

Kitsap County established the Water Pollution Hotline and received 118 calls from citizens and municipal staff in 2009-2010. Of these calls, 79% (93) were confirmed to be an illicit discharge (Fohn et al., 2011). A more recent survey of Kitsap County residents found that although most would report a spill (76%), many do not know the correct number to call (CEC, 2011a). Other respondents didn't know what to do or would probably do nothing.

e. Does fundraiser car washing education reduce surfactants in stormwater?

This is a good question about outcomes. Behavior and attitudes about car washing have changed in recent years, but I found no studies that evaluated whether surfactants have been reduced.

The preferred behavior is to use a commercial car wash that treats the wastewater; second best is to wash on the grass or use a car wash kit to capture the run-off. A survey of Puget Sound residents found that 77% of respondents know that washing cars on the street is harmful; and 60% report that they seldom or never wash cars on the street (PSP, 2012a,b). A similar survey in King County found a steady increase in appropriate car washing from 54% to 62% from 2005 to 2011 (Tarnai, 2011). Although the number of people who washed cars at home in Kitsap County increased (from 58% to 75%), the good news is that the number who let waste water run to the street or a storm drain decreased by 21% (from 47% to 26%; CEC, 2011a).

Fundraiser car washes continue to be popular. A recent phone survey of ~800 residents of Kitsap County found that 55% of respondents use them and that number did not change from 2008 to 2011. Nonetheless, there was a big change in attitude: an increase of 22% of respondents thought car washes should be restricted to places where the stormwater and run-off is treated (42% to 64%; CEC, 2011a).

Issaquah, Bellevue, Woodinville, Reston, and Redmond lend car wash kits to charity events and businesses (Sage Enviro, 2009b). Bellevue found too much human error associated with the kits and Redmond is currently evaluating their program. One problem with fundraiser car washes is that 67% of people surveyed believe that biodegradable soap is safe to use for washing cars on the street, it's not (seven-city survey, Klima and Buttenob, 2009)

9. Does public education increase awareness and change behavior?

The answer is yes. The peer-reviewed literature broadly supports the idea that public education is effective (Taylor and Wong, 2002). As an example, in Puget Sound a recent survey found that 96% of 2000 respondents reported that they never flush chemicals such as paint thinner down the drain; and 94% never flush prescription drugs (PSP, 2012b). Past education campaigns for these issues, such as *Puget Sound Starts Here*, were obviously effective.

Residents of Puget Sound are also highly aware of stormwater problems and how they threaten the health of Puget Sound. A survey of 2000 residents in Puget Sound found that 61% believe that clean up is urgent (PSP, 2012a). A majority of respondents know that lawn chemicals (89%), car washing on the street (77%), weed and feed (77%), and leaving dog waste (63%) are all harmful to Puget Sound (PSP, 2012a). Demonstrating a similar knowledge of local issues, a focus group in a Kitsap County study was able to name all the behaviors associated with stormwater runoff problems (CEC and GRG, 2008).

Two recent studies document a change in Puget Sound residents' attitudes and behaviors. When residents of Kitsap County were surveyed in 2011, they showed a 33% increase in awareness of ways that people can prevent water pollution since 2008 (40% to 73%; CEC, 2011a). Clearly education campaigns are increasing awareness.

Experts emphasize that awareness is not equal to behavior change; nor is a change in awareness a good predictor of a change in behavior (PSP, 2012a; Taylor and Wong, 2002). For example, in Pierce County no relationship was found between awareness of the correct behavior and the actual behavior related to lawn chemicals and lawn care (Elway, 2009). The reverse is also true, people may do the right behavior without knowing why it's the right thing to do. For example, small business owners can reliably be taught not to put pollutants down the storm drain without knowing that stormwater is untreated (CEC, 2011b).

For these reasons, public surveys have shifted to questions about specific behaviors rather than attitudes. A comparison of responses by ~800 Kitsap County residents from 2008 to 2011 found that self-reported chemical fertilizer use declined dramatically (31%); pesticide use declined dramatically (47%); and organic fertilizer use increased (12%; CEC, 2011a). Car washing behavior also changed with more respondents washing cars away from storm drains and streets. In King County a similar survey of ~2000 residents showed a dramatic decline in the reported use of chemical lawn fertilizer (73%) from 2005 to 2011; and a 22% increase in dog owners who always pick up waste (Tarnai, 2011).

Puget Sound Partnership's recent regional survey identified a group of respondents described as "ready and willing." They represented 50% of respondents and agree that Puget Sound is in poor condition and it's going to get worse. They believe clean up is extremely urgent and they know what's harmful to water quality and want to do all they can to protect the environment (PSP, 2012a). Furthermore, 83% of respondents agreed with the statement that one person's actions can make a difference. These are the people who could be asked to do more.

a. *What is the change over time of various target audiences willing to make a simple change in their daily lives to help Puget Sound?*

This question is very general; a better question would focus on specific behaviors and whether there has been a change in the behavior, rather than the willingness to change.

A survey of Pierce County 700 residents found that 43% of respondents were willing to change their behavior to prevent water pollution even if it involves sacrifices; another 40% were willing to make changes if they are easy (Elway, 2009). In Snohomish County, a survey of 400 residents found that 78% were willing to do more to reduce their impact on rivers and streams (33% very and 43% somewhat willing); however, many were not sure what to do (Grove Quirk Insight, 2002). Focus groups were not effective in that learning about problems did not change participants' willingness to do more.

b. *What is the change over time of various target audiences willing to invest over $1,000 to make a change in their property to help Puget Sound?*

This question is very general and not focused on a specific behavior change. I found no surveys of the change in residents' willingness to pay a specific amount to change their property. Related surveys suggest that respondents are willing to pay more money to protect Puget Sound. A survey of Puget Sound residents in 2008 found that 46% of respondents were willing to pay more to clean up Puget Sound (Elway, 2008). In Pierce County, a survey of 700 residents found that most respondents (60%) support additional fees for surface water management projects (39% somewhat supportive and 21% strongly supportive; Elway Research, 2009).

A survey of small business owners found they were not interested in applying for grants or being provided with government help to make structural changes (CEC, 2011b). Many small contractors don't want to be involved with government programs and prefer to keep a low profile. In contrast, small farmers in Kitsap County pursued grants and funding to clean up animal waste and the result was a measureable reduction of fecal bacteria in Dogfish Creek (Puget Sound Action Team, 2005).

c. *What is the change over time of car owners to fix leaks?*

This is a good question because it focuses on specific behavior that can be measured. I found no studies that compared the change in this behavior over time. In a survey of 1800 residents of King County, the majority reported in 2011 that they always fix car leaks (67%) and others sometimes fix car leaks (10%; Tarnai, 2011). A similar survey of 900 people living in seven cities in Puget Sound found that 90% of respondents reported that they fix car leaks within three weeks (Klima and Buttenob, 2009). Stormwater Outreach for Regional Municipalities (STORM), City of Seattle, King County ECO Net, and the Puget Sound Partnership are actively working on this issue.

d. What is the change in stormwater drain awareness of various business sectors involved in commercial property maintenance inspections?

This question asks about awareness rather than behavior change. A better question would be: What types of educational materials are successful in promoting the desired changes in behaviors?

A summary of programs targeting businesses was reviewed by CEC (2011b) for Kitsap County. The study addressed social marketing strategies for grocery stores, mobile painters and cleaners, automotive businesses, and restaurants. Several studies asked participants about which types of education are most effective. Simple graphic posters and photographs of the preferred behaviors were rated most highly. Interviews and focus groups support the idea that these methods are more effective in changing behavior because many small businesses are hard to reach with mailed or written materials, workshops, or offers of grants to make changes (CEC, 2011b). The review did not clarify which businesses are involved in property maintenance inspections.

e. Does a fundraiser car wash education program decrease the number of fundraiser car wash events?

Behavior and attitudes about car washing have changed in recent years, but it's not clear if the actual number of car washes has declined. See more detail about car wash behavior above under question 3.e.

16. Does public education of lake property owners reduce summer algae blooms?

a. Are summer algae blooms due to excess runoff or recycling of nutrients?

This question is somewhat outside the scope of this review; however, a recent review by Schindler (2012) summarizes the evidence for causes of eutrophication and concluded that the only proven way to reduce algal blooms is to reduce the input of phosphorus. The Department of Ecology agrees that for Western Washington lakes, phosphorus is generally implicated more than nitrogen in algal lake blooms. The good news is that it may not be necessary to reduce nitrogen as well, which can be more difficult to eliminate than phosphorus. On the legislative side, in 2011 Washington State passed the "Clean Fertilizers, Healthier Lakes and Rivers" legislation (ESHB 1489) into law. The legislation manages the sale of phosphorus in fertilizers.

b. Can education and prevention of phosphorus loads from runoff influence the frequency and duration of lake algae blooms?

This question goes right to the ultimate desired outcome, reducing lake algal blooms. I found no studies that directly measured the impact of education on algal blooms. On related topics, other studies evaluated the impact of education programs to reduce phosphorus in urban areas and farms. See detail on phosphorus reduction under Question #3.b. above.

17. Does storm drain stenciling increase awareness about untreated stormwater?

a. What is the level of awareness of adjacent land owners to storm drain stencils compared to landowners with no storm drain stencils?

This is a very general question, and assumes that an increase in awareness will cause a change in behavior. One study found that some people assumed all unmarked drains meant the stormwater was treated. Fortunately, most people (>75%) in Puget Sound know that that they should not use lawn chemicals or wash cars on the street (PSP, 2012a), even if they don't know precisely why. A seven-city survey found that only 44% knew that most stormwater is untreated (Klima and Buttenob, 2009).

A better question about the effectiveness of monitoring would be more specific and measure closer to the outcome. For example, Do people living near stencils put fewer chemicals in the drains? Or, Are fewer chemicals found in stenciled drains? Or, ultimately, Are nearby water bodies healthier? The reality is that testing for these types of affects are expensive while funding a volunteer drain stencil effort is relatively cheap and creates other benefits such as community engagement (Taylor and Wong, 2003).

Regional Connections – Groups Working on Behavior Change

Stormwater Outreach for Regional Municipalities (STORM) is a coalition of city and county governments that is working with Puget Sound Partnership to design and manage behavior change programs. Membership includes more than 50 municipalities, both Phase 1 and Phase 2 permit holders. Their mission is to improve surface water quality by reducing non-point source pollution. STORM fulfills this mission by advancing public behavior change through the promotion of targeted, measurable actions. STORM is working to create a "menu" of options for specific pollutants and behaviors so that new programs can take advantage of lessons learned from programs that are working.

The Puget Sound Partnership has developed a Sound Behavior Index and a Social Capital Index to measure change in behavior and attitudes every two years. The Sound Behavior Index measures 29 behaviors related to yard care, vehicles, home maintenance, pet waste, septics, livestock and boats. The Social Capital Index includes 35 measures related to trust in people and groups, trust in government, public affairs, participation, social media, and feelings about self.

The Puget Sound Partnership formed ECO Net (Education, Communication and Outreach Network) which is a Sound-wide network devoted to building and strengthening relationships among organizations committed to enhancing public awareness, involvement and environmental education. ECO Net's membership is comprised of teachers, program coordinators, public outreach specialists, and volunteers. These groups work on a variety of behavior change projects, many are related to stormwater.

The Stewardship Program at Puget Sound Partnership is compiling literature regarding the scientific basis, usage and public perceptions of Weed and Feed. They will launch a behavior change initiative related to lawn care and pesticide practices this year.

The Department of Ecology uses Chemical Action Plans (CAPs) as the vehicle to reduce threats caused by toxic chemicals and metals. Current CAPs rely partially on behavior change programs to be successful, e.g., addressing lead paint, reducing engine idling and woodstoves, fixing automobile drips, reducing mercury use, and reducing backyard burning.

In their Three-Year Work Plan, the WRIA 8 Salmon Recovery Council identified 10 priority activities to support outreach and education programs and incentive-based support for land use and habitat protection regulations representing a $15 million funding need.

The Modeling Work Group of the Puget Sound Ecosystem Monitoring Program (PSEMP) includes members that have extensive experience with regional models. They could be a resource for understanding the relative importance of nutrients and toxics in stormwater.

Recommendations

1. Recognize the importance of public education and the potential impact at a regional scale of a small behavior change made by a large number of people. Recognize that a large percentage of people are "ready and willing" to do more.
2. Define the desired behavior change, determine who needs to change, identify benefits and barriers to change, remove barriers and test for changes in behavior. Work with experts to create a targeted communication campaign (Clark, 2012).
3. Identify objective, intermediate measures that can be used to measure the effectiveness of public education and behavior change programs. An example of an intermediate measure for proper disposal of dog waste could be counting the number of free dog waste bags used in public places
4. Partner or coordinate with STORM and other existing public education programs to 1) measure the effectiveness of ongoing programs or 2) design new projects that complement (and do not duplicate) existing education and outreach efforts.
5. Build on the framework of the Sound Behavior Index; specifically, assess changes in attitudes and behavior using measures of the index, target specific audiences using existing data, and frame effectiveness monitoring questions to support ongoing, regional education campaigns.

Bibliography

Note: Many of the unpublished results of surveys, focus groups, and local research can be found on the Puget Sound Partnership's web site: http://www.mypugetsound.net/index.php?option=com_mtree&task=listcats&cat_id=104&Itemid=326. Special thanks to Emily Sanford and Dave Ward (Puget Sound Partnership) for gathering many of these materials from diverse sources and posting them. The web site is being updated and the easiest way to find these titles is to search with Google.

Allred, S. B., Kurth, M., Klocker, C. and A. Chatrychan. 2011. Understanding Landowner Potential to Improve Water Quality. Cornell University Human Dimensions Research Unit (HDRU), HDRU Outreach Series Publication No. 11-2.

Bissonnette, P. and Parametrix. 2010. Final Review Draft – Task 1: Urban Stormwater Runoff Preliminary Needs Assessment. Technical Memorandum. Prepared by Bissonnette Environmental Solutions, Seattle, WA and Parametrix, Bellevue, WA.

Clark, R. 2012. WRIA 6 Salmon Recovery Communication Strategy. Island County Public Health: Environmental Public Health. http://www.islandcountyeh.org/documents/236.

Cunningham Environmental Consulting (CEC). 2011a. Residential Stormwater Survey: Public Attitudes, Awareness and Behavior. Report to Kitsap Peninsula Clean Runoff Collaborative. Bainbridge Island, WA.

Cunningham Environmental Consulting (CEC). 2011b. Social Marketing Strategies for Stormwater Business Outreach: Summary of Recent Research in the Puget Sound Region: Assistance for Developing and Implementing Local Programs. Prepared for Kitsap County Public Works.

Cunningham Environmental Consulting and the Gilmore Research Group (CEC and GRG). 2008. Stormwater Hotline Focus Groups: Report of Citizen Focus Groups. Prepared for Kitsap County Public Works, Kitsap County, WA.

Department of Ecology. 2012a. Phase I Municipal Stormwater Permit. http://www.ecy.wa.gov/programs/wq/stormwater/municipal/phaseIpermit/phipermit.html.

Department of Ecology. 2012b. Western Washington Phase II Municipal Stormwater Permit. http://www.ecy.wa.gov/programs/wq/stormwater/municipal/phaseIIww/wwphiipermit.html.

Elway Research. 2008. Puget Sound Health: A somewhat more optimistic view and less urgency than two years ago. The Elway Poll, November/December. http://www.mypugetsound.net/index.php?option=com_mtree&task=viewlink&link_id=161&Itemid=326.

Elway Research, 2009. Stormwater Runoff: Pierce County Public Attitudes, Awareness and Behavior. Report to Public Works and Utilities, Surface Water Management, Pierce County, WA.

Fohn, M., S. Olsen, and M. Heine. 2011. Illicit Discharge Detection and Elimination Program: Summary Report 2000-2010. A comparison of Outfall Screening, Reporting, and Inspection Programs. Kitsap County Department of Public Works, Surface and Stormwater Management Program, Kitsap County, WA.

Grove and Quirk Insight. 2002. Motivating Public Involvement in Salmon Conservation and Water Quality. Analysis of Findings From two Focus Groups and a Survey of 500 Residents in Unincorporated Snohomish County. Powerpoint Presentation. www.mypugetsound.net.

Klima, K., and B. Buttenob. 2009. Stormwater Community Research Report. Final report to Edmonds, Mountlake Terrace, Kenmore, Mill Creek, Woodinville, and Duvall. Hebert Research, Bellevue, WA.

Lee, N., and P. Kotler. 2008. Social Marketing: Influencing Behaviors for Good, 4th edition, Sage Publications, Los Angeles.

Lehman, J. T., D. W. Bell, K. E. McDonald. 2009. Reduced river phosphorus following implementation of a lawn fertilizer ordinance. Lake and Reservoir Management 25:307-312.

Lura Consulting. 2010. Developing a research instrument for uncovering benefits and barriers to phosphorus reduction management practices in the agricultural landscape of the Innisfil Creek subwatershed. Final report to Ontario Ministry of Agriculture, Nottawasaga Valley Conservation Authority. http://www.nvca.on.ca/OurProgramsandServices/EngineeringTechnicalServices/Groundwater_Management/SpecialProjects/.

Puget Sound Action Team (PSAT). 2005. Kitsap County Surface and Stormwater Management Program: A Case Study.

Puget Sound Partnership (PSP). 2012a. General Public Opinion Survey. Final report to Puget Sound Partnership. http://www.psp.wa.gov/index.php.

PSP. 2012b. Sound Behavior Index and Social Capital Index – 2012 Survey Report. Final report to Puget Sound Partnership. http://www.psp.wa.gov/index.php.

Ryan, C. 2009. Managing nonpoint source pollution in western Washington: landowner learning methods and motivations. Environmental Management 43:1122-1130.

Sage Enviro. 2009a. Gap Analysis. Lake Washington/Cedar River/Sammamish Watersheds (WRIA 8): Chinook Salmon Conservation Plan Education/Outreach. Report to WRIA 8. http://www.govlink.org/watersheds/8/reports/default.aspx.

Sage Enviro. 2009b. Recommendations for WRIA 8 Education and Outreach Strategy. Lake Washington/Cedar River/Sammamish Watersheds (WRIA 8): Chinook Salmon Conservation Plan Education/Outreach. Report to WRIA 8. http://www.govlink.org/watersheds/8/reports/default.aspx.

Sargeant, D. E. Newell, P. Anderson, and A. Cook. 2013. Surface Water Monitoring Program for Pesticides in Salmon-Bearing Stream, 2009-2011 Triennial Report: A Cooperative Study by the Washington State Departments of Ecology and Agriculture. Department of Ecology Publication No. 13-03-002. Dept. of Agriculture Publication No. AGR PUB 102-377. Olympia, WA.

Schindler, D. W. 2012. The dilemma of controlling cultural eutrophication of lakes. Proceedings of the Royal Society B: Biological Sciences. DOI: 10.1098/rspb.2012.1032.

Tarnai, J. 2011. King County Environmental Behavior Index Survey. Report 11-030 to King County Dept. of Natural Resources and Parks, Seattle WA. http://your.kingcounty.gov/dnrp/measures/performance/en-resident-stewardship.aspx.

Taylor, A. C., Curnow, R., Fletcher, T. D., & Lewis, J. F. (2007).Education campaigns to reduce stormwater pollution in commercial areas: do they work? Journal of Environmental Management 84:323-335.

Taylor, A. and T. Wong. 2002. Non-structural stormwater quality best management practices – A literature review on their value and life cycle costs. Technical Report 02/13. Melbourne, Victoria: Cooperative Research Centre for Catchment Hydrology. http://www.catchment.crc.org.au/archive/pubs/prog4.html.

Taylor, A., and T. Wong T. 2003. Non-structural stormwater quality best management practices – Guidelines for monitoring and evaluation. Technical Report 03/14. Melbourne, Victoria: Cooperative Research Centre for Catchment Hydrology. http://www.catchment.crc.org.au/archive/pubs/prog4.html.

Vlach, B., J. Barten, J. Jonhson, and M. Zachay. 2010. Case Study #9: Assessment of source reduction due to phosphorus-free fertilizers. *In* Gulliver, J. S., A. J. Erickson, and P. T. Weiss (eds.), "Stormwater Treatment: Assessment and Maintenance." University of Minnesota, St. Anthony Falls Laboratory. Minneapolis, MN. http://stormwaterbook.safl.umn.edu/content/case-studies.

Appendix 1. Effectiveness Study Topics and Questions from the Stormwater Work Group

Stormwater management topics related to public education and outreach and their relative rank of importance compared to all the proposed effectiveness study topics. Out of a total of 22 ranked topics, 4 were related to public education and outreach. Shown also are questions related to each topic.

Rank	Effectiveness Study Topic Null Hypothesis (H_o)	Potential Questions that could be addressed by an RFP
3	Permit-required public education programs do not result in decreased levels of pollutants in stormwater.	• Are fecal coliform levels in stormwater reduced after an extensive pet waste education program? • Are nutrient levels in stormwater reduced following an extensive natural yard care education program? • Are pesticide concentrations and number of hits reduced in an urban stream following general awareness? • Does establishing a spill hotline result in reduced stormwater pollutants? • Does a fundraiser car washing education program result in reduced surfactants in stormwater?
9	Permit-required public education programs promoting behavior change do not result in increased awareness and behavior change.	• What is the increase or decrease over time of various target audiences willing to make a simple change in their daily lives to help Puget Sound? • What is the increase or decrease over time of various target audiences willing to invest over $1,000 to make a change in their property to help Puget Sound? • What is the increase or decrease over time of car owners to fix leaks? • What is the increase or decrease in stormwater drain awareness of various business sectors involved in commercial property maintenance inspections? • Does a fundraiser car wash education program decrease the number of fundraiser car wash events?
16	Public education of lake property owners about residential pollutants will not reduce summer algae blooms.	• Are summer algae blooms due to excess runoff or recycling of nutrients? • Can education and prevention of phosphorus loads from runoff influence the frequency and duration of lake algae blooms?
17	Storm drain stenciling does not raise awareness about where stormwater goes or that it is not treated.	• What is the level of awareness of adjacent land owners to storm drain stencils compared to landowners with no storm drain stencils?

FINAL

WHITE PAPER
for
Stormwater Management Program Effectiveness Literature Review

Source Control

May 2013

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

Prepared by:
James J. Packman
Cardno TEC, Inc.
2825 Eastlake Avenue East, Suite 300
Seattle, Washington 98102

EXECUTIVE SUMMARY

Source control best management practices (BMPs) can effectively contribute to the reduction in the generation of stormwater pollutants. This white paper summarizes literature on source control and other BMPs used at construction sites, at private stormwater facilities, with illicit discharge detection and elimination (IDDE) programs, and in the context of inspections at businesses. The intended audience for this white paper is local government stormwater management program staff in Washington State, especially in the western Washington. Literature reviewed was from a preselected database of publication titles, and a series of ranked questions provided the organizing principle for this white paper. Key findings are as follows:

Construction Source Control and BMPs

- Effective use of construction site TESC BMPs depends on the BMP type and operation and maintenance as well as the site and soil conditions. Based on the literature reviewed, compost blankets and filter socks, permeable check dams, and polyacrylamide (PAM) treatment of other BMPs have the best performance characteristics for controlling sediments and treating erosion at the source.
- A combination of source control BMPs, runoff BMPs, and chemical treatment BMPs are usually required to reduce construction site runoff down to permit benchmark levels (25 NTU) to meet water quality standard levels for turbidity.
- As a widely used TESC BMP, literature indicates that sediment ponds have relatively low performance for containing sediments. This could be improved by a review of sediment pond sizing and design standards.

Source Control at Private Stormwater Facilities

- Site visits and inspections of private stormwater facilities can have positive effects on the management of stormwater. As a non-structural BMP, site visits to private facilities can be enhanced by building good relationships between agency personnel and facility operators.
- The optimum frequency of site visits to private stormwater facilities depends on the type of facility. Few publications addresses site visit frequency; however, a bacterial pollution study in Kitsap county found improved results when switching from site visits every other year to yearly.

Illicit Discharge Detection and Elimination

- Foreknowledge of the nature of the potential illicit discharges is a key step in deciding which IDDE methods to use.
- Several methods for detecting illicit connections and discharges work well. Information from local western Washington NPDES permittees indicates that an IDDE hotline, inspections of manholes/catch basins, and inspections of outfalls have had the greatest effectiveness for their IDDE efforts.

- Two forthcoming resources that can help agencies decide which IDDE methods to use are Ecology's Source Identification Information Repository and an IDDE field screening manual being prepared by King County.

Business Inspections as Source Control

- In-person inspections at businesses can help encourage the proper operation and maintenance of BMPs. Regular follow-up inspections can help improve long-term compliance.
- Knowledgeable staff is required to inspect the range of source control BMPs in use at businesses and identify proper usage, recommend corrections, and determine compliance.
- The frequency of site visits needed to affect lasting changes in behavior related to stormwater pollution prevention is a topic better addressed in a public education and outreach context.

Although many of the ranked questions that drove this white paper were not directly addressed in the effectiveness literature database, outside literature was identified and reviewed as much as possible within the constraints of the scope of work for writing this paper. In addition, professional experience by this author performing source control in various settings was used to inform the results and recommendations, especially for site visits to private stormwater facilities and business inspections. Recommendations for effectiveness studies and additional information are as follows:

1. Expand the literature database to include more studies on the range of construction TESC BMPs offered in the SWMMWW.
2. Study the effects of PAM on Puget Sound area soils as well as the typical combinations of TESC BMPs in use at construction sites in western Washington.
3. Review the sizing and design specifications for TESC sedimentation ponds in the SWMMWW. Use the Revised Universal Soil Loss Equation or another appropriate model to estimate sediment loading to ponds to adjust their size and design for maximum sediment retention, not just peak flow attenuation.
4. Investigate what combinations of education, inspection, and enforcement work best for improving compliance with stormwater BMPs and other source control activities in use at private stormwater facilities and at businesses. Ecology's Local Source Control Partnership is a valuable resource with recent and current data and experience of performing business and private facility inspections of stormwater BMPs.
5. Establish a regional chemical indicators database for local agencies to compare water quality profiles of discharge from various distinct areas to help inform which IDDE methods work best.
6. Investigate which combination of IDDE methods work best for wet weather screening and for specific land uses and business types.

TABLE OF CONTENTS

List of Tables

ABBREVIATIONS AND ACRONYMS

Al	Aluminum
AKART	all known and reasonable methods of prevention, control, and treatment
BMP	best management practice
Ca	Calcium
CCTV	closed circuit television
CESCL	certified erosion and sedimentation control lead
CTAPE	Chemical Technology Assessment Protocol - Ecology
CFS	cubic feet per second
CWA	clean water act of 1972
CWP	Center for Watershed Protection
Ecology	Washington State Department of Ecology
ESARRMP	Endangered Species Act Regional Road Maintenance Program
Fe	Iron
$kg\ ha^{-1}$	kilograms per hectare
$lb\ ac^{-1}$	Pounds per acre
LID	low impact development
LSC	local source control
Mg	Magnesium
$mg\ L^{-1}$	milligrams per liter
MS4	municipal separate storm sewer system
NPDES	National Pollutant Discharge Elimination System
NTU	nephelometric turbidity unit
P	Phosphorus
PAM	polyacrylamide
POTW	publically owned treatment works
RUSLE	revised universal soil loss equation
SIIR	source identification information repository
SWG	stormwater work group
SWMMWW	stormwater management manual for western Washington
SWMP	stormwater management program
SWPPP	stormwater pollution prevention plan

TESC	temporary erosion and sedimentation control
TSS	total suspended solids
USEPA	United States Environmental Protection Agency
UW	University of Washington
WAC	Washington Administrative Code

1.0 INTRODUCTION AND PROBLEM STATEMENT

This white paper presents a review of literature from a database of selected publication titles and abstracts (Ecology 2011a). The aim of the literature review and white paper is to identify and summarize available publications to support a decision process to prioritize stormwater effectiveness studies in western Washington. The topics of literature for the database were organized by the Washington State Department of Ecology (Ecology) Stormwater Work Group (SWG). The effectiveness literature topics were identified by input from local governments, permittees of Ecology's National Pollutant Discharge Elimination System (NPDES) Western Washington Phase II Municipal Stormwater Permit (Ecology 2012a), and other interested parties. The intent of identifying potential effectiveness studies is to provide information to Puget Sound governments and other western Washington NPDES Phase II permittees to assist them with implementation of the NPDES requirements. In addition, the activities of the SWG contribute to the stormwater component of a comprehensive regional ecosystem monitoring program in Puget Sound being organized by Ecology and Puget Sound Partnership. Funding for this white paper was provided by Ecology.

1.1 SCOPE OF THIS WHITE PAPER

The topic of this white paper is source control as related to stormwater management. The scope of the investigation into source control was guided by a series of ranked questions developed by the SWG Effectiveness subgroup. The scope and context for the literature summarized in this white paper is related to erosion and sediment management at construction sites, site visits and inspections of private stormwater facilities, illicit discharge detection and elimination, and source control inspections at businesses. These topics come directly from the western Washington Phase II Municipal Stormwater Permit (Ecology 2012a). Because the ranked questions and the Phase II permit guided this effort, the topics covered in this white paper include more than what is conventionally defined as source control.

The basic concept of source control in a stormwater context refers to the idea of preventing pollutants from entering stormwater runoff. Stormwater runoff refers to surface water flow that is created by rainfall coming in contact with any surface that sheds water that eventually flows into receiving waters. Ideally, source control is achieved by a variety of practices, techniques, and activities referred to as best management practices (BMPs) that serve to prevent the generation of potential pollutants or manage and treat them at the source once generated.

1.2 REGULATORY CONTEXT

The NPDES rules and regulations have been promulgated by the United States Environmental Protection Agency (USEPA) since 1972 as part of the Clean Water Act (CWA). The NPDES program is intended to prevent unwanted discharges into natural waters and was originally focused on point sources, such as publically owned treatment works (POTW) and businesses with a high risk of pollution-generating activities. In 1987, Congress expanded the scope of the CWA via the Water Quality Act (USEPA 1987) and included stormwater as a "nonpoint" source of potential pollution. The application of the NPDES program was then expanded to include many urban areas, small and medium industrial dischargers, and all municipalities.

In Washington State, the NPDES program is administered by Ecology who issues permits for all aspects of the NPDES program, including the Construction Stormwater General Permit

(Ecology 2010a), the Industrial Stormwater General Permit (Ecology 2009a), the Sand and Gravel General Permit (Ecology 2010b), the Municipal Stormwater Permit (Ecology 2012a, Ecology 2012b, and Ecology 2012c), and the Washington State Department of Transportation Municipal Permit (Ecology 2009b). The Municipal Stormwater Permit is divided into three sections for Washington state entities – the Phase I Municipal Permit (Ecology 2012b), the Phase II Municipal Permit for Western Washington (Ecology 2012a), and the Phase II Permit for Eastern Washington (Ecology 2012c). Phase I and Phase II permits refer to which entities are covered, with Phase I intended for larger entities and municipalities such as the cities of Seattle and Tacoma, and Phase II intended for smaller entities. Current permits extend to 2018 and cover a range of activities. Each permit has source control requirements for sediments and illicit discharges to the municipal separate storm sewers (MS4).

The current Phase II Municipal Stormwater Permit for western Washington (2013-2018) has significant changes from the previous permit (2007-2012, Ecology 2007). Two of the most significant changes are the increased requirements for a stormwater management program (SWMP) and the expanded monitoring requirements. The SWMP requirements in both permits include source control as part of section S5.C.4 *Controlling Runoff from New Development, Redevelopment and Construction Sites*. However, source control is indirectly relevant to other permit sections, especially *Illicit Discharge Detection and Elimination* (IDDE) and *Public Education and Outreach.* Both of these topics are related to source control: the goal of IDDE is to find and eliminate the sources of illicit connections and discharges; and the goal of education and outreach is behavior change that includes preventing the generation of pollutants at their source, including stormwater. Thus, this paper covers topics related both directly and indirectly to source control from the Washington state NPDES permits.

When developing or redeveloping a property, NPDES permittees are required to follow the Ecology Stormwater Management Manual (SWMM, Ecology 2012d) or an equivalent approved manual. Ecology has developed stormwater management manuals for western Washington and eastern Washington with specific guidelines on a variety of BMPs that are intended to be applied at a project level, including those for the purpose of source control. The manual defines BMPs as “schedules of activities, prohibitions of practices, maintenance procedures, and structural and/or managerial practices, that when used singly or in combination, prevent or reduce the release of pollutants and other adverse impacts to waters of Washington State.” In addition to source control BMPs, the SWMM categorizes two other general types of BMPs – treatment BMPs and flow control BMPs – since source control BMPs are not intended to prevent all impacts, a combination of BMPs are required in practice. Furthermore, the methods used with some source control BMPs overlap into treatment BMPs and flow control BMPs.

The selection, design, implementation, and maintenance of source control BMPs are all important steps for their successful use. Each NPDES permittee is required to develop a stormwater pollution prevention plan (SWPPP) in which the specific BMPs and procedures for their implementation are identified. A successful source control program relies on both structural and operational BMPs, and the SWMM provides guidance and a menu of options for including both of these types of BMPs in SWPPPs. Structural BMPs are “physical, structural, or mechanical devices or facilities” intended to prevent pollution from entering stormwater while operational BMPs are non-structural practices (Ecology 2012d). An example of a structural source control BMP is to cover a potential pollution source, such as exposed soil, to prevent erosion, and an example of an operational source control BMP is good-housekeeping practices to prevent spills. Volume I of the SWMM (Minimum Technical Requirements and Site Planning) contains instructions on preparing SWPPPs and the minimum requirements for stormwater pollution prevention, and Volumes II (Construction Stormwater Pollution Prevention) and IV (Source Control BMPs) contain specific BMPs related to source control used in a wide range of industries.

Ecology periodically updates and revises the SWMM, the most recent of which was in 2012 seven years after the previous edition. The timing of this revision intentionally coincided with the current NPDES permit period (2013-2018) and is intended to provide current information about BMPs for NPDES permittees. While the SWMM incorporates information about new BMPs and their performance, its prescriptive use of BMPs is provided in the context of AKART - all known and reasonable methods of prevention, control, and treatment. The AKART approach is a presumptive one in which if the appropriate BMPs are selected and used then "compliance with water quality standards is presumed" (Ecology 2012d). An alternative approach is allowed by the SWMM, which is the demonstrative approach in which alternative selection, design, construction, implementation, operation and maintenance of BMPs is allowed but requires an individualized review process by Ecology. The demonstrative approach can sometimes be more cost effective than the presumptive approach for large projects; however, the burden of proof that the alternative approach will work falls to the permittee and the review process by Ecology can be very time consuming (Ecology 2012d). For these reasons, the presumptive approach is usually followed.

1.3 PROBLEM STATEMENT

Numerous studies indicate that although source control and other BMPs can reduce the generation of pollutants and their transport into stormwater runoff, their efficacy varies widely depending on the design and implementation of the BMP as well as local site, soil, and climate conditions. Furthermore, non-structural BMPs tend to have less tangible performance characteristics than structural BMPs due to the qualitative nature of actions like certain types of public outreach. These factors present a complexity to BMP selection, usage, and performance. Furthermore, the presumptive AKART approach does not make a direct connection to the ultimate goal, which is to prevent unwanted discharges into receiving waters that cause violations of state water quality standards. This white paper seeks to address specific null hypotheses and questions developed by the Ecology SWG that probe the performance and usefulness of selected BMPs and related practices as they are relevant to the Phase II permit.

2.0 LITERATURE SUMMARY AND TALKING POINTS

This section presents the summary of source control literature. First, the methods and results of the literature selection are described. Then the guiding questions and null hypotheses are provided for reference followed by a summary of key regulatory and BMP guidance information to which the questions make reference. Following that is the summary of the source control literature with talking points about each of the four main source control topics. Talking points for each main topic are provided at the end of each source control topic subsection.

2.1 LITERATURE SELECTION

The publications reviewed for this white paper came from a database of effectiveness study literature (Ecology 2011a). The literature database is composed of 336 titles from a variety of sources, including journals/primary literature, books, technical guidance manuals, marketing and public information flyers, and internally published agency reports. Key fields by which the database could be sorted include NPDES Permit Area, Specific BMP, and Study Location.

Source control publications were identified by sorting the literature database and by keyword searches. The database was sorted by each of the six NPDES Permit Areas then by each Specific BMP topic. Publications were chosen based on the title, review of the summary/abstract, and if there was relevance to the source control topics in the ranked questions.

Source control literature was present in all six NPDES Permit Areas, in 12 Specific BMP categories, and in over a dozen geographic areas including western Washington and Puget Sound cities. Location was often not specified in the literature database, so the most meaningful summary of source control literature found in the database was by Permit Area and BMP type. Tables 1 and 2 show the distribution of source control literature among these two fields.

Table 1 Publications by NPDES Permit Area

NPDES Permit Area	No. Publications	No. Source Control-related Publications
controlling runoff	267	18
monitoring	8	1
Multiple	4	2
pollution prevention & municipal operations	50	21
public education and outreach	10	5
other	2	1
Total	341[1]	48

Notes
1 Includes overlap of NPDES Permit Areas discussed among 336 discrete articles in the database.

Table 2 Publications by BMP Type

Specific BMP	No. Publications	No. Source Control-related Publications
biofilter	46	1
Catch basin cleaning	9	
detention basin	34	1
education	8	5
infiltration	21	1
LID	47	1
maintenance practice	8	
manufactured device	28	
media filter	34	
multiple	5	2
oil water separator	5	
other	35	4
porous pavement	48	1
rain garden	84	
retention pond	33	1
source control	33	18
street sweeping	25	12
wetland/wetlands	42	
(blank)	2	1
Total	547[1]	48

Notes
1 Includes overlap of BMPs discussed among 336 discrete articles in the database.

Keyword searches in the database were also used to identify source control publications. Keyword searches were best suited to searching among the publication titles and abstract/literature summaries. The keyword searches performed were: source control (12 hits), construction (12 hits), inspection (four hits), business or businesses (one hit), temporary erosion and sedimentation control or TESC (no hits), compliance (two hits), private (one hits), education or outreach (five hits), and illicit or IDDE (no hits). In total, 48 publications were identified by sorting and by keyword searches that addressed one or more aspect of the source control questions posed.

In addition, some publications listed in the database were available only via paid subscription or purchase of a book. We primarily used the University of Washington (UW) libraries to obtain journal articles, and while many publications in the effectiveness database were available, articles from two journals were not consistently available: Water Science & Technology and the Water Quality Research Journal of Canada. Between these two journals and other book references, seven publications in the database were not obtained that appeared relevant based on the title and/or abstract. The scope of this white paper was to review publications listed in the effectiveness literature database; however, due to the absence of literature for some of the topics covered in this paper, outside literature was identified and summarized as possible within the constraints of the project scope, budget, and schedule.

2.2 NULL HYPOTHESES AND RANKED QUESTIONS

The organizing principle for this white paper is the ranked questions (Ecology 2011b) posed by the SWG about source control. Those questions guided the literature review and summary and are provided in Table 3 for reference.

Table 3 Ranked Effectiveness Questions for Source Control (Ecology 2011b)

Rank[1]	Null Hypothesis	Questions	Source Control Topic
1	Construction site inspections are not effective at controlling sediments and turbidity from permitted construction sites.	• Are the temporary erosion and sediment control (TESC) BMPs required during development or redevelopment adequate to control erosion and sediment from construction sites?	• Construction Source Control and BMPs.
		• Are the TESC BMPs used at construction sites effective at reducing turbidity/TSS for compliance with water quality standards?	
		• What frequency of construction erosion and sediment control inspections are most effective for achieving compliance with codes/ordinance requirements at new development and redevelopment project sites?	
2	Education and inspection of private stormwater facilities does not affect water quality.	• Do more frequent site visits and contact with private facility owners improve compliance with operation and maintenance (O&M) requirements?	• Source Control at Private Stormwater Facilities
		• What is the optimum frequency of inspections to maintain the functionality of private stormwater facilities?	
4	IDDE program components are not effective at reducing pollutants.	• Which combination of methods work best for detection of illicit connections: smoke testing, dye testing, CCTV, flow monitoring and outfall screening (wet and dry season)?	• Illicit Discharge Detection and Elimination
		• How effective is wet weather screening as a tool to detect illicit connections?	
		• Which parameters should be measured during dry weather screening to improve the ability to detect illicit connections?	
8	Business inspections and outreach are not effective source control techniques.	• Are businesses that receive an in-person visit/inspection more likely to implement source control BMPs?	• Business Inspections As Source Control.
		• What frequency of business inspections is most effective for implementing and maintaining source control requirements/BMPs at businesses?	

Notes
1 Rank assigned by the SWG.

2.2.1 Regulations and Guidelines for Source Control

Some of the ranked questions refer to water quality standards. The water quality standards refer to section of 173-201A of the Washington Administrative Code (WAC, Ecology 2011d) for surface waters of Washington state. For construction discharge water quality, the main pollutant of concern is suspended sediment, which is expressed in turbidity as a surrogate parameter. The turbidity standards are organized by fish usage and habitat available in fresh water or on the quality of the marine waters as applicable. Background turbidity is defined as the “biological, chemical, and physical conditions of a water body, outside the area of influence of the discharge under consideration" (Ecology2011d). Thus, background turbidity at a construction site would be determined immediately upstream and outside the area of influence of a construction discharge point. The water quality standards also allow for a mixing zone in the receiving water body under special circumstances, which is applicable only if identified in a site-specific NPDES permit (Ecology 2011d). For reference, the turbidity criteria from the water quality standards are summarized in Table 4.

Table 4 Turbidity Criteria from 173-201A WAC (Ecology 2011d).

Fresh Water Aquatic Life Use Categories	Maximum Allowed
Char Spawning and Rearing	5 NTU over background <50, or 10% increase over background >50
Core Summer Salmonid Habitat	5 NTU over background <50, or 10% increase over background >50
Salmonid Spawning, Rearing, and Migration	5 NTU over background <50, or 10% increase over background >50
Salmonid Rearing and Migration ONLY	10 NTU over background <50, or 20% increase over background >50
Non-anadromous Interior Redband Trout	5 NTU over background <50, or 10% increase over background >50
Indigenous Warm Water Species	10 NTU over background <50, or 20% increase over background >50
Marine Water Aquatic Life Use Categories	**1-day Max**
Extraordinary Quality	5 NTU over background <50, or 10% increase over background >50
Excellent Quality	5 NTU over background <50, or 10% increase over background >50
Good Quality	10 NTU over background <50, or 20% increase over background >50
Fair Quality	10 NTU over background <50, or 20% increase over background >50
Mixing Zone	**Maximum Flow**
Mixing zone allowed for in-water work	Max flow 10 cfs, mixing zone 100 ft
Mixing zone allowed for in-water work	Flow 10-100 cfs, mixing zone 200 ft
Mixing zone allowed for in-water work	Flow >100 cfs, mixing zone 300 ft
Lakes ponds, wetlands	Mixing zone radius of 150 ft

In addition to the surface water quality standards that apply to waters of the state, the Construction General Stormwater Permit (Ecology 2010a) lists a turbidity benchmark of 25 NTU for construction site discharge. At construction sites, both the state water quality standards and the turbidity benchmark values apply; however, construction permittees are required only to measure turbidity in construction site discharge and not in the receiving waters. Section S3 of the permit notes the AKART approach that "Ecology presumes that a Permittee complies with water quality standards unless discharge monitoring data or other site-specific information demonstrates…a violation of water quality standards."

The ranked effectiveness questions also make reference to the TESC BMPs required at construction sites. Requirements for construction erosion and sediment control are in the Construction Stormwater Permit (Ecology 2010a). Guidelines and design requirements exist for designing and implementing TESC BMPs at construction sites in western Washington; Volume II of the SWMMWW (Ecology 2012d) includes approved lists of the two main types of TESC BMPs applicable at construction sites: source control BMPs and runoff conveyance and treatment BMPs. For reference, Tables 5 and 6 lists the source control BMPs and runoff conveyance and treatment BMPs, respectively, from the SWMMWW along with the number of relevant publications from the effectiveness literature database and the SWPPP element(s) that each BMP addresses.

Table 5 Source Control BMPs from the SWMMWW (Ecology 2012d).

Source Control BMPs	No. Relevant Publications in Database	SWPPP Elements that BMP Addresses
Preserving Natural Vegetation		Preserve Vegetation
Buffer Zones		Preserve Vegetation, Protect LID
High Visibility Plastic or Metal Fence		Preserve Vegetation, Protect LID
Stabilized Construction Entrance/Exit		Establish Construction Access
Wheel Wash		Establish Construction Access
Construction Road/Parking Area Stabilization		Establish Construction Access
Temporary and Permanent Seeding		Stabilize Soils, Protect Slopes
Mulching	2	Stabilize Soils, Protect Slopes
Nets and Blankets	3	Stabilize Soils, Protect Slopes, Stabilize Channels and Outlets
Plastic Covering		Stabilize Soils
Sodding		Stabilize Soils
Topsoiling/Composting	4	Stabilize Soils
Polyacrylamide for Soil Erosion Protection	4	Stabilize Soils
Surface Roughening		Stabilize Soils, Protect Slopes
Gradient Terraces		Stabilize Soils, Protect Slopes
Dust Control		Stabilize Soils
Materials on Hand		Maintain BMPs, Manage the Project
Concrete Handling		Control Pollutants
Sawcutting and Surfacing Pollution Prevention		Control Pollutants
Material Delivery, Storage, and Containment		Control Pollutants
Concrete Washout Area		Control Pollutants
Certified Erosion and Sediment Control Lead		Maintain BMPs, Manage the Project
Scheduling		Manage the Project

As is evidenced in Tables 5 and 6, the literature selected for the effectiveness database does not directly address many of the BMPs listed in the Ecology SWMMWW. Publications included in Tables 5 and 6 are those that had effectiveness information. Other publications available in the database related to source control focused on design elements or source control in contexts not related to the questions posed by the SWG. The publications that focused on effectiveness in context of the ranked questions are summarized below along with some outside publications that were used to fill information gaps. One publication not in the effectiveness literature database but relevant to TESC BMPs used with road construction is the guidelines document from the Endangered Species Act Regional Road Maintenance Program (ESARRMP, WSDOT 2008). The ESARRMP guidance documents list over 50 BMPs with design details for use on road construction and maintenance projects with the additional purpose of meeting ESA requirements. It is recommended that road construction and maintenance projects refer to the ESARRMP guidance document, which has grown out of an adaptive management process with input from multiple state and federal agencies.

Table 6 Runoff Conveyance and Treatment BMPs from the SWMMWW (Ecology 2012d).

Runoff Conveyance and Treatment BMPs	No. Relevant Publications in Database	SWPPP Elements that BMP Addresses
Interceptor Dike and Swale	1	Protect Slopes, Protect LID
Grass-Lined Channel		Protect Slopes, Protect LID
Channel Lining		Stabilize Channels and Outlets
Water Bars		Control Flow Rates, Protect Slopes, Control Dewatering
Pipe Slope Drains		Protect Slopes
Subsurface Drains		Protect Slopes
Level Spreader		Protect Slopes
Check Dams	1	Control Flow Rates, Protect Slopes, Stabilize Channels and Outlets, Protect LID
Triangular Slit Dike(Geotextile Encased Check Dam)	1	Protect Slopes, Protect LID
Outlet Protection		Control Flow Rates, Stabilize Channels and Outlets
Storm Drain Inlet Protection		Protect Drain Inlets
Brush Barrier	1	Install Sediment Controls, Protect LID
Gravel Filter Berm		Install Sediment Controls
Silt Fence	1	Preserve Vegetation, Install Sediment Controls, Protect LID
Vegetated Strip		Install Sediment Controls, Protect LID
Wattles	1	Control Flow Rates, Install Sediment Controls
Vegetative Filtration		Control Dewatering
Sediment Trap		Control Flow Rates, Install Sediment Controls
Temporary Sediment Pond	3	Control Flow Rates, Install Sediment Controls
Construction Stormwater Chemical Treatment		Install Sediment Controls, Control Pollutants
Construction Stormwater Filtration		Install Sediment Controls, Control Pollutants
High pH Neutralization Using CO_2		Control Pollutants
pH Control for High pH Water		Control Pollutants

2.3 SUMMARY OF LITERATURE: CONSTRUCTION SOURCE CONTROL

2.3.1 Question: Are the TESC BMPs required during development or redevelopment adequate to control erosion and sediment from construction sites?

To answer this question, literature from the effectiveness database was reviewed in light of the potential BMPs used at construction sites. Several BMPs were discussed among the publications that are available choices in the SWMMWW; however, most BMPs were either not discussed in the available literature or discussed in contexts outside of construction sites. The most prevalent construction BMPs in the literature database are polyacrylamide (PAM) treatment, compost treatment, temporary sediment ponds, and erosion control blankets with various combinations of mulch and compost.

In the context of erosion and sediment control, PAM refers to an anionic non-toxic powder that helps small soil particles bind together so they discourage separation and helps particles settle out more easily in soil-laden runoff (Daughton 1988). Treatment with PAM involves applying the powder or liquid prepared to a specified concentration to exposed soil or incorporating it into soil coverings. It is often used in agricultural settings to diminish top soil loss and promote infiltration of irrigation waters (NRCS 2011).

For PAM-related studies, data of interest is typically the application rate (mass of PAM applied per unit area) and the sediment and runoff characteristics, especially turbidity, sediment load, and runoff volume. PAM performance is affected by application rate, soil type, soil slope, and rainfall. Hayes et al. (2005) reported on a comparison of mulch to PAM applied directly to soil and in a seed mix sprayed on soil of various slopes in the North Carolina Piedmont and Coastal Plain region. They applied two PAM products at the manufacturers' recommended rates of 1.3 lb ac^{-1} and 9.3 lb ac^{-1} as well as half of the recommended rates. They found very little effect on reducing turbidity, runoff, or sediment load among the test sites and suggested that heavier application of PAM would be necessary, especially on steep slopes. For reference, PAM application rates allowed in western Washington construction sites is 0.66 lb ac^{-1} or 80 mg L^{-1} in solution applied over one acre (Ecology 2012d).

McLaughlin and Bartholomew (2007) also tested PAM on soils from North Carolina, however they tested a larger selection of PAM products (11) and performed only laboratory tests to measure the decrease in turbidity of soil samples. In general, they found that the higher the concentration of PAM, the greater reduction in turbidity. But soil clay type and content were found to influence the turbidity reduction. The greatest reduction in turbidity was from soils with high sand content and kaolinitic clays and mica, especially soils with greater than 14 percent clay. They also mentioned that soils with multivalent metal cations present (Fe, Ca, Mg, and Al) tended to have greater turbidity reduction. Given that PAM works via an electrochemical process by binding to positively charged soil particles, soils that are high in (negatively charged) clays and mineral cations understandably respond more readily to the flocculation and binding process that PAM promotes. Optimal doses of PAM were found to be one to two mg L^{-1} for the best reduction in turbidity, although the doses were not related to the mass or area of soil tested so it is not possible to relate PAM application rate to area of soil treated in this study.

Several studies of PAM applied to various soil cover or flow reduction BMPs were also present in the literature database. A paper by McLaughlin et al. (2009) tested PAM effects when it was impregnated into fiber check dams, which showed very effective results at reducing turbidity. Fiber check dams are small permeable dams placed across a swale or ditch in order to reduce the velocity of flow. For this study PAM was applied by adding 100 grams of granulated product to the lower and center portion of each check dam. Results showed significant reduction in turbidity due to PAM application, but not significant reduction in sediment loss from PAM.

McLaughlin and Brown (2006) applied PAM to common ground cover BMPs, including straw, straw blankets, wood fiber, and bonded fiber matrix on natural soils and soil test beds ranging from four to 20 percent slope. PAM was applied at 19 kg ha^{-1} (0.02 lb ac^{-1}). Results showed that ground covers significantly reduced turbidity, but reductions in turbidity due to PAM were inconsistent with only some storm events (natural and simulated) showing reduction. Faucette et al. (2007) compared soil cover blankets with wood mulch/compost mix to blankets with straw and PAM application. Two PAM products were tested individually and applied at the manufacturer's recommended rates of 34 and 370 kg ha^{-1} (0.03 and 0.30 lb ac^{-1}, respectively). Wood mulch blankets were found to have the greatest reduction in runoff and turbidity, which is likely due to lessened impact by rain drops compared to bare soil. Application of PAM to the blankets was found to significantly reduce turbidity but not runoff volume. Higher mulch content in the blankets resulted in greater turbidity reduction. The particle size profile of straw blankets was also found to be important with smaller particle sizes increasing the protection of soil. Babcock and McLaughlin (2011) compared the sediment removal performance of straw, straw plus PAM, and excelsior (natural fiber) blankets applied on steep slopes with a 2:1 ratio. As with other studies by McLaughlin, the PAM treatment showed the highest removal of total suspended solids (TSS) and the excelsior blankets had a higher removal than plain straw.

In addition to application rates, the Construction General Permit (Ecology 2010a) includes details on how and where PAM should be applied to avoid it entering a receiving water body. It is not intended as a cure-all solution to prevent erosion or remove sediment from water. Rather, it is intended to be used in combination with other BMPs with an emphasis on stabilizing soils and preventing erosion. Due to the restrictions of PAM from entering receiving waters and concern about potential toxicity, many jurisdictions in western Washington do not use PAM as a construction BMP (A. Moon, personal communication).

Another type of source control BMP discussed in the literature is the use of geotextile fabrics. Geotextile fabric can be used in conjunction with a wide variety of material to cover soil, form a low- or no-permeability barrier (silt fence), and make objects such as check dams, brush barriers, and filter berms when used as a wrap around soil, rock, straw, and other materials. One study in the database by Rickson (2006) investigated the performance characteristics of geotextiles and noted that several factors are important to their performance, including soil type being protected, water ponding ability, water-holding capacity, and roughness of the fabric texture.

Faucette et al. (2008) compared a silt fence to compost filter socks (a type of contained filter berm) for removal of TSS and phosphorus (P) and reduction in flow. Some treatments also included adding PAM to the compost mix to enhance removal. Results from this bench-top test were that the compost socks with added PAM had the best reduction in TSS and P, followed by compost socks without PAM, then the silt fence. Another study by Faucette et al. (2009) also compared compost filter socks to several other BMPs, including straw bales, mulch filter berms, and PAM-treated compost socks. They found that compost filter socks had the best sediment removal properties, but no difference was found between the plain compost filter sock and PAM-treated sock.

Eck et al. (2010) compared a manure compost/mulch blend to a wood-based hydromulch for containing sediments from a rock quarry in Texas. The treatments were spread directly on test plots of bare soil. The compost blend showed the best performance for containing soils due to the water-holding ability of the compost and the quicker establishment of vegetation than on hydromulch plots. Export of nutrients, especially dissolved phosphorus was noted as a drawback when using compost, and the authors recommended using a low-phosphorus compost blend.

Taleban et al. (2009) tested the performance of compost biofilter rolls/socks of varying sizes. They found that sediment removal increased with the number of socks placed in the path of runoff and that larger diameter socks provided better removal of TSS than smaller ones, with removal documented up to 95 percent. In addition, the TSS removal performance of the socks did not diminish with varying flow depths as long as the flow did not overtop the sock diameter.

The sedimentation pond is another type of BMP discussed in literature. Generally speaking a sedimentation pond is treatment BMP designed to capture sediment from runoff and includes BMPs variously referred to as temporary sediment ponds, detention basins, or wet ponds. Kalainesan et al. (2008) investigated four sediment ponds (called basins in this context) from highway construction sites in Pennsylvania and monitored for removal of sediment, a few particulate metals, and phosphorus. They found that sediment basins managed high flows well but were not very effective at capturing sediment with only 15 percent removal. Because the basins were designed following the specifications published by the Pennsylvania Department of Environmental Protection, Kalainesan recommends that an update to the design standards of sedimentation ponds in Pennsylvania is needed. Another publication by Kalainesan et al. (2009) provides a suggested methodology for sizing sediment basins based on a combination of local rainfall probability, the Revised Universal Soil Loss Equation (RUSLE), and setting low outflow rates to encourage particle settling in the pond. Their alternative design had better performance of sediment removal and peak flow attenuation than the traditional sediment pond design specified by the state of Pennsylvania. Their methodology has the potential to be an improvement to the sediment removal ability of temporary sediment ponds in Washington since it includes a step for estimating sediment delivery to the pond via the RUSLE.

Gharabaghi et al. (2006) compared two sediment pond designs following the Ontario (Canada) Ministry of the Environment Stormwater Management Planning and Design Manual (2003). They found that treatment of suspended solids was primarily influenced by the length-to-width ratio of the ponds. They cautioned against creating dead-zones of eddies in ponds that can decrease usable sediment accumulation area on the pond bottom.

In the James River basin that flows into the Chesapeake Bay, the CWP (2009) reported on field surveys of BMPs that included sedimentation ponds. The wet ponds, as they are referred to, have an overall performance score in the middle to lower range of the BMPs surveyed. The other BMPs included newer techniques like permeable pavement that emphasize infiltration, which generally performed better than more traditional techniques such as ponds, grass channels, and infiltration trenches. The report rated ponds by a variety of factors that includes shortest flow path through a pond, conditions upstream/downstream of the pond, maintenance, and detailed design information. However, information did not include pollutant treatment performance, especially for sediment, turbidity, and nutrients. The CWP does report on nutrient removal by ponds in their “Extreme Makeover BMP” (CWP 2008), with wet ponds showing similar ranges of nutrient removal as green roofs, permeable pavement, and bioretention (50 to 80 percent).

2.3.2 Question: Are the required TESC BMPs used at construction sites effective at reducing turbidity/TSS for compliance with water quality standards?

Of the studies noted above in addressing the previous question, many reported turbidity reduction from the BMP treatment. However, the presumptive approach in effect as stated in the Construction General Permit (Ecology 2010a) presumes that if the turbidity benchmark of 25 NTUs is met (and other permit requirements), then the water quality standards are not being violated. Several studies reported high BMP treatment levels, but the reduction was usually in comparison to bare soil, which had values as high as in the tens of thousands. The application of PAM to soil and other BMPs including compost, fiber check dams, and erosion control blankets and socks has the potential to reduce turbidity to less than the 25 NTU construction permit benchmark according to the literature reviewed (McLaughlin et al. 2009, Faucette et al.

2007); however, this was not the case across the board. Multiple factors affected the performance of PAM, especially in combination with other BMPs. These factors include PAM application concentration, time of exposure to sediment-laden runoff, soil characteristics, composition of the other BMP that PAM was added to (for example, compost mix), soil slope, and rainfall intensity. Other source control BMPs were noted to contribute to the reduction of turbidity at construction sites, such as temporary sediment ponds and the use of geotextile fabrics.

Treatment of construction site stormwater is intended to be done using a combination of TESC BMPs. The literature available in the effectiveness database was lacking in studies that focused on multiple BMPs used in series that would be common at a construction site. Specifically, no studies were available with BMP effectiveness results from construction sites in Washington. Instead, studies often focused on one or a few BMPs and their performance in reducing turbidity in a controlled situation, such as benchtop test, experimental plots, or customizable elevated soil beds.

Chemical treatment BMPs for treating stormwater from construction sites are an emerging technology, and Ecology added several chemical treatment BMPs to the latest version of the SWMMWW (Ecology 2012d). Chemical treatment BMPs were not discussed in the publications available in the effectiveness literature database. Some chemical treatment BMPs are very effective at reducing turbidity to low levels and include chitosan treatment and electrocoagulation (for example, see Sekine et al. 2006). Ecology has an evaluation program for certifying chemical treatment technologies for stormwater at construction sites (Chemical Technology Assessment Protocol-Ecology [CTAPE], Ecology 2003). The CTAPE program has a list of approved technologies that can be a useful reference for selecting chemical treatment BMPs for construction site stormwater.

2.3.3 Question: What frequency of construction erosion and sediment control inspections is most effective for achieving compliance with codes/ordinance requirements at new development and redevelopment project sites?

The frequency of inspecting erosion and sediment control BMPs at construction sites was not addressed in the literature available. Inspection of TESC BMPs would usually fall to the erosion and sedimentation control specialist at a construction site who is a Certified Erosion and Sediment Control Lead (CESCL). Per the SWMMWW (Ecology 2012d), the CESCL is responsible for ensuring compliance with erosion and sediment control and water quality requirements, and required inspection frequency ranges from weekly to twice per year depending the activities at the construction site (Ecology 2010a) with special inspections required immediately following storm events of 0.5 inches or more in 24 hours. While a thorough review of CESCL training information was outside the scope of this white paper, answering this question would benefit from such a review, including ensuring training materials cover emerging technologies.

2.3.4 Talking Points for Construction Source Control

Talking Point 1: TESC BMPs used at construction sites can control erosion and sediment. Effective use depends on BMP selection, operation and maintenance, and site conditions. Additional literature is needed to review the full range of TESC BMPs. A review of PAM performance in western Washington is warranted as is a review of sediment pond sizing and design.

The literature available in the effectiveness database discusses several TESC BMPs used on construction sites. However, many BMPs were not discussed in the available literature; more extensive literature search and review is needed to describe which BMPs work best of the options presented in the SWMMWW. Conclusions from available literature are that compost blankets and filter socks, permeable check dams, and polyacrylamide (PAM) treatment in combination with other BMPs have the best performance characteristics for controlling sediments and treating erosion at the source. Soil characteristics and site conditions can affect the effectiveness of BMPs with lower slope gradients and higher clay content in soil correlating to higher effectiveness for PAM treatment. Ecology has strict guidelines for the use of PAM to prevent it from entering receiving waters, and for this reason PAM is currently not widely used for construction erosion control in western Washington. In addition, a review of sediment pond design and sizing is warranted based on the literature. Specifically, the addition of a step to estimate sediment loading to a pond should be included to inform both the size and design of a pond as well as the potential maintenance schedule for dredging.

Talking Point 2: A combination of TESC BMPs is required to treat the full range of sediment in construction site runoff down to construction benchmark levels for turbidity. Additional literature or effectiveness studies are needed to describe the combinations of TESC BMPs typically in use in western Washington.

The literature available was insufficient to address the question about meeting water quality standards as most of it focused on controlled experiments of one or a few TESC BMPs. Much of the reported water quality treatment for sediment, nutrients, and other parameters was related in percent removal compared to bare soil. So, although several publications touted high removal of sediment (and reduction in turbidity), the effluent in some studies remained above construction permit benchmark levels of 25 NTU. In practice, reducing turbidity levels in construction site discharge to below benchmark levels for meeting water quality standards is done using a combination of TESC BMPs in series. Chemical treatment BMPs should be included to obtain low turbidity in construction site discharge.

An alternative question to guide future effectiveness studies is which combinations of the TESC BMPs listed in the SWMMWW are the most effective at controlling erosion and sediment from construction sites in western Washington.

Talking Point 3: Inspection of source control BMPs for erosion and sedimentation control is most effective when done on a consistent schedule that includes special inspections after significant precipitation and runoff events. Additional literature or effectiveness studies are needed to identify the optimum frequency of construction BMP inspections.

The inspection frequency of TESC BMPs was not addressed in the literature available. The SWMMWW specifies various frequencies of inspections of construction site erosion control BMPs depending on the type of site and the activity. Weekly inspections are a minimum at active construction sites in addition to inspections immediately after storm events 0.5 inches or more rain in 24 hours. Additional literature is needed that addresses inspections of construction site erosion and sedimentation BMPs, and a review of CESCL training requirements is warranted to ensure erosion control leads and inspectors have latest information on maintenance practices for TESC BMPs, especially for emerging technologies.

2.4 SUMMARY OF LITERATURE: SOURCE CONTROL AT PRIVATE STORMWATER FACILITIES

2.4.1 Question: Do more frequent site visits and contact with private facility owners improve compliance with operation and maintenance (O&M) requirements?

Only a few publications were available in the effectiveness literature database that addressed site visits to private stormwater facilities. None of these, however, specifically addressed the frequency of site visits and contact with private facility owners. This question is related to public outreach and education as much or more than to source control. Fohn (2010) reported on Kitsap County's efforts to reduce bacterial pollution in Dyes Inlet in western Puget Sound that included private property inspections. Inspections of private stormwater systems in Kitsap County were not done prior to 2006 and for the bacterial pollution study, an inspection was done once in 2006 or 2007 and a second inspection was done in 2008 for properties with deficiencies. After the first year of the program, the deficiency in private stormwater facilities dropped from 41 to 8 percent of inspected properties. After initial corrections were made during the first inspections, compliance was noted to flatten out at 85 percent (M. Fohn, personal communication). In addition, water quality improved at two marine water quality monitoring stations influenced by runoff from the inspected areas (presumably because of factors that include more consistent and correct operation and maintenance of private stormwater facilities). Because of these positive results, Kitsap County increased their inspection frequency from once every two years to annually.

Taylor et al. (2007) reported results from an education campaign in commercial areas in Melbourne, Australia. The program did not include inspections of private facilities, rather it focused on education including community workshops, one-on-one visits with merchants, and observation of behaviors with the objective of reducing litter and increasing proper waste disposal. Their findings were that behaviors changed for a while, but knowledge of litter and waste management information did not significantly change. These results, while not from a stormwater study, do emphasize the difference between education and behavior. Their findings suggest that private facility owners can be more compliant when simply told what to do rather than attempts at education around waste issues.

Hillegass (undated) reported on an approach for measuring stormwater program effectiveness in NPDES Phase II communities in Chesapeake, Virginia. The report was a summary of SWMP goals, measurement parameters, and evaluation objectives for an indicator database that included inspection of private stormwater facilities. However, the frequency of inspections was not mentioned and no data were presented.

2.4.2 Question: What is the optimum frequency of inspections to maintain the functionality of private stormwater facilities?

This question is a focused version of the previous question. The literature available did not address inspection frequency of private stormwater facilities except as noted for the Kitsap county bacterial pollution study (Fohn 2010). To answer this question, the range and variety of private stormwater facilities needs to be identified and the inspection frequency may be different for different types of facilities. More literature or effectiveness studies are needed to address this question.

2.4.3 Talking Points for Private Stormwater Facilities

> *Talking Point 4*: Site visits and/or inspections of private stormwater facilities can have positive effects on the operation and maintenance of stormwater BMPs. Communications with private facilities need to be tailored to specific agency goals for building relationships with owners and managers of private stormwater facilities. Additional literature or effectiveness studies are needed to address how inspections of private stormwater facilities affect operations and maintenance of those facilities.

The nature, scope, and frequency of inspections of private stormwater facilities was addressed by only one publication available. That publication indicates that inspections of private stormwater facilities can generally contribute to overall benefits in water quality (Fohn 2010) and annual inspections were implemented as the norm to some facilities in Kitsap county following this study. However, the connection of inspections to the operation and maintenance of these facilities was not addressed and requires additional literature or effectiveness studies. Personal experience by this author with the Washington State Local Source Control Program (LSC) indicates that corrective actions to private stormwater facilities can be short-lived and regular site visits may be needed depending on the type of facility, the risk of pollution-generating activities, and the willingness of the facility owner or personnel.

Different jurisdictions have different approaches and resources available for building relationships with private stormwater facility owners and managers. A blanket approach in the message and tone of communications with private facilities may not work for every jurisdiction. For this reason, there should be some flexibility for jurisdictions to choose the types and frequencies of communications with private facility owners in order to build positive relationships that can help motivate compliant pollution prevention behaviors.

An alternative question to consider is what combination of education and inspection of private stormwater facilities is most effective for improving compliance with operations and maintenance requirements.

> *Talking Point 5*: The optimum frequency of site visits at private stormwater facilities depends on the types of facilities. Additional literature or effectiveness studies are needed to address what frequency of inspections is best to maintain private stormwater facilities.

As noted above, the frequency of inspecting private stormwater facilities was not addressed in the literature available. However, the frequency of inspecting private stormwater facilities depends partly on the type of facility. A recommendation to address this question is to find literature about or implement effectiveness studies that explore how inspection frequencies affect the maintenance of the range of private stormwater facilities.

2.5 SUMMARY OF LITERATURE: ILLICIT DISCHARGE DETECTION AND ELIMINATION

2.5.1 Question: Which combination of methods work best for detection of illicit connections: smoke testing, dye testing, CCTV, flow monitoring, or outfall screening (wet and dry season)?

IDDE was not specifically addressed in the literature in the effectiveness database. Outside publications were used, and include CWP and Pitt (2004) and Pitt (2001) who provide detailed resources for creating IDDE programs and source tracing of illicit discharges. Some methods, such as chemical monitoring, can work well for detecting a general presence or absence of illicit discharges and establishing a history of water body chemical profiles. Other methods can work well to detect the location of illicit connections, such as closed circuit television (CCTV), flow monitoring, and smoke or dye testing. The selection of which IDDE methods to use is greatly enhanced by some foreknowledge of what the illicit discharge may be. Such foreknowledge can be obtained by a desktop assessment of activities and conditions in an area to determine the potential for the presence and type of illicit discharges. Gaining this foreknowledge can provide significant time and cost savings compared to uninformed IDDE investigations. Additional literature or effectiveness studies are needed to determine which methods work best under which circumstances and what, if any, foreknowledge was used to help select IDDE methods.

A resource currently in progress that will help Washington state NDPES permittees choose IDDE methods is a field screening manual for Washington Phase I and Phase II permittees. The precursor to the manual, a draft report of IDDE survey results and literature review (King County 2012) is available that has summary information about which IDDE methods work best for this region. Methods were ranked low, medium, and high based on input from NPDES jurisdictions around the state. The most effective methods were having an IDDE hotline, inspections of manholes/catch basins, and inspections of outfalls. However, these were also some of the more expensive options. The report also provides the pros and cons of 14 IDDE methods, and this information should provide a useful toolbox of IDDE methods and approaches for SWMP staff to use in their IDDE efforts.

An additional resource currently under development that could help western Washington NPDES permittees in the selection of IDDE methods is a regional repository of information about IDDE findings. The Source Identification Information Repository (SIIR, Monsey et al. 2012) is a project of the SWG's Source Identification and Diagnostic Monitoring subgroup. The SIIR project is envisioned to be an information source that will address the Permit Fact Sheet guidance to "allow permittees to share source identification program information and provide a regional understanding of stormwater pollutant sources" (Ecology 2011e). Resources from SIIR will include a database of findings from IDDE-related activities around the region that can help jurisdictions compare results from IDDE efforts and help inform which IDDE methods work best under different conditions.

2.5.2 Question: How effective is wet weather screening as a tool to detect illicit connections?

The effectiveness of wet weather screening to detect illicit discharges was not specifically addressed in the literature in the effectiveness database. Dilution during wet weather is the most significant challenge for detecting chemical indicators of illicit discharges. Dry season screening is the preferred method in general, but dry periods may not coincide with when illicit discharges occur, especially from seasonal or intermittent activities or when discharges are diluted by fluctuating baseflow and groundwater levels in a watershed. Observation of certain deposits and algal or biological growth at stormwater outfalls can indicate the presence of illicit discharges in areas that experience frequent wet weather. In addition, the CWP (2004) promotes the use of a chemical indicators database where the presence of ammonia, fluoride, potassium, and other parameters are used to establish “fingerprint” profiles of water chemistry. When established on a regional scale, jurisdictions can review chemical profiles in water bodies in the region as well as the IDDE efforts by others to help identify what methods work best during wet weather flows. A chemical indicators database uses the principle that the presence of combinations of certain chemicals can indicate the source of an illicit discharge. For example the presence of fluoride and potassium together can indicate industrial discharge. Chemical indicator monitoring is not meant to be stand-alone IDDE method and is not the least expensive method either. Rather, it is intended to be used selectively in combination with other IDDE methods and investigations. Additional literature or effectiveness studies are needed to provide a more thorough review of how a variety of IDDE methods can be used successfully during wet weather.

2.5.3 Question: Which parameters should be measured during dry weather screening to improve the ability to detect illicit connections?

The parameters to be measured during dry weather screening to improve the detection of illicit discharges were not specifically addressed in the literature in the effectiveness database. As with the selection of IDDE methods in general, detecting illicit discharges during dry weather is greatly enhanced by some foreknowledge of what the illicit discharge may be (CWP 2004). Several western Washington jurisdictions have already developed dry weather screening manuals or procedures as part of the IDDE requirement in the previous NPDES permit (Ecology 2007). These include the City of Seattle (Seattle 2010), Snohomish County (2009), and City of Bainbridge Island (2009), among others. Seattle recommends screening for 15 parameters during dry weather screening, ranging from flow to discharge odor to chemical screening. Snohomish County and Bainbridge Island recommend starting with a dry weather screening for parameters including presence, color, and odor of flow.

2.5.4 Talking points for IDDE

> *Talking Point 6*: Several methods and combinations of methods work well for detecting illicit connections. Foreknowledge of what potential illicit discharges may occur from an area is an important first step that can help inform what methods may work best.

The best method(s) to be used for detecting illicit discharges and connections to a storm sewer network depends on the nature of the potential illicit discharge. Smoke and dye testing can work well for detecting illicit connections, and outfall screening and monitoring of flow and indicator chemicals can work well for detecting illicit discharges. Foreknowledge of the activities and industry types can provide essential information to establish profiles of certain areas and prioritize IDDE methods. Information from a background survey and literature review of IDDE field screening (King County 2012) from NPDES permittees reports that an IDDE hotline, inspections of manholes/catch basins, and inspections of outfalls have the highest effectiveness. However, there are pros and cons of each screening method, which should be considered along with the cost of each method prior to commencing IDDE screening. A resource currently under development that could help Washington NPDES permittees select

IDDE methods is the Source Identification Information Repository (SIIR, Monsey et al. 2012). The SIIR is envisioned to be an information resource that will allow permittees to share information about IDDE efforts. Additional information is needed in the effectiveness literature database to more thoroughly address which IDDE methods and combinations of methods work best across a range of conditions. Grouping methods by cost level and level of detail of results would be a helpful addition to sorting the many IDDE methods available.

An alternative question to consider is what combination of IDDE methods is most appropriate for specific land uses and business types.

> *Talking Point 7*: Wet weather screening can be effective when implemented with foreknowledge of what illicit discharges may be present and as part of a comprehensive IDDE program. Additional literature or effectiveness studies are needed to more thoroughly address how wet weather screening is best used.

Even though wet weather flows can dilute illicit discharges, it is still possible to successfully screen for them. The information available in the effectiveness literature database does not address wet weather IDDE screening. However, the CWP (2004) suggests establishing a regional chemical indicators database to identify profiles of chemicals in stormwater that can point toward the presence of certain types of illicit discharges. Wet weather screening especially requires a combination of methods to overcome the challenge of dilution. Additional literature or effectiveness studies are needed to more thoroughly address how wet weather screening can be most effective and what combination of methods can help verify the findings of wet weather screening.

> *Talking Point 8*: Several western Washington jurisdictions have developed dry weather screening manuals. As with selecting IDDE methods in general, gaining some foreknowledge of what to expect in certain areas can be very useful for selecting parameters to measure during dry weather screening. Outfall screening has been shown to be an effective tool.

Although dry weather screening can be easier to target discrete pollutants due to the lack of dilution by wet weather runoff, knowing what to look for is still necessary. Thus, as with other IDDE methods, some foreknowledge via desktop assessment can be valuable to select dry weather screening parameters. Several western Washington jurisdictions have developed IDDE dry screening procedures and indicate that effective parameters to investigate include flow monitoring, visual inspection of outfalls for discharge odor and color, and presence of algal growth and deposition patterns. In addition, chemical screening of dry weather discharges can be informative but also more expensive depending on what chemical parameters are analyzed.

2.6 SUMMARY OF LITERATURE: BUSINESS INSPECTIONS AS SOURCE CONTROL

2.6.1 Question: Are businesses that receive an in-person visit/inspection more likely to implement source control BMPs?

Business inspections related to source control were not covered in the publications in the effectiveness database. Business inspection is more a public education and outreach topic than a strictly source control topic. The list of source control BMPs in volume IV of the SWMMWW includes many that are specific to the activity, industry, or setting. Therefore, in-person inspections should be performed by knowledgeable personnel who can identify proper use of BMPs and specify correction actions when needed.

Since 2008, Washington state has implemented the Local Source Control Partnership (LSCP) throughout Puget Sound and in the Spokane River watershed. The LSCP focuses on inspections of small-quantity generator businesses for pollution prevention. Experience by this author with the LSCP for two cities in western Washington has indicated that in-person visits can be an effective tool for implementing source control BMPs. However, the success of a lasting positive effect for stormwater source control at businesses is the result of a combination of education, inspection, and enforcement. Businesses should be prioritized by risk of pollution and personnel turnover rate to ensure new staff are informed about source control BMP operation. Additional literature or effectiveness studies are needed that addresses the connection of inspecting businesses and the successful long-term implementation of source control BMPs.

2.6.2 Question: What frequency of business inspections is most effective for implementing and maintaining source control requirements/BMPs at businesses?

As noted above, business inspections related to source control BMPs for stormwater were not covered in the publications in the effectiveness database. Personal experience by this author has shown that, as with inspections of private stormwater facilities, the frequency of inspections at businesses is affected by the type of BMPs present. As a form of non-structural BMPs themselves, inspections require regular contact to build relationships with owners, managers, and staff at businesses. Positive relationships can encourage businesses to comply with proper BMP usage, and follow-up visits can improve compliance rates even further. Conversely, strained relationships and bad attitudes by businesses toward government agencies can negatively impact proper BMP usage. To answer this question, additional literature or effectiveness studies are needed that explore the relationship between inspection frequency and source control BMPs.

2.6.3 Talking Points for Business Inspections as Source Control

> *Talking Point 9*: In-person visits to businesses can help encourage the implementation of source control BMPs. Knowledgeable staff is necessary to competently inspect the range of source control BMPs present at businesses. Additional literature or effectiveness studies are needed to address how in-person inspections affect the use of source control BMPs.

One publication in the effectiveness literature database included incidental reference to visits to businesses in Kitsap County for source tracing and source control of bacteria (Fohn 2010). They reported positive results from business inspections but related the results only generally to control of bacterial sources by businesses due to in-person site visits. There is a wide range of BMPs at businesses due to the variety of industries that are included under the general category of “business inspections.” Inspection staff knowledgeable of the range and proper usage of BMPs expected to be encountered is necessary. Experience by this author with the LSCP in Washington has shown that in-person visit can result in effective use of source control BMPs and that follow-up is important. However, more information is needed that addresses the relationships among in-person inspections, education, and enforcement of proper use of source control BMPs.

> *Talking Point 10*: The optimum frequency of inspections at business depends on the type of BMP present and the relationship with businesses. Follow-up inspections can improve BMP compliance. Additional literature or effectiveness studies are needed to address how the frequency of in-person inspections affects the use of source control BMPs

The literature in the effectiveness database did not address frequency of business inspections. This topic fits better under public education and outreach since it relates to behavior change. The type of BMP and the nature of the relationship between agencies and businesses can affect the optimum inspection frequency. More literature or effectiveness studies are needed to identify what frequency of inspections at businesses produces the best results for source control.

3.0 CONCLUSIONS AND RECOMMENDATIONS

This review of stormwater source control best management practices has several key findings for each topic covered. The four topics are erosion and sediment management at construction sites, site visits of private stormwater facilities, illicit discharge detection and elimination, and source control inspections at businesses. The key findings and suggested effectiveness studies are as follows:

3.1 EROSION AND SEDIMENT MANAGEMENT AT CONSTRUCTION SITES

1. Temporary erosion and sedimentation control (TESC) BMPs used at construction sites can be effective at controlling erosion. Effective use depends on BMP selection, operation and maintenance, and site conditions.
2. Source control BMPs are a necessary component of erosion and sediment management at construction sites. The requirements for BMP use in western Washington are found in the NPDES stormwater permits and the details of the BMP options can be found in the SWMMWW (Ecology 2012d).
3. Construction TESC BMPs reviewed in the available literature indicate that polyacrylamide (PAM), compost and mulch mixes used in socks, rolls, and blankets, and geotextile-based BMPs show the best performance for preventing and controlling erosion. Effectiveness of PAM is highest in conjunction with another BMP, such as with compost filled blankets placed on slopes or straw filled check-dams wrapped in geotextile fabric placed in a channel directing discharge to a treatment pond or infiltration zone.
4. Application rates of PAM in the literature varied from 0.03 pounds of powder spread over one acre (lb ac^{-1}) up to 9.3 lb ac^{-1}. Washington state has strict guidelines about the use of PAM with allowable application rates of up to 0.66 lb ac^{-1}, or 80 mg L^{-1} in solution. Due to concerns about potential toxicity and the requirement that PAM not enter receiving waters, it is currently not a widely used construction BMP in western Washington.
5. Compost-based TESC BMPs have the added benefit of providing nutrients to encourage plant growth, which is a necessary component of long-term erosion management. However, compost has the drawback of the possibility of nutrient export, which can cause unwanted algal and plant growth in receiving waters.
6. Chemical treatment BMPs should be used in combination with other TESC BMPs at construction site to reduce turbidity to benchmark levels for compliance with water quality standards. Ecology's SWMMWW and C-TAPE program have lists of approved chemical treatment BMPs.
7. Sediment pond (detention basin) design and sizing can strongly influence the ability to effectively capture and contain suspended sediment. The design and sizing criteria for sedimentation ponds in western Washington could be improved by including an explicit estimation of anticipated sediment loading.

8. A review of CESCL training requirements in warranted to ensure TESC inspectors have the latest information about emerging technologies.

3.1.1 Recommendations for Additional Literature and Effectiveness Studies

1. Relatively few TESC BMPs were covered in the literature available in the effectiveness literature database. Additional literature is needed to review the full range of TESC BMPs.
2. A review of PAM performance in western Washington is warranted. Such a review should include potential toxicity of anionic PAM used for erosion control as well as PAM performance with the types of soils present in western Washington.
3. A review of sediment pond sizing and design is recommended based on literature reviewed. Current sizing in the SWMMWW is based on peak flows of anticipated stormwater runoff. Inclusion of a step to estimate sediment loading is recommended to improve sizing and design of sediment ponds for maximum sediment retention.
4. An alternative question to consider is which combinations of TESC BMPs listed in the SWMMWW are the most effective at controlling erosion and sediment from construction sites across the range of conditions in western Washington.

3.2 SITE VISITS OF PRIVATE STORMWATER FACILITIES

1. Site visits and inspections of private stormwater facilities can have positive effects on the operation and maintenance of stormwater BMPs. Effective use of stormwater facilities by private entities can be encouraged by establishing good relationships between agencies and private facility operators.
2. Positive relationships can be encouraged by tailoring communications to the specific agency goals for building relationships with owners and managers of private stormwater facilities.
3. The optimum frequency of site visits at private stormwater facilities depends partly on the types of facilities present.

3.2.1 Recommendations for Additional Literature and Effectiveness Studies

1. Inspections of private stormwater facilities in a bacterial pollution study in Kitsap county were shown to generally contribute to overall benefits in water quality. More literature or effectiveness studies are needed to verify this result and explore the connection between site visits to private stormwater facilities and downstream water quality benefits.
2. Additional literature or effectiveness studies are needed to address what frequency of inspections is best to maintain private stormwater facilities.
3. An alternative question to consider is what combination of inspection of private stormwater facilities and education of their owners and operators is most effective for improving compliance with operations and maintenance requirements.

3.3 ILLICIT DISCHARGE DETECTION AND ELIMINATION

1. Foreknowledge of what potential illicit discharges may occur from an area is an important first step that can help inform what IDDE methods may work best. A desktop assessment of activities and drainage network in an area of interest can provide this foreknowledge.

2. During wet weather screening, dilution of illicit discharges is the main challenge to overcome. Chemical indicator monitoring is recommended in the literature and should be used in combination with other IDDE methods for conclusive determination of illicit connections.

3. The forthcoming Source Identification Information Repository (a project of the SWG Source Identification and Diagnostic Monitoring subgroup, Monsey et al. 2012) will be a valuable resource for allowing local agencies to compare IDDE findings and help point toward effective IDDE methods for conditions in western Washington.

4. Several western Washington jurisdictions have developed IDDE dry weather screening manuals. Primary methods recommended in those manuals include flow monitoring and inspection of outfalls and storm catch basins for odorous or discolored discharge.

5. A forthcoming IDDE field screening manual (King County 2012) will have a useful toolbox of information for deciding which IDDE methods work best. Based on preliminary findings from a survey used to develop the manual, the most effective methods were establishing an IDDE hotline, outfall screening, and inspection of stormwater manholes and catch basins.

3.3.1 Recommendations for Additional Literature and Effectiveness Studies

1. Establish a regional chemical indicators database for local entities to compare results across the region of water quality profiles and IDDE efforts.
2. Additional literature or effectiveness studies are needed to more thoroughly address what combination of IDDE methods work best for wet weather screening.
3. An alternative question to consider is what combination of IDDE methods is most appropriate for specific land uses and business types.

3.4 INSPECTION OF SOURCE CONTROL BMPS AT BUSINESSES

1. In-person visits to businesses can help encourage the implementation of source control BMPs. Although inspections of businesses were not addressed in the literature, personal experience by this author indicates that the presence of inspectors can sometimes result in immediate correction to the proper usage of source control BMPs.

2. The optimum frequency of inspections at business depends on the type of BMPs present and the relationship with businesses. Regular follow-up inspections can improve long-term BMP compliance.

3. Knowledgeable staff is necessary to competently inspect the range of source control BMPs present at businesses.

4. The topic of business inspections for BMPs relates to human behavior and psychology as much or more so than to technical operation and maintenance of BMPs.

3.4.1 Recommendations for Additional Literature and Effectiveness Studies

1. Additional literature or effectiveness studies are needed to address how in-person inspections and the frequency of inspections affect the use of source control and other BMPs at businesses. Specifically, such literature or studies should explore the relationships among in-person inspections, education about BMPs, and enforcement for compliance.
2. A valuable resource for investigating recent and current business inspections in Washington is Ecology's Local Source Control Partnership being implemented throughout Puget Sound and in the Spokane River basin. It is recommended to confer with that program in designing an effectiveness study on business inspections.

Of the 336 publication titles in the effectiveness literature database, 48 were identified as relevant to the four main topics that served as the organizing principle for this white paper. However, only a subset of those 48 titles addressed the specific ranked questions posed by the SWG. In many ways, this white paper was an exercise in matching articles in the effectiveness literature database as best as possible to the questions posed. Results from this white paper recommend additional literature to fill gaps in knowledge for each of the four main topics. There are also recommendations of effectiveness studies that can be considered and implemented without further literature review. In this way, the conclusions of this white paper can be used to help prioritize effectiveness studies and also identify areas where additional knowledge is required.

4.0 REFERENCES

Babcock and McLaughlin 2011. Babcock, D. L., R. A. McLaughlin. Runoff water quality and vegetative establishment for groundcovers on steep slopes. Journal of Soil & Water Conservation, Mar/Apr2011, Vol. 66 Issue 2, p132-141, 10p

Bainbridge Island 2010. City of Bainbridge Island. Bainbridge Island Illicit Discharge Detection and Elimination Program Manual. Published online http://www.ecy.wa.gov/programs/wq/stormwater/municipal/IDDEresources.html.

CWP and Pitt 2004. Brown, E., D. Caraco, and R. Pitt. Illicit Discharge Detection and Elimination: A Guidance Manual for Program Development and Technical Assessment. Center for Watershed Protection. October 2004

CWP 2008. Center for Watershed Protection and Chesapeake Stormwater Network. Hirschman D., K. Collins, and T. Schueler. Runoff Reduction Method Technical Memo. April, 2008 Center for Watershed Protection, Ellicott City, MD. www.stormwatercenter.net.

CWP 2009. Center for Watershed Protection. Hirschman D., L. Woodworth, S. Drescher. Stormwater BMPs in Virginia's James River Basin: An Assess of Field Conditions & Programs. June 2009 Center for Watershed Protection, Ellicott City, MD. www.stormwatercenter.net.

Daughton 1988. C. G. Daughton. Quantitation of acrylamide (and polyacrylamide): critical review of methods for trace determination/formulation analysis and future research and recommendations. Document CGD-02/88. Prepared for California Public Health Foundation, Berkeley, CA.

Eck et al. 2010. Eck, B., M. Barrett, A. McFarland, L. Hauck. Hydrologic and Water Quality Aspects of Using a Compost/Mulch Blend for Erosion Control. Journal of Irrigation & Drainage Engineering, Sep2010, Vol. 136 Issue 9, p646-655, 10p

Ecology 2003. Guidance for Evaluation Emerging Stormwater Treatment Technologies at Construction Sites. Chemical Treatment Assessment Protocol-Ecology (CTAPE). Septmber 2003. Publication No. 03-10-078. http://www.ecy.wa.gov/programs/wq/stormwater/newtech/construction.html

Ecology 2007. Washington State Department of Ecology. Western Washington Phase II Municipal Stormwater Permit. Effective February 16, 2007 to February 15, 2012 Issued by Ecology as part of the National Pollutant Discharge Elimination Program (NPDES) Program.

Ecology 2009a. Washington State Department of Ecology. Industrial Stormwater General Permit. Effective January 1, 2010 (Modification May 16, 2012) to January 1, 2015. Issued by Ecology as part of the National Pollutant Discharge Elimination Program (NPDES) Program.

Ecology 2009b. Washington State Department of Ecology. Washington State Department of Transportation NPDES and State Waste Permit for Municipal Operations. Effective March 6, 2009 (Modification March 7, 2012) to March 6, 2014. Issued by Ecology as part of the National Pollutant Discharge Elimination Program (NPDES) Program.

Ecology 2010a. Washington State Department of Ecology. Construction Stormwater General Permit. Effective January 1, 2011 to December 31, 2015. Issued by Ecology as part of the National Pollutant Discharge Elimination Program (NPDES) Program.

Ecology 2010b. Washington State Department of Ecology. The Sand and Gravel General Permit. Effective October 1, 2010 (Modification October 1, 2011) to October 1, 2015. Issued by Ecology as part of the National Pollutant Discharge Elimination Program (NPDES) Program.

Ecology 2011a. Washington State Department of Ecology. Effectiveness Study Selection. Stormwater Work Group Published online. https://sites.google.com/site/pugetsoundstormwaterworkgroup/home/selection-of-effectiveness-studies.

Ecology 2011b. Stormwater Work Group. Recommended Effectiveness Study Topics and Questions. Published online. https://sites.google.com/site/pugetsoundstormwaterworkgroup/home/selection-of-effectiveness-studies/recommended-effectiveness-study-topics-and-questions.

Ecology 2011c. Stormwater Work Group. Source Identification and Diagnostic Information Repository (SIDIR). Published online. https://sites.google.com/site/pugetsoundstormwaterworkgroup/home/source-identification-information-repository.

Ecology 2011d. Washington State Department of Ecology. Water Quality Standards for Surface Waters of the State of Washington. Chapter 173-201A of the Washington Administrative Code Amended May 9, 2011.

Ecology 2011e. Washington State Department of Ecology. Fact Sheet for the Western Washington Phase II Municipal Stormwater Permit. Issued by Ecology as part of the National Pollutant Discharge Elimination Program (NPDES) Program

Ecology 2012a. Washington State Department of Ecology. Western Washington Phase II Municipal Stormwater Permit. Effective August 1, 2013 to July 31, 2018. Issued by Ecology as part of the National Pollutant Discharge Elimination Program (NPDES) Program.

Ecology 2012b. Washington State Department of Ecology. Phase I Municipal Stormwater Permit. Effective August 1, 2013 to July 31, 2018. Issued by Ecology as part of the National Pollutant Discharge Elimination Program (NPDES) Program.

Ecology 2012c. Washington State Department of Ecology. Eastern Washington Municipal Stormwater Permit. Effective August 1, 2014 to July 31, 2019. Issued by Ecology as part of the National Pollutant Discharge Elimination Program (NPDES) Program.

Ecology 2012d. Washington State Department of Ecology. Stormwater Mangement Manual for Western Washington. 5 volumes

Stormwater Information Resource. Published online at Dept of Ecology website http://www.ecy.wa.gov/programs/wq/psmonitoring/sourceidmonit.html.

Faucette et al. 2007. Faucette, L. B., J. Governo, C. F. Jordan, B. G. Lockaby, H. F. Carino, R. Governo. Erosion control and storm water quality from straw with PAM, mulch, and compost blankets of varying particle sizes. Journal of Soil & Water Conservation, Nov/Dec2007, Vol. 62 Issue 6, p404-413,

Faucette et al. 2008. Faucette, L. B., K. A. Sefton, A. M. Sadeghi, R. A. Rowland. Sediment and phosphorus removal from simulated storm runoff with compost filter socks and silt fence. Journal of Soil & Water Conservation, Jul/Aug2008, Vol. 63 Issue 4, p257-264, 8p

Faucette et al. 2009. Faucette, L. B., J. Governo, R. Tyler, G. Gigley, C. F. Jordan, B. G. Lockaby. Performance of compost filter socks and conventional sediment control barriers used for perimeter control on construction sites. Performance of compost filter socks and conventional sediment control barriers used for perimeter control on construction sites Journal of Soil & Water Conservation, Jan/Feb2009, Vol. 64 Issue 1, p81-88.

Fohn 2010. Mindy Fohn. Bacterial Pollution Reduction in an Urban Watershed. , S42, StormCon, Anaheim, CA, August 2010. Kitsap County.

Fohn, M. Personal communication. Mindy Fohn, Surface Water Management Program, Kitsap County, Washington.

Gharabaghi et al. 2006. Gharabaghi, B., A. Fata, T. Van Seters, R. P. Rudra, G. MacMillan, D. Smith, J. Y. Li, A. Bradford, G. Tesa. Evaluation of sediment control pond performance at construction sites in the Greater Toronto Area. Canadian Journal of Civil Engineering, Nov2006, Vol. 33 Issue 11, p1335-1344, 10p

Hayes et al. 2005. Hayes, S. A., R. A. McLaughlin, D. L. Osmond. Polyacrylamide use for erosion and turbidity control on construction sites. Journal of Soil & Water Conservation, Jul/Aug2005, Vol. 60 Issue 4, p6-6, 1p

Hillegass undated. J. B. Hillegass. Using An Indicators Database To Measure Stormwater Program Effectiveness In Hampton Roads. Hampton Roads Planning District Commission, Chesapeake, Virginia

Kalainesan et al. 2008. Kalainesan, S., R. D. Neufeld, R. Quimpo, P. Yodnane. Integrated Methodology of Design for Construction Site Sedimentation Basins. Journal of Environmental Engineering, Aug2008, Vol. 134 Issue 8, p619-627, 9p,

Kalainesan et al. 2009. Kalainesan, S., R. D. Neufeld, R. Quimpo, P. Yodnane. Sedimentation Basin Performance at Highway Construction Sites. Journal of Environmental Management, Feb 2009, Vol 90, Issue 2. p838-849.

King County 2012. Herrera Environmental Consultants. Survey Results and Literature Review: Illicit Discharge Detection and Elimination Field Screening. Draft September 2012 Prepared for King County Department of Natural Resources and Parks and the Washington Stormwater Center.

McLaughlin and Brown 2006. McLaughlin, R. A., T. T. Brown. Evaluation of Erosion Control Products with and without polyacrylamide. Journal of the American Water Resources Association, June 2006, Vol. 42 Issue 3, p675-684

MacLaughlin and Bartholomew 2007. McLaughlin, R. A., N. Bartholomew. Soil Factors Influencing Suspended Sediment Flocculation by Polyacrylamide. Soil Science Society of America Journal, Mar/Apr2007, Vol. 71 Issue 2, p537-544, 8p

MacLaughlin et al. 2009. McLaughlin, R. A., S. E. King, G. D. Jennings. Improving construction site runoff quality with fiber check dams and polyacrylamide. Journal of Soil & Water Conservation, Mar/Apr2009, Vol. 64 Issue 2, p144-154, 11p

Monsey et al. 2012. Monsey V., K. Marx, and J. Baker. Washington Stormwater Center. Source Identification and Diagnostic Monitoring Information Repository: Preparing for the Creation of a Web-based Municipal Stormwater Information Resource.

Moon, A. 2013. Personal communication. Amy Moon, Construction Permit Specialist, Washington State Department of Ecology.

NRCS 2011. Natural Resources Conservation Service. Conservation practice standard for Anionic Polyacrylamide Application. Code 450 May 2011.

Pitt 2001. R. Pitt. Source Tracking of Inappropriate Discharges to Storm Drainage Systems. National Urban Watershed Conference, Costa Mesa, CA, October 2001.

Rickson 2006. Rickson, R. J. Controlling sediment at source: an evaluation of erosion control geotextiles. Earth Surface Processes & Landforms, Apr2006, Vol. 31 Issue 5, p550-560, 11p

Seattle 2010. City of Seattle. Seattle Public Utilities IDDE Dry Weather Screening Procedure. Version updated May 27, 2010 Presentation provided by Snohomish County Public Works. Published online.

Sekine et al. 2006. Sekine M, A. Takeshita, N. Oda, M. Ukita, T. Imai, and T. Higuchi. On-site treatment of turbid river water using chitosan, a natural organic polymer coagulant. Water science and technology, 53(2): 155-61

Snohomish 2009. Snohomish County. Phase II NPDES Permit Municipal Staff Training: Illicit Discharge Detection and Elimination 2009. Presentation provided by Snohomish County Public Works. Published online. http://www.ecy.wa.gov/programs/wq/stormwater/municipal/IDDEresources.html.

Taleban 2009. Taleban, V., K. Finney, B. Gharabaghi, E. McBean, R. Rudra, T. Van Seters. Effectiveness of Compost Biofilters in Removal of Sediments from Construction Site Runoff. Water Quality Research Journal of Canada, 2009, Vol. 44 Issue 1, p71-80, 10p

Taylor et al. 2007. Taylor, A., R. Curnow, T. Fletcher, J. Lewis. Education Campaigns to Reduce Stormwater Pollution in Commercial Areas: Do They Work?. Journal of Environmental Management, Aug 2007, Vol 84, Issue 3, p323-335

United States Environmental Protection Agency (USEPA)/ 1987. Environmental Protection Agency. Nonpoint Source Management Program established by the Clean Water Act Amendments of 1987.

WSDOT 2008. Regional Road Maintenance Program Endangered Species Act. Washington State Department of Transportation. http://www.wsdot.wa.gov/maintenance/roadside/esa.htm

Final

WHITE PAPER
for
Stormwater Management Program Effectiveness Literature Review

Operation and Maintenance

April 2013

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

Prepared by:
Carla B. Milesi
Cardno TEC, Inc.
2825 Eastlake Avenue East, Suite 300
Seattle, Washington 98102

EXECUTIVE SUMMARY

Catch basins can capture sediments and sediment-bound pollutants in stormwater, providing some pollutant removal and acting as a pretreatment for other stormwater best management practices (BMPs) (USEPA 2006). A factor that is critical to the effectiveness of a catch basin at removing sediments is regular maintenance to remove accumulated sediments and other debris from its sump (USEPA 2006).

This paper summarizes articles included within the effectiveness study literature database (Ecology 2011a) for the Operations and Maintenance Stormwater Management Plan (SWMP) topic. In particular, the paper discusses the following Effectiveness Study Topic Null Hypotheses relating to catch basins, their maintenance, and their potential for contributing bacteria to stormwater runoff.

Hypothesis #1: Frequency of inspecting and cleaning catch basins is not dependent on land use or road size.

Several studies have been conducted that determined that different land uses result in significantly different sediment accumulations rates. These studies have shown varying sediment accumulations rates among land uses with industrial land use reporting the highest sediment accumulations followed by commercial then residential. In general these studies indicate the frequency of inspecting and cleaning catch basins is dependent on land use or road size.

Hypothesis #2: Catch basins do not contribute sufficient fecal coliform bacteria to exceed water quality standards.

The studies available within the literature database indicate catch basins are likely not a significant source of fecal coliform, but they do have the ability to re-suspend and transport bacteria bound to sediments that have settled out in the catch basin sump. They may be a source of bacteria that replicates and regrows on biofilm within the catch basin sump, however, this bacteria is not pathogenetic and not believed to be a human health concern.

Based on a review and summary of the articles included in the literature database it is recommended that additional studies or maintenance practices be completed.

1. Review maintenance and inspection records to assess sediment accumulation rates. Use the records to develop a maintenance schedule to assess the feasibility of maintaining catch basins before they reach 40 to 50 percent of their capacity. Determine if accumulation rates of catch basins may allow for a more flexible inspection schedule than that required by the National Pollutant Discharge Elimination System (NPDES) permit.
2. Look into the feasibility of WSDOT changing the design standards of catch basins to allow for local governments to size of catch basins sumps to accommodate the volume of sediment that enters the system. Pitt et al. (2000) proposed a sizing criterion based on the concentration of sediment in runoff. The catch basin is sized, with a factor of safety, to accommodate the annual sediment load in the catch basin sump.

3. Conduct additional studies to look at various BMPs and their effectiveness at removing indicator bacteria and fecal coliform from urban runoff.
4. Conduct monitoring to determine if newly implemented NPDES permit required catch basin maintenance standards have had an effect on pollutant levels, including sediment, fecal coliform, and other sediment bound pollutants.
5. Conduct additional studies on the presence of biofilm in local catch basins and gutters, their influence on downstream bacteria levels, and their likelihood of causing human health concerns.

TABLE OF CONTENTS

List of Tables

ABBREVIATIONS AND ACRONYMS

AADT	average annual daily traffic
BMPs	best management practices
cfu	colony forming units
CWP	Center for Watershed Protection
E-coli	Escherichia coliform bacteria
Ecology	Washington State Department of Ecology
mL	milliliters
MPN	most probable number
NPDES	National Pollutant Discharge Elimination System
TMDL	Total Maximum Daily Load
USEPA	United States Environmental Protection Agency
UV	ultraviolet
WRIA	Water Resources Inventory Area
WSDOT	Washington State Department of Transportation

1.0 INTRODUCTION AND PROBLEM STATEMENT

The Stormwater Work Group (SWG) is a group of stakeholders made up of federal, tribal, state and local governments, as well as business, environmental, agriculture and research interests. They are tasked with developing a Stormwater Monitoring and Assessment Strategy for the Puget Sound Region. The Effectiveness Study Selection Subgroup (subgroup) was formed by the SWG in October 2010 to help with the process of identifying potential effectiveness studies to be conducted during the next National Pollutant Discharge Elimination System (NPDES) municipal stormwater permit cycle. The subgroup developed a list of 22 ranked effectiveness study topics and associated questions. To help answer these questions, an Effectiveness Study Literature Review was conducted and a literature database was created (Ecology 2011a). The literature database contains over 300 publications, including journal articles, books, public information flyers and agency reports.

1.1 SCOPE OF THIS PAPER

This white paper aims to summarize the publications within the effectiveness study literature database (Ecology 2011a) that related to the ranked effectiveness study and Storm Water Management Plan topics #5 and #15: Operations and Maintenance. The paper specifically addresses the following Null Hypotheses relating to catch basins, their maintenance, and their potential for contributing bacteria to stormwater runoff.

Null Hypothesis #1: Frequency of inspecting and cleaning catch basins is not dependent on land use or road size.

- Do catch basins on arterial streets require more frequent cleaning vs. non-arterial streets?
- Can land use or road size/type be used to set an optimal frequency for inspection and cleaning catch basins?
- Does the land use surrounding a catch basin influence the rate of sediment accumulation in catch basins?
- Can catch basin maintenance frequency be determined by land use surrounding the catch basin?

Null Hypothesis #2: Catch basins do not contribute sufficient fecal coliform bacteria to exceed water quality standards.

- Are catch basins a significant source of fecal coliform or other pollutants?
- What frequency of catch basin maintenance is needed to reduce the level of fecal coliform to meet Total Maximum Daily Load (TMDL) requirements?

Funding for this white paper was provided the Washington State Department of Ecology.

1.2 PROBLEM STATEMENT

Most large municipalities include storm drain systems made up of hundreds of miles of conveyance pipes. These storm drain systems capture urban stormwater runoff from roadways and transport it to outfalls that drain to streams, lakes, oceans, and other water bodies. Catch basins, which are typically made up of a curb inlet or grate along with a sump, provide an inlet for stormwater to enter these storm drain systems. Catch basins are generally considered to be a pretreatment for other stormwater best management practices (BMPs), with the catch basin sump allowing larger sediments and associated pollutants to settle out (USEPA 2006). The effectiveness of catch basins to remove debris and sediment is highly dependent on their design and sump size. Another factor that is critical to their effectiveness is regular maintenance to remove accumulated sediments and other debris from its sump (USEPA 2006).

Common pollutants associated with urban stormwater runoff include metals, motor oil, pesticides and fertilizers, and bacteria such as fecal coliform. In the 2004 United States Environmental Protection Agency (USEPA) National Water Quality Inventory it was found that eight percent of streams, seven percent of lakes, and 12 percent of estuaries were impaired by urban stormwater (Winston et al. 2011). In addition, the USEPA's National Water Quality Inventory in 2000 determined that 13 percent of the river and stream miles that were surveyed were impaired by bacteria that was indicative of the presence of fecal coliform (Hathaway et al. 2009). The often difficult task for stormwater managers is finding the source of bacteria and other stormwater pollutants in addition to determining the best ways to reduce pollutant loads in the receiving water bodies.

2.0 LITERATURE SUMMARY AND TALKING POINTS

The Operations & Maintenance null hypotheses and ranked questions are presented in Table 1. Publications from the database of effectiveness study literature (Ecology 2011a) were reviewed to research the null hypotheses and address the ranked questions. This section presents a summary of the publications reviewed and, where possible, answers to the ranked questions.

Table 1 Ranked Effectiveness Questions for Operations and Maintenance (Ecology 2011b)

Rank[1]	Null Hypothesis	Questions
5	Frequency of inspecting and cleaning catch basins is not dependent on land use or road size.	• Do catch basins on arterial streets require more frequent cleaning vs. non-arterial streets?
		• Can land use or road size/type be used to set an optimal frequency for inspection and cleaning of catch basins?
		• Does the land use surrounding a catch basin influence the rate of sediment accumulation in catch basins?
		• Can catch basin maintenance frequency be determined by land use surrounding the catch basin?
15	Catch basins do not contribute sufficient fecal coliform bacteria to exceed water quality standards	• Are catch basins a significant source of fecal coliform or other pollutants?
		• What frequency of catch basin maintenance is needed to reduce the level of fecal coliform to meet Total Maximum Daily Load (TMDL) requirements?

Notes:
1 Rank assigned by the SWG.

2.1 IS THE FREQUENCY OF INSPECTING AND CLEANING CATCH BASINS DEPENDENT ON LAND USE OR ROAD SIZE?

Storm drain and catch basin cleanouts have been used to control storm water pollution for many years; however, relatively few studies have been conducted to statistically determine if they have an impact on water quality (CWP 2008). Existing studies indicate that catch basins can reduce pollutants by five to 25 percent depending on the conditions of the catch basin, how frequently it is maintained and cleaned, and the type of pollutant (CWP 2008).

Regular maintenance and cleaning of the catch basins is critical to their effectiveness. Aronson et al. (1993) found that, at a minimum, catch basins should be cleaned once or twice a year. A separate study found that annual cleaning removed 54 pounds of sediment, semi-annual and quarterly cleaning removed 70 pounds of sediment, and monthly cleaning removed 160 pounds of sediment (Mineart and Singh 1994a). However, there are many factors affecting sediment accumulation rates and this frequency of cleaning may not be warranted or financially feasible for many municipalities.

The subsections below summarize the publications within the effectiveness study literature database that related to the Operations and Maintenance Ranked List of Effectiveness Topics and Potential Questions approved by the Stormwater Work Group. These summaries are meant to assist local stormwater management program staff in gaining a better understanding of the topic of catch basins and their maintenance requirements. In general, cleaning and maintaining catch basins have an impact on their effectiveness at removing sediment, and the frequency of needing to inspect and clean catch basins is dependent on the surrounding land use, road size, and amount of road use.

2.1.1 Question: Do catch basins on arterial streets require more frequent cleaning vs. non-arterial streets?

The articles within the literature database did not specifically look at arterial versus non-arterial streets in relation to sediment accumulation within catch basins. One study completed by the Wisconsin Department of Natural Resources (WI DNR 1983) found that heavily traveled commercial streets had sediment accumulation rate that were two to three times greater than that seen on high density residential streets. This would seem to indicate that more heavily traveled roads such as commercial arterial streets would see a higher sediment accumulation rate than non-arterial streets. A better question may be to look at average annual daily traffic (AADT) to see if there is a correspondence between those values and the frequency of catch basin cleaning required.

2.1.2 Question: Can land use or road size/type be used to set an optimal frequency for inspection and cleaning catch basins?

While studies indicate that both land use and road type affect sediment accumulation rates within catch basins, there are many other factors that need to be considered as well. Other factors include weather, topography, particle size, erodability of soils, whether or not the streets have curbs (CWP 2006a) and if the street is deemed a "snow route". In addition, the size of the catch basin sump has a significant effect on how frequently the catch basin needs to be maintained and cleaned. Pitt and Bissonnett (1984) determined catch basins should be cleaned once the sump reaches 40-50 percent of its capacity. Once they reach this point their ability to trap sediment drops significantly and they may start releasing trapped sediment back into the flow of stormwater (Pitt and Bissonnett 1984). Volume V of the Stormwater Management Manual for western Washington states catch basins should be cleaned or maintained when sediment, trash, or debris in the sump exceeds 60 percent of its capacity (Ecology 2012c).

With this many factors affecting the ability of the catch basin to trap sediment, it seems that an optimal frequency for inspection and cleaning catch basins cannot be determined based on land use or road size/type alone.

2.1.3 Question: Does the land use surrounding a catch basin influence the rate of sediment accumulation in catch basins?

Within the literature database there were several articles that referenced other studies, which determined that different land uses result in significantly different sediment accumulations rates and different catch basin clean out frequencies. Lager et al. (1977) and the Center for Watershed Protection (CWP) (2006a) state that adjacent land use is one of several factors that can affect the accumulation rate of sediment and associated pollutants and, as a result, affect how often a catch basin should be cleaned out.

Several CWP articles looked at differences between industrial, commercial, and residential roadways. One found that commercial/industrial land use areas accumulate sediment at a rate that is 4 times greater than residential land use areas (CWP 2008). A separate article found that heavily traveled commercial streets had accumulation rates that were two to three times greater than streets in high density residential areas and streets in industrial areas tend to accumulate pollutants faster than commercial or residential areas (CWP 2006a).

2.1.4 Question: Can catch basin maintenance frequency be determined by land use surrounding the catch basin?

As is discussed in Section 2.1.3, surrounding land use does seem to affect the rate of sediment accumulation, and therefore the likely frequency of cleanouts, in catch basins. Pitt and Bissonnett (1984) suggest semiannual cleanouts in residential street while Mineart and Singh (1994b) suggest monthly cleanouts for industrial streets. However, as outlined in Section 2.1.2 there are many factors beyond land use that affect the sediment accumulation rates in catch basins. These factors include sump size, weather, topography, particle size, erodability of soils, whether or not the streets have curbs (CWP 2006a) and if the street is a “snow route”. Surrounding land use can be one, but shouldn’t be the sole, factor in determining catch basin maintenance frequency.

2.2 DO CATCH BASINS CONTRIBUTE SUFFICIENT FECAL COLIFORM BACTERIA TO EXCEED WATER QUALITY STANDARDS?

Indicator bacteria for freshwater environments, as defined by the USEPA, consist of Escherichia coliform bacteria (E. coli) and Enterococci bacteria. These bacteria are indicators of the potential for total coliform and fecal coliform (in addition to E. coli and Enterococci) contamination. There are no fecal coliform water quality standards for stormwater, however, the USEPA set the criteria for bacteria in recreational waters at the following levels (USEPA 1986):

- Enterococci: geometric mean of 33 colony forming units (cfu) per 100 milliliters (mL) in fresh water, 35 cfu per 100 mL in marine water.
- E. coli: geometric mean of 126 cfu per 100 mL in fresh water (no E. coli criterion for marine water)

Washington State Department of Ecology (Ecology) has additional state standards for fecal coliform organisms for fresh and marine waters, as presented in Table 2.

Table 2. Washington State Water Contact Recreation Bacteria Criteria in Fresh and Marine Waters

Category	Bacteria Indicator
Extraordinary Primary Contact Recreation	***Freshwater:*** Fecal coliform organism levels must not exceed a geometric mean value of 50 colonies/100 mL, with not more than 10 percent of all samples (or any single sample when less than ten samples points exist) obtained for calculating the geometric mean value exceeding 100 colonies/100 mL. ***Marine:*** No criterion.
Primary Contact Recreation	***Freshwater:*** Fecal coliform organism levels must not exceed a geometric mean value of 100 colonies/100 mL, with not more than 10 percent of all samples (or any single sample when less than ten samples points exist) obtained for calculating the geometric mean value exceeding 200 colonies/100 mL. ***Marine:*** Fecal coliform organism levels must not exceed a geometric mean value of 14 colonies/100 mL, with not more than 10 percent of all samples (or any single sample when less than ten samples points exist) obtained for calculating the geometric mean value exceeding 43 colonies/100 mL.

Category	Bacteria Indicator
Secondary Contact Recreation	***Freshwater:*** Fecal coliform organism levels must not exceed a geometric mean value of 200 colonies/100 mL, with not more than 10 percent of all samples (or any single sample when less than ten samples points exist) obtained for calculating the geometric mean value exceeding 400 colonies/100 mL. ***Marine:*** Fecal coliform organism levels must not exceed a geometric mean value of 70 colonies/100 mL, with not more than 10 percent of all samples (or any single sample when less than ten samples points exist) obtained for calculating the geometric mean value exceeding 208 colonies/100 mL.

Source: Ecology 2012a

Based on the National Water Quality Inventory conducted in 2000 by the USEPA, 13 percent of the river and stream miles that were surveyed were impaired by indicator bacteria (Hathaway et al. 2009). In addition, according to the International Stormwater BMP Database (2010) as of 2010 bacteria and pathogens were the biggest cause of stream impairments within the United States, with over 10,000 stretches of streams identified as being impaired. This is typically a result of high concentrations of indicator bacteria in these stream segments.

There are few peer-reviewed articles that detail the efficacy of BMPs at removing or inactivating bacteria, and the majority of conventional stormwater BMPs do not appear to be effective at reducing fecal indicator bacteria (Hathaway et al. 2009). However, BMPs should provide some reduction in fecal concentrations if they are designed to maximize exposure of stormwater to sunlight, provide a habitat for microbes that prey on bacteria, or provide filtration (BMP database 2010). Conversely, some BMPs may actually contribute to bacteria levels by inadvertently providing habitat, nutrients, and conditions conducive to the regrowth and replication of fecal coliform and indicator bacteria (Wildey 2006 and BMP database 2010).

As described in Section 2.1, the subsections below summarize the publications within the effectiveness study literature database that related to the Operations and Maintenance Ranked List of Effectiveness Topics and Potential Questions approved by the Stormwater Work Group. These summaries are meant to assist local stormwater management program staff in gaining a better understanding of the topic of catch basins and their potential for contributing bacteria to stormwater runoff. In general, there are limited studies on catch basins and their ability to increase or decrease levels of bacteria in stormwater.

2.2.1 Question: Are catch basins a significant source of fecal coliform or other pollutants?

In Santa Monica Bay, a study noted that high levels of bacterial indicators were found near storm drain outlets (Haile et al. 1999). In 2003, a report by the Washington State Department of Health determined that the northern area of Dyes Inlet, near Silverdale, WA, was contaminated by bacterial pollution from Clear Creek and stormwater runoff from many of the shoreline outfalls (WSDOH 2003).

In a separate study on Clear Creek in 2005, it was found that the creek had a dry weather geometric mean of 896 most probable number (MPN)/100 mL (Fohn undated). No illicit sewer connections were discovered, and it was surmised that there were two possible sources for the contamination. The first source states the possibility of bacteria binding to fine sediment particles in the stormwater system (Serdar 1993). The International BMP Database Summary of Fecal Indicator Bacteria (2010) also suggests that bacteria may bind to and survive longer in sediment than in the water column. As a result, sediments that settle out in catch basins could lead to increased downstream bacteria levels if the sediment is mobilized or transported to receiving waters during storm events. (BMP database 2010 and Serdar 1993)

The second, and likely more benign, possible source for the high levels of bacteria within Clear Creek, as surmised by Fohn (undated), is the condition within the catch basins and vaults. The moist sediments, slow moving water, and lack of ultraviolet (UV) light may allow for the growth of biofilm and the regrowth and replication of the bacteria (Fohn undated). Skinner et al. (2010) outlined studies completed by the city of Newport Beach, California, and the Orange County (California) Health Care Agency Water Quality Laboratory that found that biofilm in street gutters and storm drains may provide ideal conditions for the regrowth of bacteria. The biofilm provides nutrients and water, protection from microbial predators and UV light and moist conditions (Skinner et al. 2010). One such study measured bacteria levels in hose water that was introduced to a dry street gutter. The hose water was tested for fecal coliform and Enterococci at 10 meters, 45 meters, and 100 meters downstream of the start of flow. The study found that there was an increase in both bacteria with the increased distance of flow, reaching a level of 14,000 fecal coliform/100 mL and 26,000 Enterococci/100 mL at the 100 meter testing site (Skinner et al. 2010). They suspected the source of the high levels of bacteria to be from the biofilm within the street gutters. Testing of the biofilm itself confirmed this suspicion as they identified up to 9 million Enterococci and 6 million fecal coliform per 110 grams of biofilm (Skinner et al. 2010).

However, human enteric viruses, which are the primary concern with high fecal coliform levels in recreational waters, do not multiply in these biofilms found in gutters and storm drains (Skinner et al. 2010). Therefore, the bacteria that grow on these biofilm are not pathogenetic and do not carry the same human health concerns as fecal coliform from human sources. In fact the high bacteria levels associated with these biofilms may cause an overestimation of potential health issues.

In summary, the studies available indicate that catch basins are likely not a significant source of fecal coliform, but they do have the ability to transport bacteria bound to sediments that have settled out in the catch basin sump. They may be a source of bacteria that replicates and regrows on biofilm within the catch basin sump, however, this bacteria is not pathogenetic and not believed to be a human health concern.

2.2.2 Question: What frequency of catch basin maintenance is needed to reduce the level of fecal coliform to meet TMDL requirements?

A TMDL is a calculation of the maximum amount of a pollutant that can be discharged to a body of water while ensuring the water body still safely meets the water quality standards. They serve as a way to improve the health of our local water bodies by setting a goal of how much a certain pollutant needs to be reduced to meet water quality standards and providing implementation plans on how to reach that goal. Table 3 presents water bodies within western Washington, organized by Water Resource Inventory Area (WRIA) and county that have a TMDL for fecal coliform.

Table 3. Fecal coliform TMDLs for western Washington, listed by County and WRIA.

WRIA	Counties	Water body Name
01 – Nooksak	Whatcom	Johnson Creek Lake Whatcom[1] Nooksack River Whatcom Creek[1]
03 – Lower Skagit-Samish	Skagit	Samish Watershed Skagit Basin
05 – Stillaguamish	Snohomish	Stillaguamish River
07 – Snohomish	Snohomish	Snohomish River & Tributaries Allen Creek Quilceda Creek French Creek Woods Creek Pilchuck River Marshlands (Wood Creek) Snoqualmie River Basin
	King	Snoqualmie River Basin
08 – Cedar-Sammamish	Snohomish	Bear-Evans Creek Basin Little Bear Creek & Tributaries Trout Stream Great Dane Creek Cutthroat Creek North Creek Swamp Creek
	King	Bear-Evans Creek Basin Issaquah Creek Basin Little Bear Creek North Creek Pipers Creek Swamp Creek
09 – Duwamish Green	King	Fauntleroy Creek Soos Creek[1]
10 – Puyallup White	Pierce	Clarks Creek Meeker Creek Puyallup River Watershed South Prairie Creek
11 – Nisqually	Pierce	Nisqually Watershed Tributaries Lynch Creek Ohop Creek Red Salmon Creek Unnamed Tributary to Red Salmon Creek Wash Creek
	Thurston	Nisqually Watershed Tributaries McAllister Creek Little McAllister Creek Medicine Creek mouth
13 – Deschutes	Thurston	Budd Inlet[1] Capitol Lake[1] Deschutes River[1] Henderson Inlet Watershed
14 – Kennedy-Goldsborough	Mason	Oakland Bay and Hammersley Inlet Totten/Eld Inlets Tributaries
	Thurston	Totten/Eld Inlets Tributaries

WRIA	Counties	Water body Name
15 – Kitsap	Kitsap	Liberty Bay Tributaries
16 – Skokomish Dosewallips	Mason	Skokomish River and Tributaries Purdy Creek Weaver Creek Ten Acre Creek Hunter Creek
	Jefferson	Skokomish River
18 – Elwha-Dungeness	Clallam	Dungeness Bay Matriotti Creek Dungeness River and Tributaries Meadowbrook Creek Golden Sands Cooper Creek Dungeness River RM 1.0 Irrigation Ditch 1 Irrigation Ditch 2
22 – Lower Chehalis	Grays Harbor	Grays Harbor Wildcat Creek
23 – Upper Chehalis	Grays Harbor	Black River
	Lewis Creek	Upper Chehalis River and Tributaries Dillenbaugh Lincoln Creek Newaukum River Salzer Creek Scatter Creek Skookumchuck
24 – Willapa	Pacific	Willapa River Unnamed Creek (Central St. drain @ Coast Seafoods) Riverdale Creek Wilson Creek Falls Creek Fern Creek
27 – Lewis	Lewis	Lewis River, East Fork[1]
	Skamania	Lewis River, East Fork[1]
28 – Salmon-Washougal	Clark	Gibbons Creek Lacamas Creek[1] Salmon Creek

Notes:
[1]The fecal coliform TMDLs for these water bodies are under development
Source: Ecology 2012b

As outlined above, catch basins may be lead to increased fecal coliform levels downstream if sediment bound bacteria that have settled in the sump are mobilized or transported during storm events. To reduce the effects of the sediment bound bacteria catch basins should be maintained and cleaned once the sump reaches 40-50 percent of its capacity. After this point the ability of the catch basin to trap sediment drops significantly, and may start releasing trapped sediment, and therefore bacteria, back into the flow of stormwater (Pitt and Bissonette 1984). There are many factors that affect how quickly the catch basin sump may reach this capacity, including size of the sump, adjacent land use, weather, topography, particle size, erodability of soils, and whether or not the streets have curbs (CWP 2006a). An accurate determination of how quickly a catch basin sump will reach 40-50 percent of its capacity, and therefore how frequently they should be maintained, requires periodic site visits to measure accumulated sediments.

Catch basins may also be a source of fecal coliform from the replication and detachment of bacteria on biofilm within the storm drains. However, the bacteria that grow on the biofilm in storm drains are not likely to be associated with the human enteric viruses and therefore are not likely to be a human health concern.

3.0 CONCLUSIONS AND RECOMMENDATIONS

Catch basins can be effective at removing sediments and associated sediment bound pollutants from stormwater runoff. This includes fecal coliform and other bacteria that otherwise may impair the downstream lakes, streams and other water bodies. However, without regular maintenance catch basins may also contribute to increased pollutant levels in our receiving waters, particularly bacteria, by allowing trapped sediments to be mobilized during storm events.

How frequently catch basins need to be maintained to minimize their contribution to increased pollutant levels is dependent on several factors. These factors include size of the catch basin sump, surrounding land use, weather, topography, road type, particle size, erodability of soils, and whether or not the streets have curbs (CWP 2006a).

In western Washington, the Washington State Department of Transportation (WSDOT) has design criteria for catch basins as outlined in Table 3.

Table 4. WSDOT catch basin design criteria.

Catch Basin Type	Dimensions (inches)	Minimum Sump Depth (inches)
Type 1[1]	26 x 22	21
Type 1L[2]	32 x 28	18
Type 1P[3]	26 x 22	32
Type 2[4]	48, 65, 60, 72 or 96 (diameter)	24

Notes:
[1] WSDOT Standard Plan B-5.20-01 (2011)
[2] WSDOT Standard Plan B-5.40-01 (2011)
[3] WSDOT Standard Plan B-5.60-01 (2011)
[4] WSDOT Standard Plan B-10.20-10 (2012)

In addition, Volume V of the Stormwater Management Manual for western Washington states catch basins should be cleaned or maintained when sediment, trash, or debris in the sump exceeds "60 percent of the sump depth as measured from the bottom of the basin to invert of the lowest pipe into or out of the basin, but in no case less than a minimum of 6 inches clearance from the sediment surface to the invert of the lowest pipe" (Ecology 2012c).

Based on a review and summarization of the articles included in the literature database it is recommended that additional studies be completed. These studies should look at the feasibility and effectiveness of various maintenance practices to improve the effectiveness of catch basins at removing sediments and sediment-bound pollutants as well as their effectiveness in reducing fecal coliform levels. A few of these recommendations include:

1. Review maintenance and inspection records to assess sediment accumulation rates. Use the records to develop a maintenance schedule to assess the feasibility of maintaining catch basins before they reach 40 to 50 percent of their capacity. Determine if accumulation rates of catch basins may allow for a more flexible inspection schedule than that required by the NPDES permit.

2. Look into the feasibility of changing the design standards of catch basins to allow for local governments to size of catch basins sumps to accommodate the volume of sediment that enters the system. Pitt et al. (2000) proposed a sizing criterion based on the concentration of sediment in runoff. The catch basin is sized, with a factor of safety, to accommodate the annual sediment load in the catch basin sump.
3. Conduct additional studies to look at various BMPs and their effectiveness at removing indicator bacteria and fecal coliform from urban runoff.
4. Conduct monitoring to determine if newly implemented NPDES permit required catch basin maintenance standards have had an effect on pollutant levels, including sediment, fecal coliform, and other sediment bound pollutants.
5. Conduct additional studies on the presence of biofilm in local catch basins and gutters, their influence on downstream bacteria levels, and their likelihood of causing human health concerns.

4.0 REFERENCES

Aaronson, G., D. Watson, and W. Pisaro. 1993. Evaluation of Catch Basin Performance for Urban Stormwater Pollution Control. US Environmental Protection Agency. .

Center for Watershed Protection (CWP). 2006a. Technical Memorandum 1 – Literature Review. Research in Support of an Interim Pollutant Removal Rate for Street Sweeping and Storm Drain Cleanout Activities. October 2006.

Center for Watershed Protection (CWP). 2006b. Technical Memorandum 2 – Summary of Municipal Practices Survey: Research in Support of an Interim Pollutant Removal Rate for Street Sweeping and Storm Drain Cleanout Activities. October 2006.

Center for Watershed Protection (CWP). 2008. Deriving Reliable Pollutant Removal Rates for Municipal Street Sweeping and Storm Drain Cleanout Programs in the Chesapeake Bay Basin. September 2008.

Fohn, Mindy. Undated. Bacterial Pollution Reduction in an Urban Watershed. Kitsap County Public Works, Surface and Stormwater Management, Port Orchard, WA.

Haile, R.W. et al. 1999. The health effects of swimming in ocean water contaminated by storm drain runoff. Epidemiology, 10(4), 355-363. 2009.

Hathaway, J.M., W.F. Hunt, and S. Jadlocki. 2009. Indicator Bacteria Removal in Storm-Water Best Management Practices in Charlotte, North Carolina. Journal of Environmental Engineering. December 2009.

Lager, J.A., W.G. Smith and G. Tchobanoglous. 1977. Catchbasin Technology Overview and Assessment. EPA-600/2-77-051. USEPA. 1977.

Mineart, P. & S. Singh. 1994a. The Value of More Frequent Cleanouts of Storm Drain Inlets. Woodward-Clyde Consultants. Technical Note #35 from Watershed Protection Techniques. 1(3): 129-130. 2000.

Mineart, P. & S. Singh. 1994b. Storm Inlet Pilot Study. Woodward-Clyde Consultants. Alameda County Urban Runoff Clean Water Program. 1994.

Pitt, R. and P. Bissonette. 1984. Bellevue Urban Runoff Program. Summary Report. Characterizing and Controlling Urban Runoff through Street and Sewerage Cleaning. EPA/600/S2-85/038. 1984.

Pitt, R. M. Lilburn, S. Nix, S.R. Durrans, S. Burian, J. Voorhees, and J. Martinson. 2000. Guidance Manual for Integrated Wet Weather Flow (WWF) Collection and Treatment Systems for Newly Urbanized Areas (New WWF Systems). USEPA, Office of Research and Development.

Serdar, D. 1993. Contaminants in Vactor Truck Wastes. Washington State Department of Ecology. Pub No. 93e49.

Skinner, John. F., John Kappeler, Joseph Guzman. 2010. Regrowth of Enterococci & Fecal Coliform in Biofilm: Studies of street gutters and storm drains in Newport Beach, CA, suggest causes for high bacteria levels. June 2010.

United States Environmental Protection Agency (USEPA). 1986. Ambient Water Quality Criteria for Bacteria – 1986. Office of Water Regulations and Standards Criteria and Standards Division. EPA440/5-84-002. January 1986.

United States Environmental Protection Agency (USEPA). 2006. Catch Basin Inserts BMP Fact Sheet. 24 May 2006.

Washington State Department of Ecology (Ecology) 2011a. Washington State Department of Ecology. Effectiveness Study Selection. Stormwater Work Group Published online. https://sites.google.com/site/pugetsoundstormwaterworkgroup/home/selection-of-effectiveness-studies.

Washington State Department of Ecology (Ecology) 2011b. Stormwater Work Group. Recommended Effectiveness Study Topics and Questions. Published online. https://sites.google.com/site/pugetsoundstormwaterworkgroup/home/selection-of-effectiveness-studies/recommended-effectiveness-study-topics-and-questions.

Washington State Department of Ecology (Ecology). 2012a. Water Quality Standards for Surface Waters of the State of Washington. Chapter 173-201A WAC. Publication no. 06-10-091. Amended May 2011. Revised January 2012.

Washington State Department of Ecology (Ecology). 2012b. Water Quality Improvement Projects – Water Cleanup Plans: Listed by County and WRIA. September 2012. Web. January 24 2012.

Washington State Department of Ecology (Ecology). 2012c. Stormwater Management Manual for Western Washington: Volume V Runoff Treatment BMPs. Publication No. 12-10-030. August 2012.

Washington State Department of Health (WSDOH). 2003. Sanitary Survey of North Dyes Inlet. 2003.

Wildey, Robert A. 2006. Stormwater Management Measures and Fecal Indicator Bacteria. Thesis submitted to the University of New Hampshire in Partial Fulfillment of the Requirements for the Degree of Master of Science in Civil Engineering. May 2006.

Winston, R.J., William F. Hung III, D.L. Osmond, W.G. Lord, and M.D. Woodward. 2011. Field Evaluation of Four Level Spreader-Vegetative Filter Strips to Improve Urban Storm-Water Quality. Journal of Irrigation and Drainage Engineering. March 2011.

Wisconsin Department of Natural Resources (WI DNR). 1983. Evaluation of Urban Nonpoint Source Pollution Management in Milwaukee County. 1983.

Final

WHITE PAPER
for
Stormwater Management Program Effectiveness Literature Review

Traditional BMPs Retrofitting

April 2013

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

Prepared by:
Carla B. Milesi
Cardno TEC, Inc.
2825 Eastlake Avenue East, Suite 300
Seattle, Washington 98102

EXECUTIVE SUMMARY

Over the last ten years much attention has been paid to managing or addressing the stormwater runoff issue, with a particular focus on the use of stormwater Best Management Practices (BMPs, Sample et al. 2003). The primary purpose of using BMPs is to protect beneficial uses of water resources through the reduction of storm flow, pollutant loads and pollutant concentrations (WSDOT 2012).

While BMPs have been incorporated into much of the development that occurred over the past decade, development prior to this included little to no runoff treatment or flow control facilities. As a result stormwater from these areas remains unmanaged and is considered a major contributor to stormwater pollution (WERF 2009). One way municipalities are looking to address the issue of stormwater in these urban areas is by retrofitting urban parcels by adding BMPs to provide stormwater treatment and flow control.

BMPs are widely used and their effectiveness is well documented for site-specific applications, however, there is still some uncertainty about their effectiveness over a range of applications and circumstances (Ackerman and Stein 2008). This is due to the fact that BMPs are typically monitored in the field under certain settings, which can make it difficult to generalize or extrapolate the findings. BMP effectiveness models are a tool that are meant to provide a way to predict the pollutant removal ability under varying environmental conditions.

This paper summarizes articles included within the effectiveness study literature database (Ecology 2011a) for the Traditional BMP Stormwater Management Plan (SWMP) topic. In particular, the paper discusses the following Effectiveness Study Topic Null Hypotheses relating retrofitting existing development to include BMPs and the accuracy of model predicted effectiveness of stormwater BMPs.

Hypothesis: Retrofitting using water quality treatment devices does not reduce pollutant loads.

Several studies have looked at the effect retrofitting using BMPs has on pollutants in stormwater. These studies have been conducted both in the field and by using BMP effectiveness models. In general the articles included within the literature database indicate retrofitting using water quality treatment devices can reduce pollutant loads.

Based on a review and summarization of the articles included in the literature database it is recommended that additional studies be completed. Some suggestions include:

1. Perform field studies on existing urban retrofitted BMPs within western Washington to assess their effectiveness at removing a variety of pollutants.
2. Survey local municipalities to assess the feasibility of adding BMPs to existing developed areas. Investigate what sort of incentives landowners would need to take part in a program
3. Conduct a more extensive literature search on which retrofitted BMPs, or combination of retrofitted BMPs, are most effective at removing specific pollutants of interest.
4. Conduct field studies or more extensive literature search on studies that compare model predicted BMP effectiveness to field verified BMP effectiveness.

5. The majority of BMP effectiveness models were developed for agricultural and forested environments. Improve the models by incorporating more urban stormwater runoff data that will provide predicted results that are more practical for use by the stormwater management industry.

TABLE OF CONTENTS

ABBREVIATIONS AND ACRONYMS

BMPs	Best Management Practices
Caltrans	California Department of Transportation
CTR	California Toxics Rule
mgL^{-1}	micrograms per liter
NPDES	National Pollutant Discharge Elimination System
SWMP	Stormwater Management Plan
TMDL	Total Maximum Daily Load
TSS	total suspended solids
USEPA	United States Environmental Protection Agency
WinSlamm	Source Loading and Management Model for Windows

1.0 INTRODUCTION AND PROBLEM STATEMENT

The Stormwater Work Group (SWG) is a group of stakeholders made up of federal, tribal, state and local governments, as well as business, environmental, agriculture and research interests. They are tasked with developing a Stormwater Monitoring and Assessment Strategy for the Puget Sound Region. The Effectiveness Study Selection Subgroup (subgroup) was formed by the SWG in October 2010 to help with the process of identifying potential effectiveness studies to be conducted during the next National Pollutant Discharge Elimination System (NPDES) municipal stormwater permit cycle. The subgroup developed a list of 22 ranked effectiveness study topics and associated questions. To help answer these questions, an Effectiveness Study Literature Review was conducted and a literature database was created (Ecology 2011a). The literature database contains over 300 publications, including journal articles, books, public information flyers and agency reports.

1.1 SCOPE OF THIS PAPER

This paper aims to summarize the publications within the effectiveness literature database (Ecology 2011a) that related to the ranked effective study and the Stormwater Management Plan (SWMP) Traditional BMPs topic #10. The paper specifically address the following Effectiveness Study Topic Null Hypothesis relating to retrofitting areas to include BMPs and the accuracy of model predicted effectiveness of stormwater BMPs.

Null Hypothesis: Retrofitting using water quality treatment devices does not reduce pollutant loads.

- Which combinations of retrofit BMPs in a basin are most effective at reducing pollutants to receiving waters?
- To what extent does retrofitting, using water quality treatment devices, reduce urban stormwater pollution to receiving water bodies?
- Once installed, do model predicted quantities of stormwater controls in a basin reduce stormwater impacts enough to support the receiving water’s designated beneficial uses?

Funding for this white paper was provided the Washington State Department of Ecology.

1.2 PROBLEM STATEMENT

Across the United States, unmanaged stormwater runoff contributes to serious pollution and flooding issues in streams, rivers, lakes, and other receiving water bodies. In Washington State it is estimated that one third of all of the polluted waters in the state are polluted by unmanaged stormwater runoff (King County 2010).

Over the last 10 years much attention has been given to managing or addressing the stormwater runoff issue, with a particular focus on the use of stormwater Best Management Practices (BMPs, Sample et al. 2003). The primary purpose of using BMPs is to protect beneficial uses of water resources through the reduction of pollutant loads and concentrations (WSDOT 2012).

While a large focus has been on addressing stormwater from new developments and incorporating BMPs into the design of new projects, stormwater from existing urban areas often remains unmanaged and is considered a major contributor to stormwater pollution (WERF

2009). One way municipalities are looking to address the issue of stormwater issues in these urban areas is by retrofitting urban parcels by adding BMPs to treat the stormwater and provide flow control.

Despite the widespread use of BMPs there is still some uncertainty over their effectiveness over a range of applications and circumstances (Ackerman and Stein 2008). This is due to the fact that BMPs are typically monitored in the field under certain settings, and relying on empirical evaluation can make it difficult to generalize or extrapolate the findings. BMP effectiveness models are a tool that is meant to provide a way to predict the pollutant removal ability under varying environmental conditions.

2.0 LITERATURE SUMMARY AND TALKING POINTS

The Traditional BMP null hypotheses and ranked questions for Topic #10 are presented in Table 1. Publications from the database of effectiveness study literature (Ecology 2011a) were reviewed to research the null hypotheses and address the ranked questions. This section presents a summary of the publications reviewed and, where possible, answers to the ranked questions.

Table 1 Ranked Effectiveness Questions for Traditional BMPs Topic 10 (Ecology 2011b)

Rank[1]	Null Hypothesis	Questions
10	Retrofitting using water quality treatment devices does not reduce pollutant loads.	• Which combinations of retrofit BMPs in a basin are most effective at reducing pollutants to receiving waters?
		• To what extent does retrofitting using water quality treatment devices reduce urban stormwater pollution to receiving water bodies?
		• Once installed, do model predicted quantities of stormwater controls in a basin reduce stormwater impacts enough to support the receiving water's designated beneficial uses?

Notes:

1 Rank assigned by the SWG.

2.1 DOES RETROFITTING USING WATER QUALITY TREATMENT DEVICES REDUCE POLLUTANT LOADS?

A few studies included in the literature database looked at the effect of retrofitting using BMPs on pollutants in stormwater. The California Department of Transportation (CALTRANS) constructed five Austin-style sand filters within existing maintenance yards and park-and-ride facilities in Los Angeles and San Diego (Barrett 2003). The sand filters were analyzed for a variety of common stormwater pollutants, including total suspended solids (TSS), total and dissolved copper, lead and zinc, nutrients, total petroleum hydrocarbons, and fecal coliform. The concentrations of TSS and particle associated pollutants in the effluent was consistently low, and significant removal of dissolved constituents was seen at higher influent concentrations (Barrett 2003).

Another study conducted in Boston used the Source Loading and Management Model for Windows (WinSLAMM) to evaluate the potential reductions of phosphorus loading by retrofitting two developed sites with various arrangements of wet detention ponds and biofiltration cells (Hurley and Forman 2011). The sites drained to the Charles River which has a phosphorus Total Maximum Daily Load (TMDL) that was issued in 2007. The TMDL requires a 65 percent reduction in phosphorus loading from industrial, commercial, institutional, and high density residential land uses in the watershed (Hurley and Forman 2011). The model indicated that the 65 percent reduction goal could be met for the developed sites if they were retrofitted with a detention pond or biofilter than covered 5 percent of the site's area and received 100 percent of the runoff (Hurley and Forman 2011).

A final study included in the literature database looked at the effects of retrofitting an existing BMP in Austin, Texas to improve the pollutant removal ability. In this study an extended detention basin was retrofitted to provide batch treatment rather than flow through treatment of stormwater runoff. The USEPA reports that the likely TSS removal efficiency for extended detention basins is between 50-95 percent (Shamma et al. 2002). However, additional literature indicates the removal efficiency is closer to 60 or 70 percent (Middleton and Barrett 2008). The extended detention basin that was retrofitted to a batch treatment system had TSS removal efficiencies of 91 percent, even with relatively low influent concentrations (Middleton and Barrett 2008). In addition there were statistically significant reductions in the concentrations of total copper, lead, and zinc, chemical oxygen demand, total phosphorus, nitrate and nitrite, and total Kjeldahl nitrogen. Overall the retrofitted or modified basin had substantially better pollutant removal than the conventional extended detention basins (Middleton and Barrett 2008).

An additional study no included in the literature database was conducted by King County, Ecology, City of Kirkland, and WSDOT. This study looked at seven mitigation scenarios within the Juanita Creek basin and used the Hydrologic Simulation Program-Fortran (HSPF) model to evaluate their potential to improve flow and water quality. The study found that one mitigation scenario, which included a combination of rain gardens and dry/wet ponds, greatly reduced annual loads from existing and future unmitigated conditions for TSS, dissolved and total copper, nitrate-nitrite, total nitrogen, orthophosphate, and total phosphorus (King County et al 2012). The annual loads of ammonia did increase due to decaying organic matter.

In general the articles included within the literature database indicate retrofitting using water quality treatment devices can reduce pollutant loads. The subsections below summarize the publications within the effectiveness literature database that related to the Traditional BMP Ranked List of Effectiveness Topic #10 and Potential Questions approved by the Stormwater Work Group. These summaries are meant to assist local stormwater management program staff in gaining a better understanding of the topic of retrofit BMPs and models that predict BMP effectiveness. In general, retrofitting developed areas to install BMPs reduces stormwater pollution and there don’t appear to be enough studies to determine if model predicted quantities of stormwater control reduce stormwater impacts.

2.1.1 Question: Which combinations of retrofit BMPs in a basin are most effective at reducing pollutants to receiving waters?

There were no studies found in the effectiveness literature database that assessed various combinations of retrofit BMPs to compare their pollutant removal ability. A study completed by King County, Ecology, City of Kirkland, and WSDOT used a model to assess the effectiveness of seven different mitigation scenarios, presented in Table 2 (King County et al. 2012). The goal of the mitigation is to restore water quality and flow conditions supportive of aquatic beneficial uses. The ECY08 scenario was the best performing mitigation scenario and the only one that achieved this goal. This scenario included a basin-wide retrofit using a combination of rain gardens and combined detention/wet ponds.

Table 2. Flow and water quality mitigation scenarios (King County et al. 2012).

Scenario	Description
LEVEL2	Future land use with King County Level 2 stormwater ponds applied basin-wide.
LID40	Future land use with 40% total impervious area (TIA) captured by rain gardens.
LID80	Future land use with 80% total impervious area (TIA) captured by rain gardens.
ECY08	Ecology-proposed matching durations to 8% of the 2-year forested to the 50-year forested, using a combination LID80 and stormwater detention ponds stacked on basic wetponds applied basin wide.
LID40+	Combination of LID40 throughout the basin and King County Level 2 stormwater detention ponds stacked on basic wetponds in three catchments.
LVL2WET	Future land use with King County Level 2 stormwater detention ponds stacked on basic wetponds applied basin-wide.
CISTERNS	Future land use where roof area runoff from a mild wet season of rainfall is captured then released July-Sept each calendar year at a constant rate.

2.1.2 Question: To what extent does retrofitting using water quality treatment devices reduce urban stormwater pollution to receiving water bodies?

Retrofitting urban parcels by adding BMPs is one way municipalities are looking to manage the issue of stormwater runoff in already developed areas. CALTRANS retrofitted five maintenance yards or park-and-ride facilities by constructing Austin-style sand filters (Barrett 2003). The sand filters were analyzed for a variety of common stormwater pollutants, including TSS, total and dissolved copper, lead and zinc, nutrients, total petroleum hydrocarbons, and fecal coliform. The retrofit sand filters removed 90 percent of TSS concentrations, with an average effluent concentration of 7.8 mgL^{-1} (+/- 1.2 mgL^{-1}) (Barrett 2003). Removals of total copper, total lead, and total zinc were 50 percent, 87 percent, and 80 percent, respectively. In addition, sand filters are generally expected to have limited removal ability for dissolved constituents, yet for dissolved copper and other metals the data from this study indicate significant reduction in concentration when the influent concentrations were sufficiently high (Barrett 2003).

As noted in Section 2.1, a study in Boston used the model WinSLAMM to evaluate the potential phosphorus reductions achieved by retrofitting two developed sites with various arrangements of wet detention ponds and biofiltration cells (Hurley and Forman 2011). The sites drained to the Charles River which has a TMDL which requires a 65 percent reduction in phosphorus loading from industrial, commercial, institutional, and high density residential land uses in the watershed (Hurley and Forman 2011). The model indicated that the 65 percent reduction goal could be met for the developed sites if they were retrofitted with a detention pond or biofilter than covered five percent of the site's area and received 100 percent of the runoff (Hurley and Forman 2011).

One study also looked at the effects of retrofitting an existing BMP in Austin, Texas to improve the pollutant removal ability. In this study an extended detention basin was retrofitted to provide batch treatment rather than flow through treatment of stormwater runoff. The retrofitted batch treatment detention basin had TSS removal efficiencies of 91 percent, whereas the likely TSS removal for a traditional extended detention basin is closer to 60 or 70 percent (Middleton and Barrett 2008). In addition the retrofitted detention basin showed statistically significant reductions in total copper, lead, and zinc, chemical oxygen demand, total phosphorus, nitrate and nitrite, and total Kjeldahl nitrogen (Middleton and Barrett 2008).

2.1.3 Question: Once installed, do model predicted quantities of stormwater controls in a basin reduce stormwater impacts enough to support the receiving water's designated beneficial uses?

Several studies included in the literature database used models to evaluate the effectiveness of BMPs at reducing pollutant loads or pollutant concentrations. However, only one study was found that looked at how closely the model predicted stormwater controls matched the effectiveness of those BMPs once installed in the field. There were no studies found within the effectiveness study literature database that looked at the effectiveness of retrofit BMPs and providing flow control.

One study conducted at two sites in Australia focused on the sediment removal effectiveness of grass swales and filter strips and verifying the TRAVA, which is a model of sediment behavior in grass. The difference between the predicted and measured sediment loading rates from the two sites was +/- 25 percent and +/- 50 percent for the filter strip, and +/- 17 percent and +/- 11 percent for the grass swales (Deletic and Fletcher 2005). Overall, the study determined that TRAVA is a reliable tool to predict the performance of filter strips and swales at removing sediments from stormwater runoff. The study did state that most models of grass filter performance have been developed for agricultural and forested environments and relatively few field studies have been completed on grass filter performance in an urban environment.

A study conducted by Ackerman and Stein (2008) used a model to assess how well two types of BMPs reduced pollutant runoff from a generic one-acre land parcel. The BMP types included a retention facility and a flow through swale and the model looked at removal of solids and total copper in terms of concentration, load reduction, and frequency of exceedance of the California Toxics Rule (CTR). The model predicted copper and solids reductions of over 60 percent for both BMPs; however, the effectiveness was reduced during larger storms or during wet years (Ackerman and Stein 2008). Both BMPs all reduced the frequency of the effluent event mean concentration exceeding the CTR (Ackerman and Stein 2008).

As outlined in Section 2.1, another study conducted in Boston used the WinSLAMM model to evaluate the potential reductions of phosphorus loading by retrofitting two developed sites with various arrangements of wet detention ponds and biofiltration cells (Hurley and Forman 2011). The sites drained to the Charles River which has a phosphorus TMDL that was issued in 2007. The TMDL requires a 65 percent reduction in phosphorus loading from industrial, commercial, institutional, and high density residential land uses in the watershed (Hurley and Forman 2011). The model indicated that the 65 percent reduction goal could be met for the developed sites of they were retrofitted with a detention pond or biofilter than covered five percent of the site's area and received 100 percent of the runoff (Hurley and Forman 2011).

As noted above, there was only one study found in the literature database that compared how well model predicted BMP effectiveness matched BMP effectiveness once installed in the field. And the study noted that few models have been developed that specifically look at BMP effectiveness in urban environments. However, assessing the accuracy of model predicted BMP effectiveness, both for stormwater quality and quantity issues, seems to be an important topic that would be beneficial to investigate more thoroughly.

3.0 CONCLUSIONS AND RECOMMENDATIONS

Stormwater often contains oil, chemicals, and toxic metals and unmanaged stormwater can have devastating effects on the quality of lakes, streams and other water bodies. In Washington State stormwater is the leading contributor to water quality pollution in urban waterways. BMPs are regularly incorporated and often required with new developments, however, existing developments with traditional BMPs are a major contributor to stormwater pollution and often do not have adequate stormwater control or treatment measures (WERF 2009). Retrofitting these existing developments by installing BMPs is one way municipalities are looking to address issues with stormwater pollution.

Retrofitting existing developed areas to include BMPs can be difficult to accomplish due to a variety of factors including cost, lack of space and existing drainage or site conditions. In addition, despite the relatively widespread use of BMPs and their known effectiveness on site-specific installations, there is still some uncertainty over their effectiveness over a range of applications and circumstances (Ackerman and Stein 2008). This is due to the fact that BMPs are typically monitored in the field under certain settings, which can make it difficult to generalize or extrapolate the findings. BMP effectiveness models are one tool that can be used to predict BMP effectiveness under varying environmental conditions. These models can be valuable in helping to assess effectiveness as well as the cost versus benefit of various types and sizes of BMPs that may be appropriate for retrofits.

Based on a review and summarization of the articles included in the literature database it is recommended that additional studies be completed to further investigate the benefits of retrofitted BMPs and BMP effectiveness models. A few of these recommendations include:

1. Perform field studies on existing urban retrofitted BMPs within western Washington to assess their effectiveness at removing a variety of pollutants.
2. Survey local municipalities to assess the feasibility of adding BMPs to existing developed areas. Investigate what sort of incentives landowners would need to take part in a program.
3. Conduct a more extensive literature search on which retrofitted BMPs, or combination of retrofit BMPs, are most effective at removing specific pollutants of interest.
4. Conduct field studies or more extensive literature search on studies that compare model predicted BMP effectiveness to field verified BMP effectiveness.
5. The majority of BMP effectiveness models were developed for agricultural and forested environments. Improve the models by incorporating more urban stormwater runoff data that will provide predicted results that are more practical for use by the stormwater management industry.

4.0 REFERENCES

Ackerman, Drew and Eric D. Stein. 2008. Evaluating the Effectiveness of Best Management Practices Using Dynamic Modeling. Journal of Environmental Engineering. Vol. 134, No. 8: pp 628-639.

Barrett, Michael E. 2003. Performance, Cost, and Maintenance Requirements of Austin Sand Filters. Journal of Water Resources Planning and Management. Vol. 129, No. 3: pp 234-242.

Deletic, Ana and Tim D. Fletcher. 2005. Performance of Grass Filters used for Stormwater Treatment – A Field and Modelling Study. Department of Civil Engineering. Monash University. Melbourne, Australia.

Hurley, Stephanie E. and Richard T.T. Forman. 2011. Stormwater ponds and biofilters for large urban areas: Modeled arrangements that achieve the phosphorus reduction target for Boston's Charles River, USA. Ecological Engineering. Vol. 37, No. 6: pp 850-863.

King County Department of Natural Resources and Parks, Washington State Department of Ecology, City of Kirkland, Washington State Department of Transportation. 2012. Stormwater Retrofit Analysis and Recommendations for the Juanita Creek Basin in the Lake Washington Watershed.

King County Stormwater Services Section (King County). 2010. Stormwater runoff pollution and how to reduce it. 2010. Web. http://www.kingcounty.gov/environment/waterandland/stormwater/introduction/stormwater-runoff.aspx

Middleton, John R. and Michael E. Barrett. 2008. Water Quality Performance of a Batch-Type Stormwater Detention Basin. Water Environment Research, Volume 80, Number 2.

Sample, D.J., J.P. Heaney, L.T. Wright, C.Y. Fan, F.H. Lai, and R. Field. 2003. "Costs of best management practices and associated land for urban stormwater control." Journal of Water Resources Planning and Management. 129(1), 59-68.

Shamma, Y. Zhu, D.Z,. Gyurek, L.L., and Labatiuk, C.W. 2002. Effectiveness of Dry Ponds for Stormwater Total Suspended Solids Removal. Canadian Journal of Civil Engineering, 29, 316-324. 2002.

United States Environmental Protection agency (USEPA). 2011. Stormwater Retrofit Techniques for Restoring Urban Drainages in Massachusetts and New Hampshire. Small MS4 Permit Technical Support Document. April 2011.

Washington State Department of Ecology (Ecology) 2011a. Washington State Department of Ecology. Effectiveness Study Selection. Stormwater Work Group Published online. https://sites.google.com/site/pugetsoundstormwaterworkgroup/home/selection-of-effectiveness-studies.

Washington State Department of Ecology (Ecology) 2011b. Stormwater Work Group. Recommended Effectiveness Study Topics and Questions. Published online. https://sites.google.com/site/pugetsoundstormwaterworkgroup/home/selection-of-effectiveness-studies/recommended-effectiveness-study-topics-and-questions.

Washington State Department of Transportation. 2012. Stormwater Management Manual for Western Washington. Publication Number 12-10-030. August 2012.

Water Environment Research Foundation (WERF).2009. Stormwater BMP Concepts and Policies. 2009. Web. February 1 2012.

FINAL

WHITE PAPER
for
Stormwater Management Program Effectiveness Literature Review

Traditional BMPs
Filter Strips

April 2013

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

Prepared by:
Carla B. Milesi
Cardno TEC, Inc.
2825 Eastlake Avenue East, Suite 300
Seattle, Washington 98102

EXECUTIVE SUMMARY

Vegetative filter strips (VFS) are best management practices (BMPs) that are designed to treat sheet flow and are often used along roads and highways. They are effective at reducing total suspended solids (TSS) as well as concentrations of particulate pollutants (Schmitt et al. 1999) and are an approved BMP by the Washington State Department of Ecology (Ecology) for the treatment of TSS (WSDOT 2011). The effectiveness of VFS is dependent on several factors, including width, slope, vegetated cover, flow rate and whether there is an equal flow distribution across the length of the VFS.

This paper summarizes articles included within the effectiveness study literature database (Ecology 2011a) for the Traditional BMP Stormwater Management Plan (SWMP) topic. In particular, the paper discusses the following Effectiveness Study Topic Null Hypothesis relating to how the VFS width and other design aspects affect its ability to remove sediments and other pollutants.

Hypothesis: Reducing the size of a filter strip does not alter its effectiveness at reducing pollutant concentrations.

A number of studies have been conducted that look at how the size, particularly the width, of a VFS affects its effectiveness at reducing pollutant concentrations. These studies show varied sediment and pollutant removal results at different widths, slopes, and grass types. However, most of the studies indicate the width of the filter strip is a significant factor affecting its ability to remove pollutants and reducing the size of a filter strip can alter its effectiveness at reducing pollutant concentrations. In addition, based on the available studies the filter strips that showed good removal of sediments were at a minimum five meters (16.4 feet) wide.

Based on a review and summarization of the articles included in the literature database it is recommended that additional studies or literature searches be completed. Some suggestions include:

1. Performance of filter strips generally decreases with increasing flow rates (Magette et al. 1989). Conduct effectiveness studies of filter strips in Western Washington where light to moderate rainfall and flow intensities may show increased effectiveness of narrower filter strips.
2. Conduct a literature search that is specific to western Washington to assess current widths and effectiveness of filter strips employed in Western Washington.
3. Perform local field studies on filter strips of varying widths, slopes, and vegetation to determine if there is an optimal combination.
4. Construct and perform field studies on a filter strip that is narrower than eight feet Washington State Department of Transportation (WSDOT) minimum to determine if it meets Ecology's guidelines for basic treatment of TSS.

[This page intentionally left blank.]

TABLE OF CONTENTS

List of Tables

ABBREVIATIONS AND ACRONYMS

VFS	vegetative filter strips
BMPs	Best Management Practices
TSS	total suspended solids
µm	micrometers
Ecology	Washington State Department of Ecology
NPDES	National Pollutant Discharge Elimination System
WSDOT	Washington Department of Transportation
SWMP	Stormwater Management Plan

1.0 INTRODUCTION AND PROBLEM STATEMENT

The Stormwater Work Group (SWG) is a group of stakeholders made up of federal, tribal, state and local governments, as well as business, environmental, agriculture and research interests. They are tasked with developing a Stormwater Monitoring and Assessment Strategy for the Puget Sound Region. The Effectiveness Study Selection Subgroup (subgroup) was formed by the SWG in October 2010 to help with the process of identifying potential effectiveness studies to be conducted during the next National Pollutant Discharge Elimination System (NPDES) municipal stormwater permit cycle. The subgroup developed a list of 22 ranked effectiveness study topics and associated questions. To help answer these questions, an Effectiveness Study Literature Review was conducted and a literature database was created (Ecology 2011a). The literature database contains over 300 publications, including journal articles, books, public information flyers and agency reports.

1.1 SCOPE OF THIS PAPER

This white paper aims to summarize the publications within the effectiveness study literature database (Ecology 2011a) that related to the ranked effectiveness study and Storm Water Management Plan topic #12: Traditional BMPs. The paper specifically addresses the following Null Hypothesis relating to how size may affect the effectiveness of vegetative filter strips.

Null Hypothesis: Reducing the size of a filter strip does not alter its effectiveness at reducing pollutant concentrations.

- Are existing sizing criteria for vegetative filter strips (based on bioswales) overly conservative?
- Which combinations of length, width, slope, soil types and vegetation types result in greatest removal of sediment by vegetative filter strips?

Funding for this white paper was provided the Washington State Department of Ecology (Ecology).

1.2 PROBLEM STATEMENT

During the 2004 National Water Quality Inventory it was determined that eight percent of streams, seven percent of lakes, and 12 percent of estuaries in the United States were impaired by urban storm water (USEPA 2009). In the National Water Quality Inventory 1990 Report to Congress it was estimated that roughly 30 percent of identified cases of water quality impairment were attributable to urban storm water runoff.

Vegetative filter strips (VFS) are best management practices (BMPs) that are designed to treat storm water that sheet flows directly off of pavement. They are gently sloping and densely vegetated and remove pollutants from runoff by filtering, slowing, and providing some infiltration of stormwater (USEPA 2012). They are widely used in the United States to treat runoff in urban areas (Gharabaghi et al. 2006), especially along roads and highways. They are effective at reducing total suspended solids as well as concentrations of particulate pollutants, but are less effective at reducing soluble pollutants (Schmitt et al. 1999). In Washington State, filter strips are approved for “basic treatment” which is the designation used for BMPs that are able to achieve a goal of 80 percent removal of total suspended solids (TSS) (WSDOT 2011). They can also be used as part of a treatment train for removal of phosphorus and dissolved metals.

The Washington State Department of Transportation (WSDOT) Highway Runoff Manual (2011) outlines the following sizing requirements for vegetative filter strips:

- The greatest flow path from the contributing area delivering sheet flow to the vegetated filter strip should not exceed 150 feet in length.
- The slope of the filter strip should be between 2 and 33 percent.
- The width[1] of the vegetated filter strip is determined by the residence time of the flow though the vegetated filter strip. A nine-minute residence time is used to calculate vegetated filter strip width. A minimum width of eight feet is recommended in order to ensure long term effectiveness of the vegetated filter strip will occur.
- Filter strips may be planted with a combination of grass and native vegetation such as small shrubs. Grasses should be selected that can withstand relatively high-velocity flows as well as wet and dry periods. The addition of native shrubs can provide soil stability and more effective runoff treatment.

[1] Width of the filter strip refers to the dimension parallel to the flow path.

2.0 LITERATURE SUMMARY AND TALKING POINTS

The Traditional BMP null hypotheses and ranked questions for Topic #12 are presented in Table 1. Publications from the database of effectiveness study literature (Ecology 2011a) were reviewed to research the null hypotheses and address the ranked questions. This section presents a summary of the publications reviewed and, where possible, answers to the ranked questions.

Table 1 Ranked Effectiveness Questions for Traditional BMPs Topic 12 (Ecology 2011b)

Rank[1]	Null Hypothesis	Questions
12	Reducing the size of a filter strip does not alter its effectiveness at reducing pollutant concentrations.	• Are existing sizing criteria for vegetative filter strips (based on bioswales) overly conservative?
		• Which combinations of length, width, slope, soil types and vegetation types result in greatest removal of sediment by vegetative filter strips?

Notes:
1 Rank assigned by the SWG.

2.1 DOES REDUCING THE SIZE OF A FILTER STRIP ALTER ITS EFFECTIVENESS AT REDUCING POLLUTANT CONCENTRATIONS?

A number of studies included in the literature database have looked at the effect of size of VFS on their ability to reduce pollutant concentrations in runoff. One study conducted by Barrett et al. (1998) looked at two grassed medians between divided highways that had different length, width, slope, drainage area, vegetation cover, and highway traffic load. The water quality results showed similar reductions in pollutants between the two medians. However, most studies found the size of a VFS, particularly its width, does have an effect on its pollutant removal ability.

One field study was conducted on vegetated filter strips in Aberdeen, Scotland and Brisbane Australia. The study saw an exponential decrease of TSS along the width of the filter strip (Deletic and Fletcher 2005).

Another study compared two pairs of level spreader vegetated filter strips in North Carolina. Two filter strips that were 7.6 meters (25 feet) wide were paired with two filter strips that were 15.2 meters (50 feet) wide. The study showed that all of the filter strips reduced TSS concentrations significantly and substantially; however, both of the 15.2 meter filter strips had greater TSS reductions than the 7.6 meter filter strips (Winston et al. 2011). The 15.2 meter wide filter strips had 75 percent and 67 percent TSS reductions while the 7.6 meter wide filter strips had TSS reductions of 51 and 65 percent, with one of the 15.2 meter wide filter strips having significantly lower TSS concentrations than its paired 7.6 meter wide filter strip (Winston et al. 2011).

A series of field experiments conducted in Ontario saw similar results. A total of 10 VFS plots with widths ranging from 2.5 to 20 meters were constructed at three locations. The results showed that TSS removal increased from 50 to 98 percent as the width of the filter strip increased from 2.5 meters to 20 meters (Gharabaghi et al. 2006). In addition the study indicated the width of the filter strip is a significant factor affecting the ability of the filter strip to remove TSS (Gharabaghi et al. 2006).

Lastly a study completed by Schmitt et al. (1999) concluded that filter strips of 7.5 and 15 meters in width can reduce sediments by 76 and 93 percent, respectively, and Abu-Zreig et al. (2003) found that the ability of a vegetated filter strip to remove sediments varied directly with the width of the filter strip. In general the articles included within the literature database indicate reducing the size of a filter strip is likely to alter its effectiveness at reducing pollutant concentrations.

The subsections below summarize the publications within the effectiveness literature database that related to the Traditional BMP Ranked List of Effectiveness Topic #12 and Potential Questions approved by the Stormwater Work Group. These summaries are meant to assist local stormwater management program staff in gaining a better understanding of the topic of VFS and how their design can impact their effectiveness. In general, it was found that filter strips greater than 5 meters in width have better pollutant removal results.

2.1.1 Question: Are existing sizing criteria for vegetative filter strips (based on bioswales) overly conservative?

According to the WSDOT Highway Runoff Manual (2011) the width of a filter strip should be designed using a function of:

- Slope,
- Length of the contributing area,
- Design flow rate,
- Design flow velocity, and
- Residence time of the flow through the filter strip.

A nine-minute residence time is used when calculating the width. At a minimum, a filter strip width of eight feet is recommended in order to ensure long term effectiveness (WSDOT 2011).

As outlined in Section 2.1, a number of studies included in the literature database have looked at the how the size of a filter strip may affect its ability to reduce pollutant concentrations in runoff. A series of field experiments conducted in Ontario, Canada looked at 10 VFS plots with widths ranging from 2.5 to 20 meters. The results showed that about 50 percent of sediments were removed within the first 2.5 meters, with an additional 25 to 45 percent within the next 2.5 meters (Gharabaghi 2006). Almost all of the large sediment particles (larger than 40 micrometers [µm]) were captured within the first 5 meters; however, the remaining smaller particles were very difficult to remove. Overall, Gharabaghi et al.(2006) found that the first five meters (16.4 feet) are critical to the removal of suspended sediments.

Other studies suggest wider filter strips may be needed if trying to meet the 80 percent removal goal set by Ecology for Basic Treatment BMPs. A study of two pairs of level spreader VFS in North Carolina found that filter strips 7.6 meters wide removed 51 and 65 percent of TSS concentrations while filter strips 15.2 meters wide removed 75 and 67 percent of TSS concentrations (Winston et al. 2011). Chaubey et al. (1994) saw a 66 percent removal rate for TSS and 27 percent removal rate for total phosphorus with a 4.6 meter wide filter strip and Line and Hunt (2009) found that a 7.3 meter wide filter strip removed 83 percent of TSS and 48 percent of total phosphorous.

Since the WSDOT sizing criteria uses a series of calculations to determine the width of a filter strip, it is difficult to know the average size of filter strips in Washington and determine if this criterion is overly conservative. However, based on the available studies, the WSDOT filter strip minimum width of eight feet does not seem to be overly conservative since the filter strips that showed good removal of sediments were five meters (16.4 feet) or wider. It should be noted, however, that the performance of a filter strip tends to decrease as flow rates increase (Magette et al. 1989). None of the studies within the literature database were conducted in western Washington, so narrower filter strips may perform better here where rainfall and associated stormwater runoff is typically light to moderate intensity. Additionally, as noted by Winston et al. (2011) few studies have documented the effectiveness of filter strips at removing pollutants from urban runoff. Most studies have instead looked at agricultural runoff. Local field studies should be conducted to more accurately determine if the current sizing criteria are overly conservative.

2.1.2 Question: Which combination of length, width, slope, soil types and vegetation types result in the greatest removal of sediment by vegetative filter strips?

Several studies included in the literature database looked at how width, slope, and vegetation types affect the ability of a filter to remove sediments and other pollutants. However, these studies looked at these factors independently and did not examine what combination were the most effective at removing sediment or other pollutants.

No studies were obtained through the literature database that looked at how different lengths or soil types affect the pollutant removal ability; however, the *Vegetated Filter Strip Low Impact Development Fact Sheet* (Godwin et al. 2011) put out by the Oregon Sea Grant Extensions found online did provide some recommendations for soil type.

Length

No studies found in the literature database discussed how the length of the filter strip may affect its pollutant removal ability.

Width

A number of studies have looked at whether the width (flow path length) of a filter strip affects how effective it is at removing suspended sediments and other pollutants. Gharabaghi et al. (2006) observed that the first five meters (16.4 feet) of a filter strip plays a large role in removal of suspended sediments, capturing more than 95 percent of particles larger than 40 μm. Other studies indicate wider filter strips may be needed to achieve desired pollutant removals. A study completed by Schmitt et al. (1999) concluded that filter strips of 7.5 and 15 meters in width can reduce sediments by 76 and 93 percent, respectively while a study of two pairs of level spreader VFS in North Carolina found that filter strips 7.6 meters wide removed 51 and 65 percent of TSS concentrations while filter strips 15.2 meters wide removed 75 and 67 percent of TSS concentrations (Winston et al. 2011).

Slope

A study conducted by Correll (1996) suggests filter strips will not work effectively if the slope is greater than 5 percent; however, results from a study done by Bren et al. (1997) showed excellent removal of TSS in filter strips with slopes of up to 23 percent as long as there was uniform flow distribution. Arnold et al. (1993) and Field et al. (2007) found that the ideal slope for filter strips are five percent or less, and slopes up to 15 percent are acceptable but should not be encouraged.

A study done more recently at Washington State University (WSU) (Navickis-Brasch 2011) looked at 45 sites in Eastern Washington. This study found that VFS with a slope up to 33 percent still allow for dispersed flow and meet the treatment and flow control goals, depending vegetative cover and soil characteristics (Navickis-Brasch 2011). The slope of the VFS alone was not found to be statistically significant to concentrated flows and erosion, rather low vegetation coverage and a high sand content in the soil were found to have the strongest correlation to the severity of embankment erosion (Navickis-Brash 2011). The WSDOT Highway Runoff Manual (2011) recently increased their maximum slope criteria from 15 to 33 percent and calls for filter strips to have a slope between 2 and 33 percent.

Soil Type

As with the filter strip length, no studies were found in the literature database that discussed optimal soil type. A study conducted at WSU did find that soils with a high percentage of sand had greater erosion severity on steeper slopes (Navickis-Brasch 2011). In addition, a Vegetated Filter Strip Low Impact Development Fact Sheet put out by the Oregon Sea Grant Extension listed some recommendations. The fact sheet indicated the top 18 inches of soil should be amended with an ideal infiltration rate of between ½ inch and 12 inches per hour (Godwin et al. 2011). In addition, it recommended a soil mix of 60 percent sandy loam and 40 percent compost (Godwin et al. 2011).

Vegetation Type

In general, filter strips with denser vegetation have been found to be better at reducing embankment erosion and more efficient at removing sediments and pollutants from runoff. The WSDOT Highway Runoff Manual (2011) states filter strips in Washington should be designed to include grass that can withstand relatively high velocity flows as well as both extended wet and dry periods. The addition of native vegetation such as small shrubs may help with pollutant removal effectiveness by providing root penetration into the subsoil and increasing infiltration.

One study conducted by Gharabaghi et al. (2006) looked at how various grass mixes affected the effectiveness of filter strips in Ontario, Canada. The filter strips were planted with one of three types of mixtures: Type A—an equal mixture of Perennial Ryegrass, Kentucky Bluegrass and Reed Canary grass; Type B—a mixture of Birdsfoot Trefoil and Creeping Red Fescue; and Type C—existing native vegetation, undisturbed for many years, consisting of native species including wild oat, quack, tall fescue grass and dandelions. The study found that Type B significantly increased the concentration based removal rate when compared to Type A and Type C.

3.0 CONCLUSIONS AND RECOMMENDATIONS

Vegetated filter strips have proven to be an effective BMP at removing suspended sediments from stormwater runoff. However, studies show the level of effectiveness varies depending on the width, slope, vegetated cover, and flow rate. A uniform or equal distribution of flow across the filter strip is also critical to its effectiveness no matter the size or design.

While a number of studies have been conducted that look at how various design aspects affect the pollutant removal ability of filter strips, there were no articles found in the literature database that looked at the optimal combination of filter strip length, width, slope, and vegetation. Additionally, as noted by Winston et al. (2011) few studies have documented the effectiveness of filter strips at removing pollutants from urban runoff. Most studies have instead looked at agricultural runoff. Therefore, it is recommended that additional studies be considered to better understand how different design combinations may affect the ability of a filter strip to treat urban runoff. A few of these recommendations include:

1. Performance of filter strips generally decreases with increasing flow rates (Magette et al. 1989). Conduct effectiveness studies of filter strips in western Washington where light to moderate rainfall and associated runoff intensities may show increased effectiveness of narrower filter strips.
2. Conduct a literature search that is specific to Western Washington to assess current widths and effectiveness of filter strips employed in Western Washington.
3. Perform local field studies on filter strips of varying widths, slopes, and vegetation to determine if there is an optimal combination.
4. Construct and perform field studies on a filter strip that is narrower than 8 foot WSDOT minimum to determine if it meets Ecology's guidelines for basic treatment of TSS.

4.0 REFERENCES

Abu-Zreig M., Rudra R.P., Whiteley H.R., Lalonde M.N., and Kaushik N.K. 2003. Phosphorus Removal in Vegetated Filter Strips. Journal of Environmental Quality. 32:613-619.

Arnold, J.A. (ed.), D.E. Line, S.W. Coffey, and J. Spooner. 1993. Stormwater Management Guidance Manual. North Carolina Cooperative Extension Service and North Carolina Division of Environmental Management.

Barrett, M.E., Jenks, R., and Aubourg, D., 1998. An Assessment of the Availability of Pollutant Constituents on Road Surfaces. The Science of the Total Environment. 209: (2-3), 243-254.

Bren, L., Dyer, F., Hairsine, P., Riddiford, J., Siriwardhena, V., Zierholz, C. 1997. Controlling Sediment and Nutrient Movement within Catchmants. Vol. 97, No. 9. Cooperative Research Centre for Catchment Hydrology.

Chaubey I., Edward D.R., Daniel T.C., Moore Jr. P.A., and Nichols D.J. 2004. Effectiveness of Vegetative Filter Strips in Reducing Transport of Land-applied Swine Manure Constituents. Soil Science Society of America Journal. 60: 246-251.

Correll, D.L. 1996. Buffer zones and water quality protection: general principles. In: Buffer Zones: Their Processes and Potential in Water Protection. pp 7-20.

Deletic, Ana and Tim D. Fletcher. 2005. Performance of Grass Filters used for Stormwater Treatment – A Field and Modeling Study. Department of Civil Engineering. Monash University. Melbourne, Australia.

Field, R., T.N. Tafuri, S. Muthukrishnan, R.A. Acquisto, and A. Selvakumar. 2007. The Use of Best Management Practices (BMPs) in Urban Watersheds. Lancaster, PA: DEStech Publications, Inc.

Gharabaghi, Bahram, Ramesh P. Rudra, and Pradeep K. Goel. 2006. Effectiveness of Vegetative Filter Strips in Removal of Sediments from Overland Flow. School of Engineering, University of Guelph.

Godwin, Derek C., Marissa Sowles, Desiree Tullos, and Maria Cahill. 2011. Vegetated Filter Strips. Low Impact Development Fact Sheet. Oregon Sea Grant Extensions. ORESU-G-11-003.

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. Journal of Irrigation and Drainage Engineering. Vol 135, No. 2. pp 217-224.

Magette, W.L., R.B. Brinsfield, R.E. Palmer, and J.D. Wood. 1989. Nutrient and Sediment Removal by Vegetated Filter Strips. Transactions of the American Society of Agricultural Engineers. 32 (2), 663-667.

Navickis-Brasch, Aimee Shay. 2011. Eastern Washington Steep Slope Research for Management of Highway Stormwater. WSDOT Research Report. WA-RD 771.1.

Schmitt TJ, Dosskey MG, and Hoagland KC. 1999. Filter strip performance and processes for different vegetation widths, and contaminants. Journal of Environmental Quality. 28: 1479-1489. 1999.

United States Environmental Protection Agency (USEPA). 1992. NPDES storm water sampling guidance document. EPA 833-B092-001. Office of Water, Washington DC.

United States Environmental Protection Agency (USEPA). 2009. National Water Quality Inventory: Report to Congress. EPA 841-R-08-001, Office of Water, Washington DC. 2009.

United States Environmental Protection Agency (USEPA). 2012. Vegetated Filter Strip BMP Fact Sheet. Web. http://cfpub.epa.gov/npdes/stormwater/menuofbmps/index.cfm?action=factsheet_results&view=specific&bmp=76

Washington State Department of Ecology (Ecology) 2011a. Washington State Department of Ecology. Effectiveness Study Selection. Stormwater Work Group Published online. https://sites.google.com/site/pugetsoundstormwaterworkgroup/home/selection-of-effectiveness-studies.

Washington State Department of Ecology (Ecology) 2011b. Stormwater Work Group. Recommended Effectiveness Study Topics and Questions. Published online. https://sites.google.com/site/pugetsoundstormwaterworkgroup/home/selection-of-effectiveness-studies/recommended-effectiveness-study-topics-and-questions.

Washington State Department of Transportation. 2011. Highway Runoff Manual. M 31-16-03. Olympia, WA, .

Winston, R.J., William F. Hunt III, D.L. Osmond, W.G. Lord, and M.D. Woodward. 2011. Field Evaluation of Four Level Spreader-Vegetative Filter Strips to Improve Urban Storm-Water Quality. Journal of Irrigation and Drainage Engineering. Vol 137. pp 170-182.

[This page intentionally left blank.]