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Lack of Data for Predicting Storm Water Pollutant Removal by Post-Construction Best Management Practices

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16. Abstract

The project objective was to conduct a detailed literature review of storm water pollutants and mitigation technologies and synthesize the information so that INDOT can implement project results into standards. Because it is a municipal separate storm sewer system (MS4), INDOT is required to minimize storm water pollution. A literature review was carried-out to gauge pollutants examined by other transportation agencies, the pollutant's relevance to Indiana roadways, and the effectiveness of storm water pollution minimization best management practices (BMP). A cost benefit analysis was also conducted for a few BMP devices used in Indiana. Results showed that a variety of databases contained BMP testing studies and the same type of BMP may not perform similarly at different sites. Some BMPs can also generate pollutants. Very little BMP design, cost, and performance data were obtained during this study from INDOT and municipalities contacted due to the organizations being unable to access it. Manufacturer self-reported BMP device performance data found was not corroborated by independent device testing data. Reliance on manufacturer reported data greatly overestimated the device's cost benefit; field validated device performance data are needed. Based on project results INDOT should consider (1) establishing agency-wide procedures to begin collecting pertinent storm water BMP information from ongoing and planned projects, (2) surveying which and how many BMPs are under INDOT control, (3) applying caution when estimating BMP performance based on manufacturer reported data or BMP performance data from other parts of the U.S., (4) conducting a field investigation to determine pollutant removal effectiveness for select BMPs.

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EXECUTIVE SUMMARY

LACK OF DATA FOR PREDICTING STORM WATER POLLUTANT REMOVAL BY POST-CONSTRUCTION BEST MANAGEMENT PRACTICES

Introduction

The project objective was to conduct a detailed literature review of storm water pollutants and available mitigation technologies and then synthesize that information so that INDOT can implement project results into standards. All tasks were specifically required to comply with the Rule 13 general permit from the Indiana Department of Environmental Management (IDEM). This project pertains to an after construction obligation due to the fact that INDOT is a Municipal Separate Storm Sewer System (MS4). MS4s have an obligation to install permanent storm water pollution reduction best management practices (BMP) within the right-of-way. This project was conducted to meet IDEM deadlines for Rule 13 general permit compliance and also help expand and deepen the agency's understanding of available storm water pollutant and mitigation technologies.

A literature review of government documents, peer-review and trade industry literature was conducted to ascertain the types of storm water pollutants that are of relevance to Indiana roadways. Several past INDOT storm water BMP related projects and products were also reviewed. Through the analysis of collected information, the pollutants of concern to other transportation agencies, the pollutant's potential for relevance to Indiana roadways, and the field-tested effectiveness of storm water pollution technologies where available. A cost-benefit analysis was conducted for BMP devices being used in Indiana. This project built upon previously supported INDOT efforts to improve storm water quality and identified data-gaps inhibiting technology selection and performance.

Findings

- Storm water pollutants considered in this project were grouped into six categories: sediment, nutrients, bacteria, oil and grease, trace metals, and salts. Each category of pollutants has a series of documented impacts in the environment.
- A variety of storm water BMP databases that describer specific BMP testing studies show that the performance of each BMP can be site specific. The same type of BMP may not perform similarly at different sites. Some BMPs actually generate pollutants (Tables 2.3–2.5).
- Very little BMP design, cost, and performance data was obtained during this study from INDOT or municipalities contacted. Follow-up with several municipalities also revealed this type of data was not easily accessible once the projects are completed. INDOT was not unique in its lack of cost data sought for this project. Due to this lack of information the National Cooperative Highway Research Program's recently developed storm water BMP Evaluation Tool could not be applied.
- Manufacturer self-reported BMP device performance data found was not corroborated by independent device testing data found during this study. Reliance on manufacturer reported data greatly overestimated the device's cost benefit. To develop a more applicable CBA storm water treatment device pollutant removal data is needed. This could be conducted by bench-scale, pilot-scale or field-scale device testing.

Implementation

Based on results of this study INDOT should consider the following actions.

- Establish agency-wide procedures to begin collecting pertinent storm water BMP information from ongoing and planned projects so that (a) the existence of each BMP and its design parameters are documented in a centralized location, easily accessible, and (b) future CBAs can be conducted. An example of the information that is needed can be found in the final report. BMP design and cost data are examples. It is recommended that this information be a required submittal by the installer before final payment on a series of forms.
- Survey which and how many BMPs are under INDOT control. This survey could identify the types of BMPs that are most commonly used across Indiana enabling INDOT to understand its current stock of BMPs. The survey could also help identify if any BMPs, once installed, precipitated problematic maintenance demands. The degree maintenance has or has not been routinely conducted on those assets could also be determined. This type of survey would be best conducted if all Districts participated.
- Apply caution when estimating BMP performance based on manufacturer reported data or BMP performance data from other parts of the U.S. As of today, there are no nationally recognized standardized test methods for BMP performance. DOTs and municipalities across Indiana (and the country) are conducting their own investigations to gauge BMP performance INDOT however should be cautious in that there are various studies in the literature where some "BMPs" have been shown not to be effective at all for removing pollutants and some "BMPs" generate pollutants. BMP performance is highly influenced by a variety of design, location, and environmental factors. Some BMPs may not remove detectable amounts of pollutants when storm water that it is treating contains a low level of pollutants to begin with.
- Types of BMPs in Indiana be prioritized then down selected for a field investigation to determine pollutant removal effectiveness. Monitoring should be carried out over a 1- to 3-year period to be in line with other BMP field studies conducted across the U.S. At the same time BMP design and cost data should be collected for those assets so that a more rigorous CBA can be conducted. Planned roadway construction activities provide an opportune time to institute new data collection policy and being field monitoring.

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DEFINITION OF ACRONYMS AND TERMS

AES	Applied Ecological Services
AMEC	AMEC Earth and Environmental Inc.
BMP	Best Management Practice
BOD	Biological Oxygen Demand
Caltrans	California Department of Transportation
CBA	Cost-Benefit Analysis
COD	Chemical Oxygen Demand
CWP	Center for Watershed Protection
DOT	Department of Transportation
IDEM	Indiana Department of Environmental Management
IOWADOT	Iowa Department of Transportation
INDOT	Indiana Department of Transportation
MDOT	Michigan Department of Transportation
NCDOT	North Carolina Department of Transportation
NCHRP	National Cooperative Highway Research Program
NDOT	Nebraska Department of Transportation
NOAA	National Oceanic and Atmospheric Association
NOx	Nitrite and Nitrate
NPDES	National Pollution Discharge Elimination System
PADEP	Pennsylvania Department of Environmental Protection
TDS	Total Dissolved Solids
TKN	Total Kjeldahl Nitrogen
TOC	Total Organic Carbon
TSS	Total Suspended Solids
TxDOT	Texas Department of Transportation
VSS	Volatile Suspended Solids
SSC	Suspended Solid Concentrations
EMC	Even Mean Concentration
SOL	Sum of Loads
SAC	Study Advisory Committee
OP	Orthophosphate
DP	Dissolved Phosphorus

1. INTRODUCTION

1.1 Problem Statement

In April 2014 the Indiana Department of Transportation (INDOT) received Rule 13 general permit authorization from the Indiana Department of Environmental Management (IDEM) (Indiana Administrative Code, 2014). This permit requires that the INDOT evaluate and enhance its storm water management within the Urbanized Area Boundaries statewide. One of the expectations is to investigate pollutants of concern to storm water relevant to roadway operation. To be in compliance with the issued IDEM permit, proper management of storm water pollutants is required. To properly manage storm water pollutants, INDOT requires an in-depth understanding of existing pollutant minimization measures and their effectiveness.

1.2 Research Objective

The project objective was to conduct a detailed literature review of storm water pollutants and available mitigation technologies and then synthesize that information so that INDOT can implement project results into standards.

1.3 Business Case

All tasks outlined in this scope are specifically required to comply with the Rule 13 general permit from the IDEM (INDOT, 2014). Previous storm water BMP projects completed by and for INDOT, in and before 2010, supported Rule 5. Rule 5 pertained to temporary storm water BMP's for construction, not permanent structures. This project pertains to enable INDOT to meet IDEM deadlines for Rule 13 general permit compliance. Moreover, project results help expand and deepen the agency's understanding of available storm water pollutant and mitigation technologies.

1.4 Technical Approach

A literature review of government documents, peer-review and trade industry literature was conducted to ascertain the types of storm water pollutants that are of relevance to Indiana roadways. Several past INDOT storm water BMP related projects and products were also reviewed (Corson, 2004, 2006, 2007, 2010; IDEM, 2007). The literature review included National Cooperative Highway Research Program (NCHRP) reports and many referenced documents. Through the analysis of collected information, the project team found the pollutants of concern to other transportation agencies, the pollutant's potential for relevance to Indiana roadways, and the field-tested effectiveness of storm water pollution technologies where available. This project built upon previously supported INDOT efforts to improve storm water quality.

With INDOT central office staff assistance, the project team contacted INDOT Districts to determine (1) which post-construction BMPs have been installed in the past two years, and (2) obtain cost data for the construction and operation of those BMPs. This cost data was incorporated into the cost-benefit analysis (CBA). The following information was requested of Districts: post-construction BMP (a) capital cost, (b) operations and maintenance cost, (c) equipment cost, and (d) contractor cost.

The project team reviewed work from other DOTs and researchers, and integrated the most current advancements in storm water treatment mitigation and technologies into this project. Several vendors who have technologies installed near Indiana roadways were also contacted about their self-reported pollutant reduction performance and costs. BMPs that have emerged into the market place were reviewed. The project team identified data-gaps inhibiting technology selection and performance.

1.5 Work Plan

The following tasks were defined in this project:

1. Research and determine pollutants of concern from the operation of INDOT roadways to include water quality and quantity concerns,
2. Research the available storm water pollution BMPs including both manufactured mechanical and passive,
3. Develop a library of the current community of practice for the BMPs by transportation projects which will include typical details and drawings of each BMP type,
4. Develop a cost-benefit analysis (CBA) for each BMP for future INDOT design guidance preparation. This CBA should include life-cycle costs including installation, cost of right of way, inspection, as well as maintenance and functional lifespan.

Also important to this project was that INDOT staff expressed interest in knowing "when" post-construction BMPs should be installed and "which" BMP is most appropriate based on a certain array of site/environmental conditions. Results of this project were intended to enable INDOT to translate results into INDOT standards through a subsequent implementation Task Force following the conclusion of the present project. The goal of that Task Force could be to take the recommendations, and incorporate the information into INDOT's Storm Water Quality Management Plan, INDOT design, construction, and maintenance standards. Results from this project were also intended to be used to train INDOT employees on how to identify, track, inspect, monitor and maintain INDOT's storm water assets in compliance with INDOT's Storm Water Quality Management Plan.

This project began May 2015 with a project study advisory committee (SAC) meeting at INDOT central office. The project team conducted a literature review from May 2015 to October 2015 and also contacted storm water BMP vendors, and other storm water BMP researchers. In August 2015 the INDOT La Porte District, INDOT central office staff, and the project team met to exchange information. In October 2015

INDOT La Porte District provided the project team with helpful storm water pollution control information. The draft final report was provided to INDOT central office in October 2015 and was revised once comments were received.

2. LITERATURE REVIEW

2.1 Background

To prevent flooding, property damage, and improve roadway safety, storm water must be rapidly removed from thoroughfares. Roadways and other impervious surfaces facilitate large volumes of water being collected and/or running off into lowland areas during wet-weather events. Unimpeded large volumes of storm water can reach waterways carrying with it all of the pollutants it has collected during transport (i.e., solids, organic matter, bacteria, oil and grease, and metals). Not only is the volume of water considered a pollutant because it can hydraulically overwhelm receiving waters, but the pollutants can also be acutely toxic to aquatic organisms and plants, damage property (i.e., sediment accumulation). Pollution caused by storm water, if remain unchecked, can cause prolonged damage to the environment.

To remove storm water from roadways and reduce contaminant loading into waterways, many storm water BMP have been found effective. Storm water BMPs are methods and technologies used for the diversion of water, but some also remove pollutants by acting as filters or sedimentation basis removing particles, or biological reactors transforming chemicals from a toxic compound to a less toxic compound. In order to properly design a BMP for storm water drainage, several factors must be understood. At the minimum, these include runoff intensity (flow rate, ft^3/s) and volume (ft^3), as well as BMP pollutant removal effectiveness.

When designing a BMP, cost is a major concern as well as local hydrology and geology. It is also important to understand pollutant loading that the BMP would expect to encounter and allowable pollutant discharge limit to the waterway or desired reduction in pollutants by the BMP. Where pollutant loading is high or a variety of pollutants are targeted for removal (sediment and nutrients), a series of BMPs are installed.

2.2 Pollutants of Concern

Storm water pollutants considered in this project were grouped into six categories including sediment, nutrients, bacteria, oil and grease, trace metals, and salts. Each category has a series of documented impacts in the environment. For example, sediment originates from the degradation of paved surfaces, construction sites, disturbed areas near roadways, streambank erosion, and sand treatment on roadways. Sediment accumulation in waterways has direct and indirect negative impacts. Sediment accumulation can suppress fish, mussel, and aquatic vertebrate populations. Sediment can increase the turbidity or cloudiness of the water, making it difficult for organisms to navigate and find food sources. As this pollutant settles to the bottom of the waterway, it can form ridges or barriers that prevent aquatic organisms from moving from one location to another much like a dam built on a river. These sediment barriers can also reduce the use of the waterways for recreation and fishing (IDEM, 2007). A secondary consequence of sediment loading to a waterway is that other pollutants such as nutrients and metals can be carried with the sediment and dissolve into the water column. Sediment accumulation reduces the ability for plant vegetation and algae to absorb sunlight and can increase the water's turbidity (IDEM, 2007).

Sediment is typically characterized by analysis of suspended solid concentrations (SSC) and total suspended solids (TSS). TSS and SSC are measured by filtering water through a nominal 1.5 µm glass fiber filter. The difference between these techniques is that SSC is determined by filtering an entire water sample whereas the TSS is determined by filtering an aliquot of the water collected by the samplers (Liu, 2009). A variety of other parameters are monitored, such as volatile suspended solids (VSS) to describe organic characteristics of the water.

Nutrients such as nitrogen and phosphorous are a concern in storm water and contribute to biological activity in waterways. Primary sources of nutrients are fertilized lawns, agricultural application, leaking sewers and septic tanks, and vehicle exhaust (IDEM, 2007). Excessive nutrient addition to waterways can facilitate eutrophication, a condition where rapid biological activity occurs and results in depleted oxygen levels. Increased algal growth can be an indicator that nutrient loading into a waterbody is occurring. Algae can also be problematic because some can produce and excrete toxins that can harm humans and aquatic species. Excessive algal plant growth is also undesirable because it can impact tourism, commercial fishing, and land value in the affected area (IDEM, 2007). The consequences of nutrient loading can be evidenced by recent algal bloom events in Ohio, Indiana, and Iowa where swimming advisories were instituted for major recreational water bodies including Lake Erie. Excessive nutrient pollution can also require drinking water treatment facilities to modify their operations and may require capital facility upgrades and/or encounter reoccurring chemical costs to treat the more polluted water. Storm water nutrient levels are reported by measuring total nitrogen (TN) and total phosphorous (TP) concentration, and total kjeldahl nitrogen (TKN) is sometimes reported. TN is based on the sum of nitrite and nitrate concentrations (Brian, Richard, & Jeffrey, 2014). TKN represents organic nitrogen and ammonia nitrogen.

Bacteria are considered to be an important storm water pollutant. Bacteria most commonly found in storm water are fecal coliform and *Escherichia coli (E. coli)*. These pathogenic organisms originate from animals and people (IDEM, 2007) and indicate water contamination. In some cases, when bacteria levels exceed allowable recreational limits recreational activities in the affected waterbody are prohibited, and a consequence can be economic losses in the surrounding communities (IDEM, 2007). The cost and complexity of water treatment processes needed to remove these organisms also increases as their concentration increases. Aqueous bacteria levels are measured in terms colony forming units per milliliter (CFU/mL).

Oil and grease deposited on roadways can pollute storm water. These deposits originate from automobiles, nearby industrial areas, and illegal dumping. When oil and grease reaches a waterway, a thin film of oil can form on the water surface. Oils and grease do not readily breakdown in the environment. Accumulation of these pollutants in waterways can harm aquatic life and even humans who come into contact with the contaminated water (IDEM, 2007). Oil and grease can also clog storm drains since the accumulation starts from the top of the pipes and with trash and debris entering the system. Clogged storm drains result in water accumulating on roadways and can become a safety hazard (IDEM, 2007). For municipalities that still have combined sewer overflow systems, oil and grease from the roadway can enter the sanitary sewer and enter wastewater treatment plants. Some wastewater treatment plants can remove oil and grease, but this process is expensive. Preventing oil and grease from entering sanitary sewers and the environment is recommended.

Metals occur at relatively low levels in the environment, but on roadways, metals can accumulate quickly. Metals commonly found in storm water originate from automobile wear and tear, exhaust, and industrial areas; Copper, iron, and zinc are the most common and abundant (IDEM, 2007). If metal contaminated storm water enters nearby waterways, this can cause conditions that exceed aquatic life toxicity thresholds. Continued loading of metals to a waterway can also be problematic as some bioaccumulate.

Salt is a pollutant of interest in Indiana and is applied to roadways during winter months to help removing ice from roadways. Thus, peak storm water salt concentrations would be observed during the winter months when salt is deposited on roadways for deicing. The US EPA's acute and chronic concentration limits for chloride are 860 mg/L and 230 mg/L respectively (Erickson, Weiss, & Gulliver, 2013). It has been found that in high traffic volume areas such in metropolitan areas US EPA's water quality chloride limits can be exceeded during the winter months (Erickson et al., 2013). Sometimes chloride levels have been several thousand milligrams per liter. Currently, very few BMPs are capable of removing salt from storm water runoff.

2.3 Ranges of Select Pollutants Detected in Storm Water Runoff

Numerous research studies have documented storm water pollutant concentrations across the US, but no studies were found for Indiana roadways. Six studies were selected from different DOTs and summarized in Table 2.1. These results represent a fraction of the total amount of storm water quality data available in the *International Storm Water BMP Database* (http://www.bmpdatabase.org/). These results however are provided for illustrative purposes. Interestingly, none of the studies reported storm water SSC, but instead reported TSS concentration. There is growing evidence in the storm water field that SSC is a more accurate representation of solids in storm water than TSS measurement (Liu, 2009).

2.4 Storm Water Pollution Control Best Management Practices and Pollutant Removal Efficiency

As mentioned previously storm water pollution control products, also referred to as BMPs, collect runoff from impervious cover drainage and some channel runoff into the natural water table. Only post-construction structural BMPs were considered in this project specific to the new Rule 13 general permit. Post-construction BMPs are defined as active methods that involve constructing a device (such as a detention pond) or changing a particular pattern of activity (such as lawn fertilizing) that can decrease storm water impacts in a given area (IDEM, 2007). The BMP's effectiveness is determined by how well each method handles runoff and reduces/removes pollutants contained in the runoff.

Several types of BMPs were reviewed. Each BMP uses a combination of treatment techniques to address flood control and pollutant removal, including infiltration, filtration, detention, and retention, and evapotranspiration. Evapotranspiration can contribute to the success of BMPs but is not used in BMP design or selection. Below is a brief description of each method utilized by storm water pollutant control BMPs. The cost and performance of each BMP is largely dependent on the design and location selected for each. Below are descriptions and design diagrams for several different BMPs that can be found in Appendix A.

- *Infiltration*: The process by which water moves into the subsoil to either reemerge to recharge streams, lakes, or other bodies of water or to recharge aquifers deep below ground. Surface flows are reduced and pollutants can sorb to the subsoil.
- *Filtration*: A process using filtering mediums such as sand or gravel to remove sediment and pollutants from storm water runoff. Filtration systems are usually used in series with other types of BMPs with the ability to store water more effectively.
- *Detention*: The process by which storm water runoff is collected into lined ponds or pipes and is slowly released into nearby streams or sewer systems to be treated. It is effective in flood control and reducing the flowrate of the water, therefore reducing the erosion caused by the runoff.
- *Retention*: The process in which runoff is collected and permanently stored in different systems such as ponds, pipes, or tanks.

TABLE 2.1
Range of Pollutants of Concern Defined in Literature from Select DOT Studies

	Water Quality Data Reported from DOTs				
Organization	**MDOT, 3 Highways (range)**	**Caltrans, 1 Highway (μ + σ)**	**NCDOT, 1 Highway (μ + σ)**	**NDOT, 1 Detention Basin BMP (range)**	**TxDOT, 3 Highways (range)**
Solids and organic materials (mg/L)					
TDS	143 to 183	87.3 + 103.7	157 + 107		
TSS	33.8 to 125	112.8 + 188.8	283 + 215	27 to 134	27 to 202
VSS					7 to 41
TOC		21.8 + 29.2			18 to 58
COD	47.7 to 132		70 + 48	34 to 74	33 to 149
BOD	13.3 to 18				4.1 to 16.5
Oil and Grease	7.9 to 55.8	4.95 + 11.41			0.5 to 6.5
Bacteria (coliform forming units/100 mL)					
Fecal bacteria	4,807 to 66,380	1,132 + 1,621			13,000 to 116,000
Nutrients (mg/L)					
Nitrate		1.07 + 2.44			1.0
Nitrate, Nitrite	0.84 to 1.5		2.25 + 0.38	0.28 to 0.8	
Total Kjeldahl Nitrogen	2.7 to 3.1	2.06 + 1.9	1.42 + 1	0.74 to 3.9	
Total P	0.2 to 0.32	0.29 + 0.39	0.43 + 0.2	0.06 to 0.74	0.1 to 0.42
Dissolved Phosphorus	0.09 to 0.1	0.11 + 0.18	0.15 + 0.08	<0.02 to 0.7	
Ammonia	1.2 to 2.1	1.08 + 1.46	0.83 + 0.66		
Metals (μg/L)					
Copper	35 to 81	33.5 + 31.6	24.2 + 15	4.4 to 12.1	(0.007 to 0.038) × 103
Lead	17 to 55	47.8 + 151.3	21 + 15	1.51 to 5.74	(0.009 to 0.099) × 103
Zinc	130 to 413	187.1 + 199.8		21.1 to 76.1	(0.019 to 0.237) × 103
Antimony	0.8 to 2.2				
Arsenic	1.5 to 1.6	2.7 + 7.9			
Cadmium	0.59 to 2.4	0.73 + 1.61	2.5 + 2.5		
Chromium	6 to 49	8.6 + 9	8.1 + 6.5		
Nickel	3.9 to 34	11.2 + 13.2	8.1 + 9		

Results presented describe the types of pollutants of interest and observed field concentrations. Many more storm quality investigation have been conducted that were not described (Barrett, Malina, Charbeneau, & Ward, 1995; Caltrans, 2003; MDOT, 1998; Simmons & Admiraal, 2014; Wu, Allan, Saunders, & Evett, 1998).

- *Evapotranspiration*: The process referring to the addition of water into the atmosphere from both evaporation and transpiration. The instant precipitation accumulates on land or in vegetation, it is susceptible to evapotranspiration either by becoming evaporated into the atmosphere or absorbed by form of vegetation to then be transpired into the atmosphere later on.

The advantages and disadvantages of BMPs reviewed in this study are listed in Table 2.2. The pollutant removal efficiency is reported several ways in the literature. The most common ways are event mean concentration (EMC) efficiency and sum of mass or load (SOL) efficiency. C_{in} is the EMC at inflow and C_{out} is the EMC at outflow. SOL_{in} is the sum of loads entering the system and SOL_{out} is the sum of loads exiting the system.

$$EventMeanConcentration(\%) = \left[\frac{Cin - Cout}{Cin}\right] x100$$

TABLE 2.2
Advantages and Disadvantages of Each BMP Reviewed

BMP	Advantages	Disadvantages
Dry Detention Basin	Reduces peak flow rate; High sediment removal possible; Recreational usage when dry; Designed with native vegetation can decrease mowing costs	Outlet de-clogging; Large footprint required
Infiltration Basin	Reduces peak flow rate therefore reducing downstream erosion; Recreation usage when dry; Helps maintain base flow of nearby streams; Reduces local flooding	Routine upkeep required; Maintenance required to keep aesthetically pleasing; Not applicable for large drainage areas
Wetland	Improves downstream water quality; Particle settling and pollutant removal; Flood attenuation and reduces peak discharge; Relatively low maintenance costs; Enhances wildlife habitat	Variety of flows could make maintaining vegetation difficult; Vegetation is important for pollutant removal; Large footprint required; High construction costs
Vegetated Swale	Flood control and groundwater recharge; Improves water quality through filtration; Simple to design and implement; Reduces erosion; Can include native vegetation and provide wildlife habitat	Routine upkeep required; Requires proper sloping; Need to be carefully placed and designed to minimize flood risk; Can only treat a limited area
Dry and Wet Swales	Remove sediment and improve water quality; Reduce runoff rate and provide groundwater recharge; Linear design works well with highways and residential streets	Routine upkeep required; Sediment and pollutant removal sensitive to slope and vegetative density; Limited to small areas; Possible re-suspension of sediment
Infiltration Trench	Highly effective pollutant removal; Reduces runoff volumes during storm events; Increases base flow in nearby streams	Periodic de-clogging
Sand Filter	High pollutant removal capability; Can be used in highly urbanized areas; Applicable in a variety of soils; Good in aquifer regions	Periodic de-clogging; Small drainage areas necessary; Dissolved pollutants not captured by sand
Vegetative Filter Strip	Flood control and groundwater recharge; Water quality improvement by filtration; Reduces peak flow rate; Able to incorporate diverse plant life as well as native vegetation; Simple design and implementation	Routine upkeep of vegetative cover; Geographically limited
Organic Filter	High pollutant removal for small drainage areas	Not suitable for areas with large sediment runoff; Frequent maintenance required
Grassland Channel	Inexpensive in comparison to other BMPs; Improves infiltration	Routine upkeep of vegetative cover; Can only treat a limited area
Pervious Pavement System	Reduces runoff volumes; Reduces impervious surface area	Periodic de-clogging due to sediment accumulation; Must be properly designed or will have a high potential for failure
Bioretention System	Flood control and increases groundwater recharge; Minimal land size necessary relative to other BMPs; Reduces site runoff volume; Aesthetically pleasing	Frequent upkeep required; Small area treated; Certain types of vegetation required; Construction of site needs to be complete before this BMP is installed
Wet Detention Pond	Reduces peak flow rate; Wildlife habitat; Recreational area for community; Property value increase possible; Aesthetically pleasing	Remove sediment periodically; Possible site for mosquito breeding; Decreases amount of available land; Possible mosquito breeding site
Oil-Grit Separator	Small space required (usually underground); Easily introduced to fully developed sites; Can be used as a pretreatment method; Useful in removing oils and metals	Observe device periodically to prevent re-suspension of pollutants; Limited pollutant removal of soluble or fine particles; Limited to small drainage areas; Cold climates could reduce performance
Wetland – Submerged Gravel	High TSS removal; Small amount of land required; High pollutant removal capabilities; Can be located in regions with high water tables	Frequent upkeep required; Cannot handle sediment-rich runoff; Cannot be installed until site construction is complete

Results from AES (2006), Caltrans (2008). Pervious paver system also includes pervious concrete, porous asphalt, and porous paver systems. Currently understood BMP pollutant removal data for each BMP can be found in Tables 2.3–2.5.

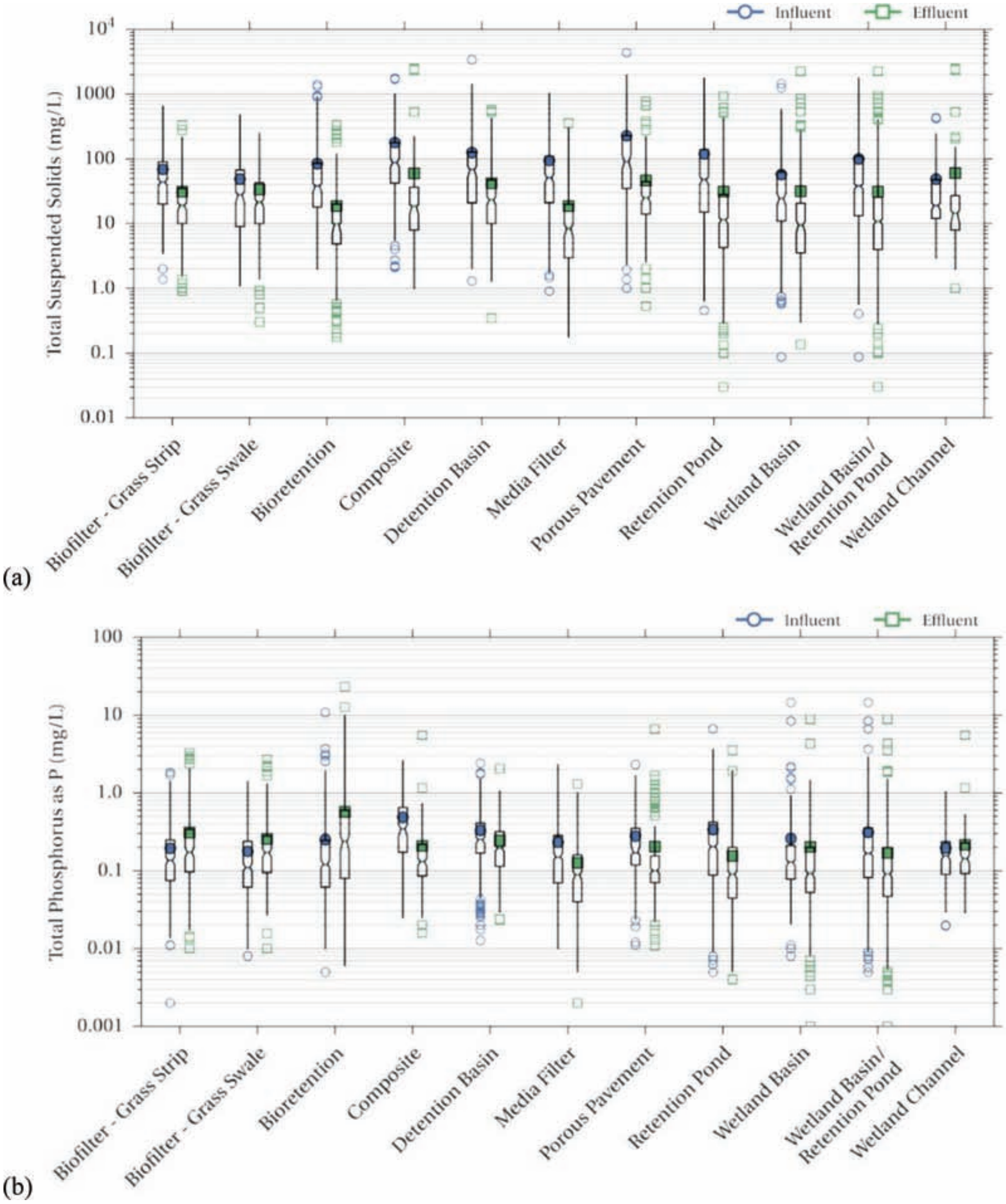

Figure 2.1 Example international BMP database graph: box plots for (a) TSS and (b) TP influent/effluent concentration for 11 storm water BMPs. Additional graphs for other pollutants are available in the database.

$$Sum of\,Loads(\%) = \left[\frac{SOLin - SOLout}{SOLin}\right] x100$$

Pollutant removal effectiveness of common storm water BMPs in Tables 2.3–2.5 can be found in several databases. These sources have been established to compile storm water BMP pollutant removal effectiveness. Specifically, biofilters (grass strips and swales), bioretention, composites, detention basin, media filter, porous pavement, retention pond, wetland basin, wetland basin/retention pond, wetland channel, porous pavement are described. The ability of these devices to remove a variety of pollutants has also been described: TSS, TDS, *Enterococcus*, *E. coli*, fecal coliform, nutrients (total phosphorous, orthophosphate, dissolved phosphorous, total nitrogen, total Kjeldahl nitrogen, nitrate, nitrite+nitrate (NOx), as well as metals total and dissolved concentration (arsenic, cadmium, chromium, copper, iron, lead, nickel, zinc).

- *International Storm Water BMP Database*, http://www.bmpdatabase.org/
- *National Storm Water Quality Database*, http://www.bmpdatabase.org/nsqd.html. Storm water quality monitoring data collected over nearly a ten-year period from more than 200 municipalities throughout the country.

TABLE 2.3
Statistically Significant Reduction in Storm Water BMP Solids and Bacteria Influent/Effluent Levels from the International BMP Database

	Solids		**Bacteria**		
BMP	**TSS**	**TDS**	***Enterococcus***	***E. Coli***	**Fecal Coliform**
Biofilter – Grass Strip	d	i			
Biofilter – Grass Swale	d				
Bioretention	d		d	d	
Composite	d				
Detention basin	d				d
Media filter	d	i			d
Porous pavement	d				
Retention pond	d	i		d	d
Wetland basin	d	i	d	d	d
Wetland basin/Retention pond	d	i	d	d	d
Wetland channel	d				

i = BMP causes an increase in pollutant concentration; d = BMP causes a decrease in pollutant concentration; i and d shown where statistically significant results were reported.

Composite BMPs are those that include one or more BMPs/treatment trains; Filters summarized in the database are mostly sand filters.

TABLE 2.4
Statistically Significant Reduction in Storm Water BMP Nutrient Influent/Effluent Levels from the International BMP Database

	Phosphorous			**Nitrogen**				
BMP	**TP**	**OP**	**DP**	**TN**	**TKN**	**NO^3**	**NO^2+NO^3**	**NOx**
Biofilter – Grass Strip	i	i	i	d		d	d	d
Biofilter – Grass Swale	i	i	i					
Bioretention	i	i		d				
Composite	d		d	d	d	d		
Detention basin	d						d	d
Media filter	d				d	i	i	i
Porous pavement	d	i	i		d		i	i
Retention pond	d	d	d	d	d	d	d	d
Wetland basin	d		d			d	d	d
Wetland basin/ Retention pond	d	d	d	d	d	d	d	d
Wetland channel		i		d	d		d	d

i = BMP causes an increase in pollutant concentration; d = BMP causes a decrease in pollutant concentration; i and d shown where statistically significant results were reported; Composite BMPs are those that include one or more BMPs/treatment trains; Filters summarized in the database are mostly sand filters.

A review the International BMP Database as well as a variety of specific BMP testing studies revealed that the performance of each BMP can be site specific. *The same type of BMP may not perform similarly at different sites so reporting pollutant removal for some studies may have no applicability for others or designers.* As shown in Figure 2.1, the pollutant removal standard deviation bars (for all of the available BMP performance data) always overlapped for each BMP. Although, statistical analysis of the BMP performance data by others revealed certain BMPs are generally effective at removing certain pollutants more than others, and some BMPs

TABLE 2.5
Statistically Significant Reduction in Storm Water BMP Metal Influent/Effluent Levels from the International BMP Database

	Heavy Metal (Dissolved/Total Concentration)							
BMP	**As**	**Cd**	**Cr**	**Cu**	**Fe**	**Pb**	**Ni**	**Zn**
Biofilter – Grass Strip	i/	d/d	/d	d/d	i/	d/d	/d	d/d
Biofilter – Grass Swale	/d	d/d	/d	d /d	/i	/d	d/d	d/d
Bioretention		d/	/d	/d	/d	d/d	/i	d/d
Composite		/i		d /d		d/d		d/d
Detention basin		i/d	/d	d /d	/d	/d	/d	d/d
Media filter		/d	/d	d /d		/d	/d	d/d
Porous pavement		d/	i/	d /d	i/d	/d	d/d	d/d
Retention pond	/d	d/d	d/d	d /d		/d	/d	d/d
Wetland basin		d/d		d /d	/i	/d		d/d
Wetland basin/Retention pond	/d	d/d	d/d	d /d		/d	/d	d/d
Wetland channel			/d				/d	/d

i = BMP causes an increase in pollutant concentration; d = BMP causes a decrease in pollutant concentration.
i and d shown where statistically significant results were reported.
Composite BMPs are those that include one or more BMPs/treatment trains.
Filters summarized in the database are mostly sand filters.
d/d represents decrease for dissolved pollutant concentration and decrease for particulate pollutant concentration.

actually generate pollutants (Tables 2.3–2.5). At present there is a poor understanding about pollutant removal effectiveness of BMPs and selectively reporting BMP performance data in this study, without acknowledging situations where BMP was less effective, or generated pollutants, would not be appropriate.

Reasons for BMPs not achieving greater efficiencies could be due to several reasons. First, the storm water BMP's pollutant removal efficiency depends on the influent pollutant concentration. For example, where there are high sediment loads to a BMP that utilizes gravity settling it is easier to detect reductions, if they take place, sediment was removed from storm water. In contrast, differences are more difficult to detect when storm water contains much lower sediment concentrations as the concentrations approach the analytical limits of detection for the water testing methods applied. Another example of why BMPs do not achieve greater removal efficiencies could be due to particle size. Smaller particles are more difficult to remove from storm water by settling than larger particles. Efficiency is also influenced by how storm events were sampled (i.e., exclusively), whether results were flow-weighted or weighted by measure of precipitation, or whether efficiency was calculated by average concentration or efficiency average of each storm event. In addition, if the assessment methods are similar, site-specific details affect the performance of BMPs which usually are not mentioned in reports. For example, as a result of different catchment ratio or retention time, two similar wet ponds could exhibit different removal efficiencies. Therefore, having access to either site characteristics or comprehensive evaluation of design is necessary for BMP performance.

At present a variety of organizations have developed their own storm water BMP device testing and field monitoring methods. The two most popular organizations include:

- Washington State Department of Ecology, http://www.ecy.wa.gov/programs/wq/stormwater/
- New Jersey Corporation for Advanced Technology (NJCAT), http://www.njcat.org/verification-process/technology-verification-database.html

In addition, the Storm Water Testing and Evaluation for Products and Practices (STEPP) Task Force is investigating the feasibility of a national testing and evaluation program for storm water products and practices. Currently, no such standard or program exists. A variety of storm water trade association, device manufacturers, BMP designers, and federal agencies are involved in the STEPP effort. The STEPP effort is being pursued for storm water products and practices:

> "…data has not been evaluated or verified by independent third parties. For some communities, a gap between expected and actual performance was evident, which led to the development of state and regional programs to test, evaluate, and in some instances verify or certify the performance of products. Some of these programs have been successful, and others have met challenges."

While promising, discussions with individuals familiar with the STEPP task force indicate that a national testing and evaluation program is not guaranteed and may be a few years away. The STEPP website can be found here: http://www.wef.org/stepp/.

In developing this project the INDOT expressed interest in the performance of a number of emerging BMP technologies not mentioned in Tables 2.2 and 2.3. BMPs listed in Tables 2.2 and 2.3 are those that have been thoroughly reviewed by the international storm water BMP community. The emerging BMP technologies of additional to INDOT were ash, peat, and other organic/absorbents. Some laboratory and field studies show that these materials can adsorb sometimes up to 70% solids, and 50% heavy metal contaminants from storm water matrices (Gorme, Maniquiz-Redillas, & Kim, 2015; Zhang Brown, Storm, & Zhang, H., 2008). These studies however are much fewer in number, breadth, and depth compared to the online storm water BMP database reports available. No guidance was found on how to design an ash, peat, or other absorbent filter that can work specifically for INDOT sites as design would be site specific and require knowledge about site pollutant loading. Some states specifically do not acknowledge these technologies in their design manuals as they have not yet been proven to meet water quality standards. Any proposal of alternative filter media (i.e., ash, peat) should be rigorously tested and monitored in-situ and possible in parallel through laboratory experiments as a demonstration project.

3. COST-BENEFIT ANALYSIS

A cost-benefit analysis (CBA) can be used to determine if a certain product or system is more costly than beneficial over the span of its lifetime. For this project, a CBA was performed on several different types of BMPs to compare their effectiveness in removing pollutants from storm water runoff to the cost associated with installing and maintaining those BMPs. Similar studies have been conducted around the country to help in deciding which BMPs to install in various locations. The team reviewed two examples of these economic analyses performed by the Minnesota Capital Region Water District (Doneux, 2011) and North Carolina Department of Transportation (Wossink & Hunt, 2003).

In 2003, North Carolina State University conducted an economic evaluation of storm water BMPs located in North Carolina, Delaware, and Virginia (Wossink & Hunt, 2003). They included 15 wetlands, 13 wet ponds, 12 sand filters, and 18 bioretention BMPs. The researchers considered cost data associated with installment (construction and land) and annual operating costs (inspection and maintenance). Construction costs and annual operating costs were statistically analyzed for effects of scale by means of the estimation of BMP specific nonlinear equations relating the costs to watershed size." The following information was reported:

> "Results showed that all BMPs, except for bioretention not in sandy soil, displayed economies of scale and large differences were found in the annual costs per acres treated between the BMPs analyzed. Researchers found that pollutant removal efficiency was less than expected resulting in an inability to determine the role of watershed size. Researchers reported that where the opportunity cost of land is very high (commercial use), a wet pond is preferable over a bio-retention area for small watersheds (2 acres or less). Installation of bio-retention areas is to be preferred over sand filters or wet ponds in smaller watershed where sandy soil prevails (less than 10 acres). A storm water wetland is the least expensive BMP for larger watersheds and sandy soils (over 10 acres). For watersheds on nonsandy soil, bioretention was the most economical option up to about 6 acres followed by wet ponds for midsize watersheds and storm water wetland for watersheds over 10 acres."

In 2010, the Minnesota Capitol Region Watershed District completed a detailed CBA of four different types of BMPs to address several different sewer problems, improve the water quality discharging to a main lake in the area, and minimize the costs associated with installing post-construction BMPs. BMPs studied include eight underground infiltration trenches, eight rain gardens, one storm water pond, and one underground storm water facility (Doneux, 2011). These devices were installed specifically for this project and monitored from 2006 to 2008. The researchers documented total capital costs, annual operating costs (inspection and maintenance). Pollutant removal, volume, total phosphorous, and total suspended solids, was monitored for 7–8 months. These costs helped determine the costs to removing certain amounts of each pollutant. The results found were shown as following:

> "Costs are largely affected by volume and pollutant load reductions. The pond had the lowest costs, however, this type of BMP is not appropriate for all situations – other types of BMPs have additional benefits which are not considered in cost calculations (i.e., volume reduction). They also recommended that properly design, construction, and maintenance are of great importance for BMPs to exhibit high volume reduction and pollutant removal efficiencies."

In 2014, the NCHRP released their BMP Evaluation Tool under *Report 792: Long-Term Performance and Life-Cycle Costs of Storm Water Best Management Practices* and this was initially intended for use in the present study (NCHRP, 2014). The evaluation tool includes models for the following post-construction BMPs: Bioretention, Dry Detention, Filter Strip, Sand Filter, Permeable Friction Course, Swale, and Wet Pond (Taylor et al., 2014). Some of the models can also be retrofitted to include other types of BMPs such as wetlands and grassed channels since the evaluation tool is heavily dependent on manual inputs such as design parameters, location, and cost for each BMP (Taylor et al., 2014).

The project team's intent was to use the NCHRP BMP Evaluation Tool using data collected from different INDOT districts and Indiana MS4s. The tool requires the following inputs: location, design parameters, pollutant removal efficiencies, capital cost, maintenance and operation cost, equipment cost, and material cost (Taylor et al., 2014). Built-in defaults were present for average design parameters, rain gauge data, and costs from several locations in Indiana to help fill in areas with insufficient data if there happened to be any. Using the input, the model would then supply several results from the data including capital costs, total design life maintenance costs, pollutant load removals, and costs of removing particular amounts of different pollutants (Taylor et al., 2014). Results would enable INDOT to compare the cost benefit of different BMP's across the state.

3.1 Approach

To conduct a robust cost-benefit analysis for storm water BMPs, cost and pollutant removal data was sought for 15 BMPs suspected to be used by INDOT (Appendix B). Table 3.1 describes the type of cost data that was sought for this analysis. As shown, many of the costs pertain to initial investments by INDOT, while operations and maintenance (O&M) costs are reoccurring events.

3.2 Results

3.2.1 Device Design, Cost, and Performance Data

Very little BMP design, cost, and performance data was obtained during this study from INDOT or municipalities contacted. The INDOT La Porte District provided useful information. Construction costs in the form of contract bid awards for the La Porte District were provided to the project team but site specifications, specific device sizes, and cost details were not available. No data was available for existing storm water BMP site land costs (right-of-way, setbacks, etc.). Associated acreage data for each BMP was also not available. As a result neither land or construction costs could be included for the CBA. Follow-up with several municipalities also revealed this type of data is not easily accessible once the projects are completed. INDOT is not unique in its lack of cost data sought for this project. Due to this lack of information the NCHRP's BMP Evaluation Tool could not be applied.

In absence of the construction and land cost data, the project team obtained data for the purchase cost, installation cost, and O&M costs of three devices that the INDOT La Porte District identified were installed recently. Costs were obtained from each manufacturer and are shown in Table 3.2. The devices considered in this CBA include the Bay Technologies, Inc. *BaySeparator*, Hydro International, Inc. *Downstream Defender*, and ADS, Inc. *SWQU*.

3.2.2 Storm Water Pollutant Removal by Device

All devices were best designed to remove suspended materials measured as suspended sediment concentration

TABLE 3.1
Types of Costs Associated with Storm Water BMP Installation, Use, and Maintenance

Description of Expense	Description	Frequency
Land	Land for device, setbacks, right-of-way; Subcategories: Commercial, residential, none	Initial
Construction	Labor, mobilization, site preparation, grading, stabilization, supplies	Initial
Device unit	Physical device(s), appurtenance(s)	Initial
Device installation	Labor, supplies	Initial
Annual Operations and Maintenance	Routine inspection, cleanout, repairs, labor, supplies	Reoccurring

TABLE 3.2
Design Information and Costs Data for Each Device Including O&M Reported by Device Manufacturers

	Device and Maximum Treatment Flowrate, cfs			
Cost Category	BaySeparator, 7.8 cfs	Defender, 8.0 cfs	SWQU, 6.8 cfs	Details
Cost to Purchase Item	$14,000	$16,400	Not provided	Manufacturer reported
Cost to Install Item	$3,000	Not provided	Not provided	Manufacturer reported
O&M per Year	$800–$1,500	$800–$1,000	Not provided	Manufacturer reported, 1x/yr
Inspection per year	$100	Not provided	Not provided	Manufacturer reported, 2x/yr
Service-life, years	100	30	Not provided	Manufacturer reported

Land and construction costs for each device were assumed to be zero due to lack of field data. Device salvage value was also assumed to be zero. Some manufacturers chose to not provide complete cost information.

TABLE 3.3
Comparison of Manufacturer and Independent Testing Laboratory Storm Water Pollutant Removal Results, %

	BaySeparator 3K Model		**Defender 6-ft Model**		**SWQU6040WQA Model**	
Pollutant	**Mfg. Lab**[a,‡]	**Ind. Lab**[b,†]	**Mfg. Lab**[c,‡]	**Ind. Lab**[d,‡]	**Mfg. Lab**[e]	**Ind. Lab**
SSC	80	46.8	80	19	nd	nd
TSS	80	33.6	80	0	80	nd
Turbidity	nd	6.9	nd	nd	nd	nd
TP	nd	19.4	80	0	40	nd
Oil and Grease	nd	nd	nd	nd	80	nd
Heavy metals	nd	nd	nd	0 (Zn only)	74	nd

nd = No data; Mfg. Lab = Manufacturer laboratory; Ind. Lab = Independent laboratory.

[a] BaySaver Technologies, Inc. (2008).

[b] Liu (2009).

[c] Hydro International.

[d] Horwatich and Bannerman (2005).

[e] ADS Inc. (2007).

[†] SOL = Summation of loads method for determining pollutant removal efficiency.

[‡] EMC = Event mean concentration for determining pollutant removal efficiency.

NOTES: Only a single independent laboratory testing study was found for BaySeparator and Downstream Defender. No independent studies were found for the SWQU. BaySaver Technologies, Inc. reported that the BaySeparator device was designed for 80% annual aggregate pollutant removal efficiency. Solids removal efficiency will be a function of particle size where larger particles are more easily removed than smaller particles. According to manufacturers the BaySeparator and Downstream Defender devices can remove oil and grease but performance data were not reported by the manufacturer or measured in an independent laboratory.

The Downstream Defender is reported to remove greater than 80% of find sand particles having a mean diameter of 106 um (ADS, Inc., 2007). Independent testing showed zero removal for particles less than 150 um size greater than 90% when particles were greater than 250 um (Horwatich & Bannerman, 2012). In July 2014, the BaySeparator manufacturer claimed 50% TSS and 20% TP removal (Rustia, 2014). The multiple documents (footnotes a–e) show different pollutant removal efficiencies.

(SSC) and total suspended solids (TSS) and manufacturers reported solids removal for all devices. Total phosphorous (TP) removal was also reported by manufacturers. Table 3.3 compares the results of manufacturer reported device performance and independent testing of the devices. Unfortunately, the performance of all devices was not examined for the same pollutants. The most common pollutants were SSC, TSS, and TP. For both *BaySeparator* and *Downstream Defender* devices, the devices actual annual pollutant removal performance was significantly less than what manufacturers reported in their specifications and brochures. In some cases up to 80% less than what manufacturers reported was observed in the field. *Downstream Defender* did not demonstrate any statistically significant pollutant removal for either TSS or TP and slight removal for SSC. No independent testing laboratory device performance data was found for the *SWQU*. Source documents for the manufacturer device performance data were also not found.

> NOTE: Percent removal is not recommended for evaluating BMP performance according to a report by the 2007 International Storm Water Database when other data are available. Unfortunately, due to a lack of storm water BMP design and performance data for Indiana sites, and lack of independently verified device performance data, percent removal was applied in this analysis. The lack of data greatly inhibited a more thorough analysis of BMPs for Indiana.

3.2.3 Cost-Benefit Analysis Assumptions

For the purpose of this analysis, initial costs (device purchase, installation) were annualized over two different service life durations and for two interest rates. This annualized initial cost is commonly referred to as Capital Recovery (the salvage value of the devices is considered to be zero in this analysis). A 100 year and 50 year service-life were chosen for examination. Two percent and 4% interest rates were examined because these are historically similar to inflation rates. Once the Capital Recovery of initial costs was completed, O&M were then added to the result to obtain a total Annual Worth cost of the device.

3.2.4 Cost-Benefit Analysis Results

Table 3.4 describes the Annual Worth ($/yr) of the cost of each device for a 2% rate of inflation. Results show that the Annual Worth of the cost of the *Downstream Defender* device is greater than the *BaySeparator* device. This result is due to the fact that initial costs associated with the *Downstream Defender* device are greater (Appendix C) than the *BaySeparator* device. When a 4% inflation rate was used, the difference between the Annual Worth of the total costs of these devices increased as well (data not shown). As expected, if a device was removed from service before its 100-year service-life, this device would have a greater Annual

TABLE 3.4
Annual Worth ($/yr) of the Cost for Each device at 2% Rate of Inflation for Maximum and Minimum Annual Operations and Maintenance Costs

Service-Life	Device					
	BaySeparator		Defender		SWQU	
	$800	$1,500	$800	$1,000	nd	nd
50 year	$1,541	$2,141	$2,213	$2,413	nd	nd
100 year	$1,194	$1,994	$2,176	$2,376	nd	nd

nd = No data.

The BaySeparator and SWQU devices have 100 year service lives while the Defender's service life is 30 years. To compare the Defender against the other two devices, the purchase, installation, and use of 3 and 1/3 Defender devices were considered to equal a 100 year service-life. To compare the defender on a 50 year service-life, 1 and 2/3 Defender devices were considered to equal a 50 yr service life. To determine the annual worth the defender device through 100 years, the present worth and inflation was considered every instance the device was purchased/installed.

Worth for the cost for INDOT than a device that performed for its entire service life. From an Annual Worth perspective, the *BaySeparator* device was the more attractive unit to select. ADS, Inc. chose not to provide cost data to the project team for their *SWQU*.

3.2.5 Comparison of the Cost of Pollutant Removed by Device

Because the only similar data available for the devices was percent pollutant removed, this was the metric applied to compare the cost of pollutant removed across devices. These costs were calculated for two conditions: (1) use of independent laboratory testing results and (2) manufacturer reported testing results. Table 3.5 shows that the Annualized Worth for *BaySeparator* device was much less than that of the *Downstream Defender* device. This result is because the initial costs of the *BaySeparator* device is less than that of the *Downstream Defender* device. Also, the *Downstream Defender* performed poorly in the sole independent laboratory storm water pollution test found in the literature. This poor pollutant removal performance resulted in a greater cost to remove pollutant. To improve pollutant removal additional *Downstream Defender* devices would need to be installed not just one. However, this would carry with it additional initial and O&M costs likely never being as less costly as the *Bay Separator* device. Not considered in any of these cost calculations are construction and land costs. These factors could significantly change the results. Because there was no independent testing data for the *SWQU* no direct comparison could be carried out for this device.

The second analysis included determining the cost benefit using manufacturer reported device performance data. Manufacturer reported results show much more cost advantageous devices than those that performed in independent testing. The Annual Worth of the cost for the devices is much less and the difference between the devices is also greatly reduced. These results demonstrate that the CBA is very sensitive to the device's pollutant removal performance and if data used in the CBA are not representative of field conditions, results of the CBA itself could be misleading.

3.3 Limitations

This cost-benefit analysis has limitations, but provides several important findings. The project team could not use the NCHRP storm water BMP cost model because data needed to run the model was lacking from INDOT projects. This includes appropriate device cost, land, construction, and device pollutant removal data for currently installed BMPs. This lack of data also inhibited the project team's conduct of a CBA using modified approach. The lack of data was not unique to INDOT, but also existed at various Indiana MS4s contacted by the project team and INDOT staff.

To develop more robust and field relevant CBA's for storm water BMPs INDOT should take efforts to procedurally document and make easily accessible or retrievable storm water BMP design, performance, and cost data. Data that should be set aside can include construction costs, right-of-way costs, acreage treated by each device, design specifications for each device installed per site. Device pollutant removal data should also be obtained as this study indicates that relying on manufacturer reported results could greatly skew the CBA from the device's actual worth.

The finding that the manufacturer reported device performance data found was not corroborated by independent device testing data is important. Manufacturer reported data greatly overestimated the device's pollutant removal performance compared to the few independent studies found. These devices may meet or exceed manufacturer device performance specifications at higher pollutant influent concentrations. Sole reliance on manufacturer reported data would have skewed the device CBA compared to actual device data from an independent testing laboratory. To develop a more applicable CBA storm water treatment device pollutant removal data is needed. This could be conducted by bench-scale, pilot-scale or field-scale device testing.

There are a variety of storm water BMPs that have been installed across the U.S. Based on the project team's literature review, the ability of these devices to remove pollutants however remains poorly understood. Some devices such as wet ponds have been found to generate *E. coli* and contribute to downstream water quality pollution. Native phosphorous can be leached from bioretention systems. For other devices, such as dry or wet swales, sediment removal is highly sensitive to slope and vegetation density. Dissolved pollutants seem unable to be removed by sand filter filtration. There are wide ranges in pollutant removal effectiveness between devices. These observations are likely due to

TABLE 3.5
Cost Benefit of Each Device per 1% of Pollutant Removed Annually

	SCC		TSS		TP	
Service-Life	**50 year**	**100 year**	**50 year**	**100 year**	**50 year**	**100 year**
Independent Laboratory Testing Results						
BaySeparator	$33	$26	$46	$36	$79	$62
Defender	$116	$115	No removal	No removal	No removal	No removal
SWQU	nd	nd	nd	nd	nd	nd
Manufacturer Laboratory Testing Results						
BaySeparator	$19	$15	$19	$15	No data	No data
Defender	$28	$27	$28	$27	$28	$27
SWQU	–	–	–	–	–	–

nd = No data.
No independent laboratory testing results were available for the SWQU.

one or more of the following: Inadequate consideration for water flowrate or pollutant loading to the BMP, improper storm water BMP construction or location, inaccurate measurements of BMP performance, or patterns of precipitation and discharges.

4. RECOMMENDATIONS

1. INDOT should establish agency-wide procedures to begin collecting pertinent storm water BMP information from ongoing and planned projects so that (1) the existence of each BMP and its design parameters are documented in a centralized location, easily accessible, and (2) future CBAs can be conducted. An example of the information that is needed can be found in Appendix B. It is recommended that this information be a required submittal by the installer before final payment on a series of forms.
2. INDOT should apply caution when estimating BMP performance based on manufacturer reported data or BMP performance data from other parts of the U.S. As of today, there are no nationally recognized standardized test methods for the performance of proprietary or passive BMPs. Some DOTs and municipalities across Indiana and the country are conducting their own investigations to gauge BMP performance. The International BMP Database provides an excellent overview of what is known for storm water BMP pollutant removal performance: http://www.bmpdatabase.org/. INDOT however should be cautious in that there are various studies in the literature where some “BMPs” have been shown not to be effective at all for removing pollutants and other “BMPs” generate pollutants. There are additional studies showing the reverse. BMP performance is highly influenced by a variety of design, location, and environmental factors. Some BMPs may not remove detectable amounts of pollutants when storm water that it is treating contains a low level of pollutants to begin with. To understand how BMPs perform in Indiana field monitoring is recommended. It is recommended that types of BMPs in Indiana be prioritized then down selected for a field investigation. Monitoring should be carried-out over a 1–3 year period to be in line with other BMP field studies conducted across the U.S. The planned construction activities on Indiana roadways provides an opportune time to institute a new data collection policy and begin field monitoring.
3. For an improved cost-benefit analysis comparison of existing, planned, and future storm water BMPs, INDOT should consider the following actions:
    a. INDOT should setup procedures to capture BMP design and cost data in the agency database and make an interface that is easily accessible. A major challenge to the present study was that data needed to evaluate the cost of BMPs to INDOT required hours of time by INDOT employees to track down. Another challenge was that most of the information needed was not found. This inefficiency can likely be addressed by establishing policies and procedures so that INDOT can better prepare to receive and track BMP costs.
    b. INDOT should not solely rely on the BMP’s manufacturer reported removal efficiency as predictor of field performance. There are few to none BMP technology validation standards. As a result, performance is highly dependent on the pollutant loading of storm water entering the BMP. For example, if pollutant concentration of storm water influent entering the BMP is low little to no pollutant removal could take place. As a result, the BMP could have low pollutant removal efficiency. In contrast, a BMP that receives excessively high pollutant loading may only be able to removal a fraction of the pollutants, thereby discharging pollutants downstream in unacceptable concentrations. The approach being more widely accepted is monitoring pollutant removal from BMPs on a total mass of pollutant removed per time basis (pounds of pollutant per year, etc.). Water quality monitoring data for storm water entering and exiting the BMP as well as BMP design information is required for this performance metric to be useful.
    c. If INDOT conducts storm water monitoring, solids removal efficiency should be considered using suspended sediment concentration (SSC) not total suspended solids (TSS) concentration. There is growing consensus

that SSC is a more accurate water quality characteristic for storm water than TSS measurement.

With a more complete data set for BMP pollutant removal and costs, a cost-benefit analysis of INDOT storm water BMPs could be conducted. Enough data was not available for determining life-cycle costs that would assist INDOT in decision making. INDOT did not have the necessary information and such data was not found elsewhere. Also, pollutant removal performance is a major factor in the cost ($) benefit (i.e., lbs of pollutant removed) of a BMP. As this study shows, there is no reliable data to use for pollutant removal performance. If the limited existing data were used, as calculations show, INDOT could significantly overestimate the benefit of the BMP. Without a validated pollutant removal dataset INDOT cannot rely on any CBA to make science based decisions. Additional information is needed. The following actions are recommended if a field-relevant CBA is desired:

a. INDOT could survey which and how many BMPs are under INDOT control. This survey could identify the types of BMPs that are most commonly used across Indiana enabling INDOT to understand its current stock of BMPs. The survey could also help identify if any BMPs, once installed, precipitated problematic maintenance demands. The degree maintenance has or has not been routinely conducted on those assets could also be determined. This type of survey would be best conducted if all Districts participated.
b. Because numerous prior studies by other DOTs and researchers across the US have shown wide variability in BMP pollutant removal performance, INDOT could consider bench-, pilot-scale or field-scale testing select BMPs to determine pollutant removal effectiveness. At the same time BMP design and cost data should be collected for those assets so that a more rigorous CBA can be conducted. Past studies that have involved determining BMP removal effectiveness have typically conducted storm water monitoring for BMPs over the course of 1–2 years as weather patterns (i.e., rainfall, drought, etc.) can drastically influence device performance.

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APPENDIX A: DESIGN VIEWS OF 15 STORM WATER BMPS REVIEWED IN THIS STUDY

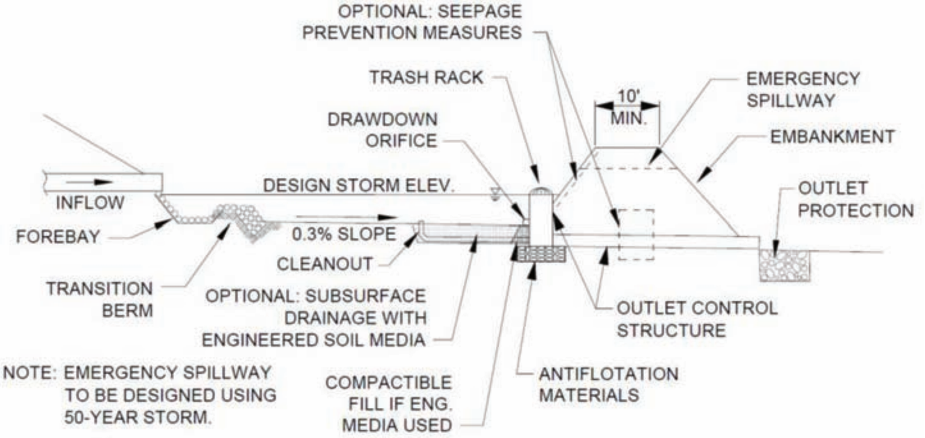


Figure A.1 Dry detention basin profile design view (NCDOT, 2014) infiltration basin.

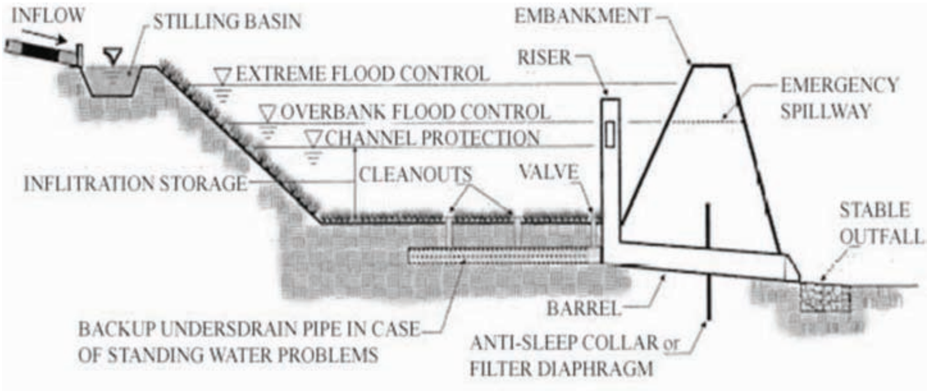


Figure A.2 Infiltration basin profile design view.

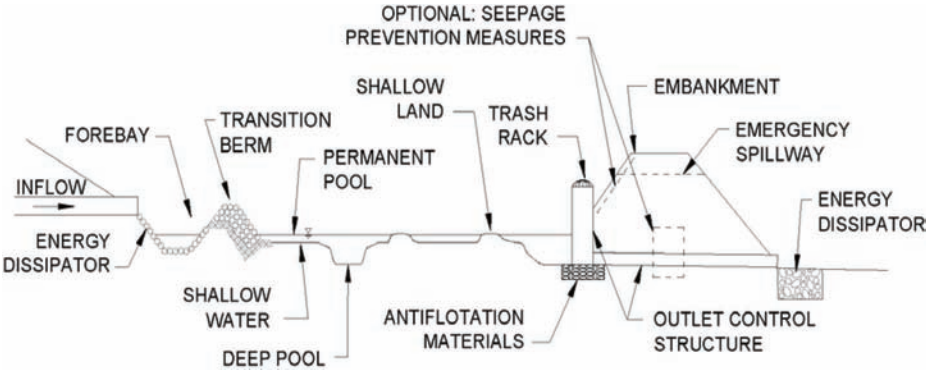


Figure A.3 Wetland profile design view (NCDOT, 2014).

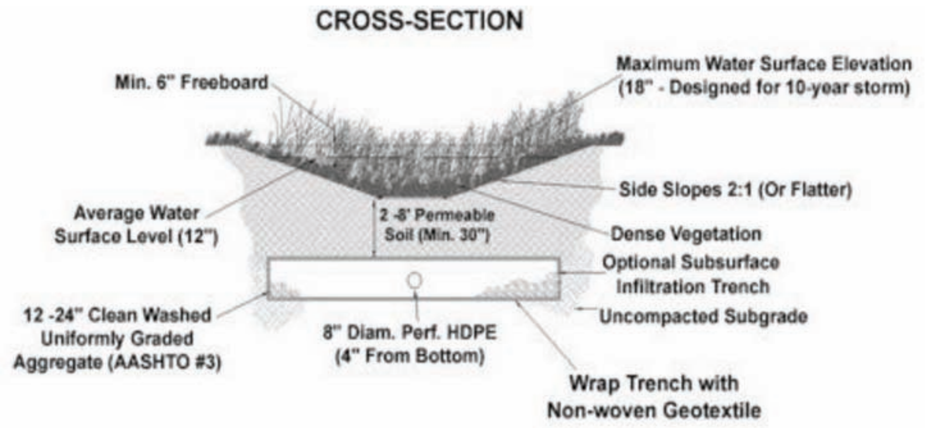


Figure A.4 Vegetated swale profile design view (PADEP, 2006).

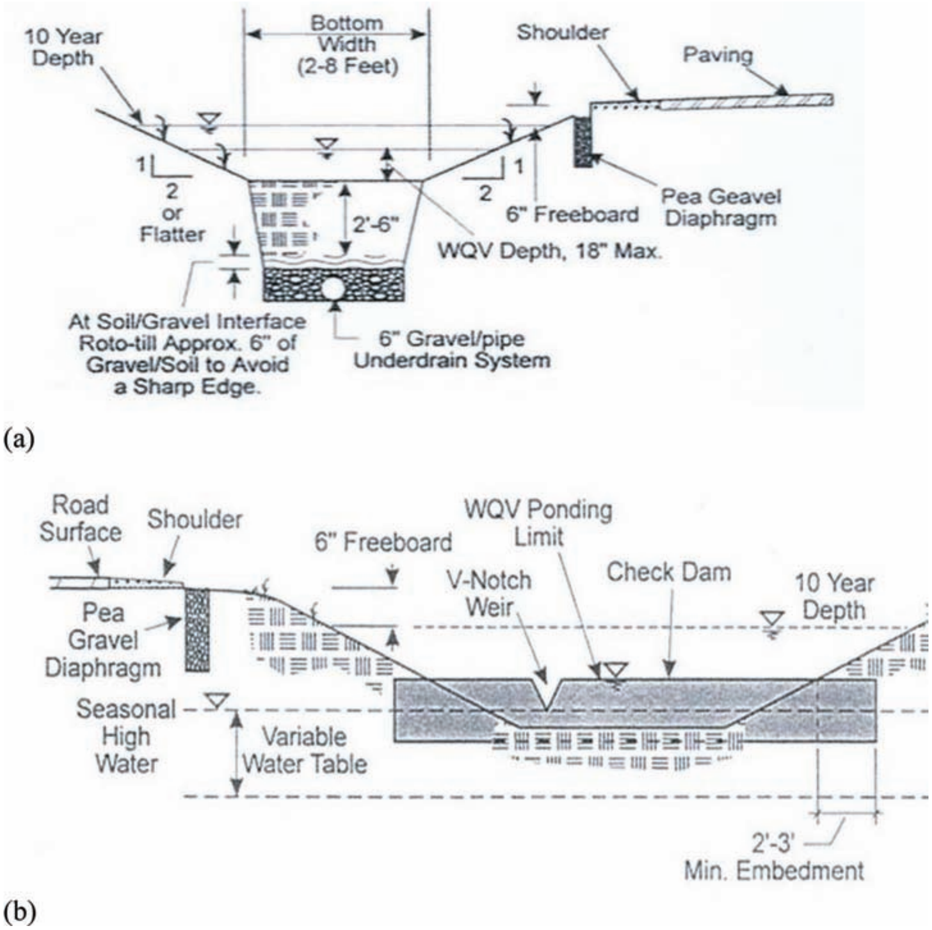


Figure A.5 (a) Dry swale and (b) wet swale (IOWADOT, 2010).

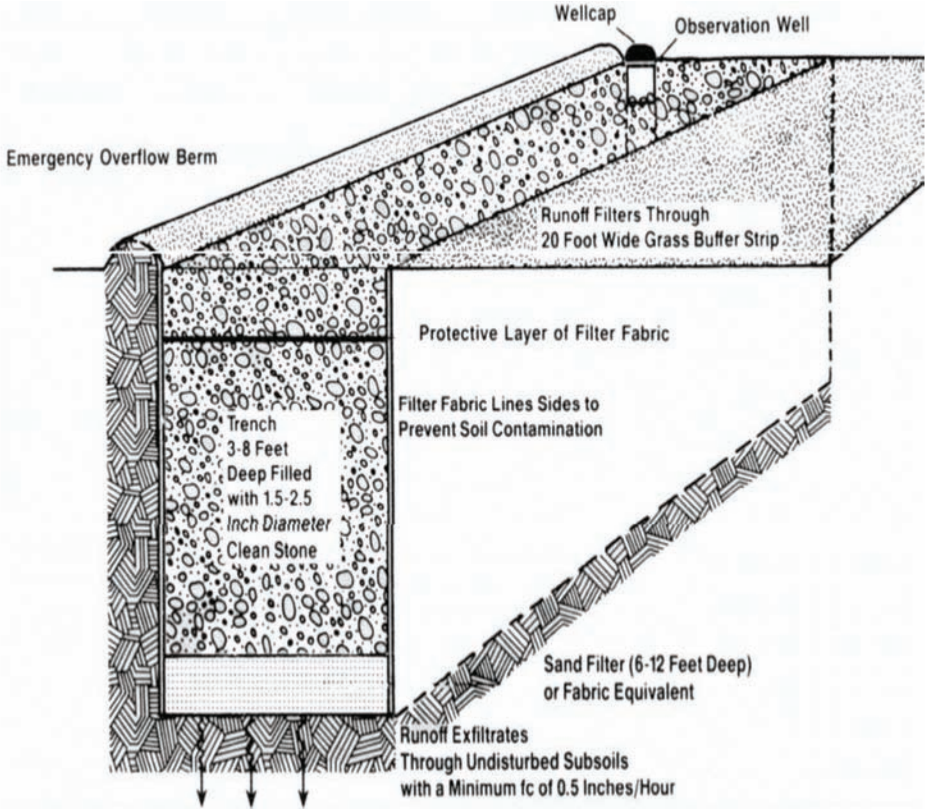


Figure A.6 Infiltration trench profile design view (AES, 2006).

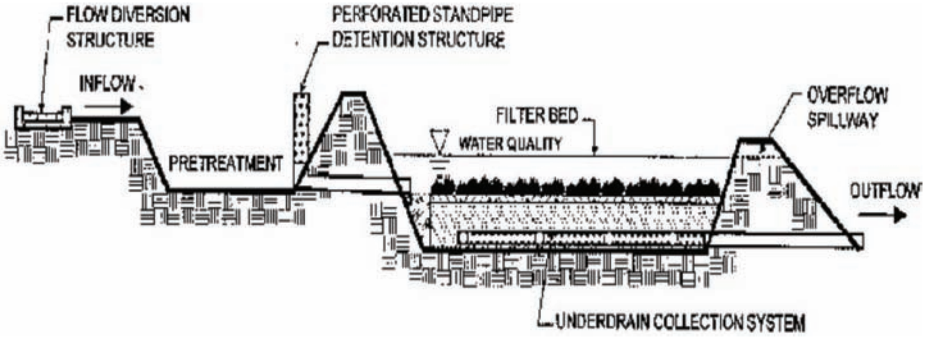


Figure A.7 A typical sand filter (CWP, 2000).

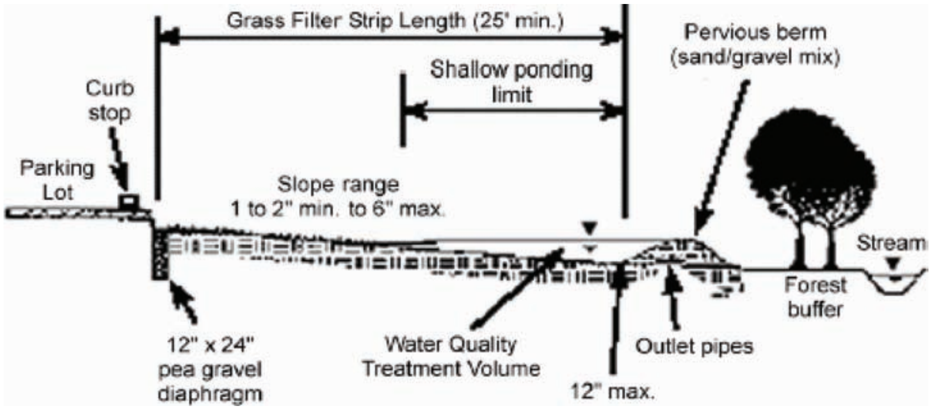


Figure A.8 Vegetated filter strip profile design view (AES, 2006).

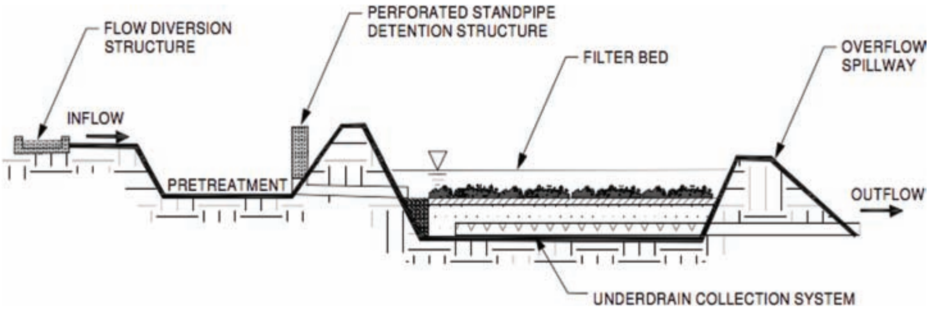


Figure A.9 Organic filter profile design view (AMEC, 2008).

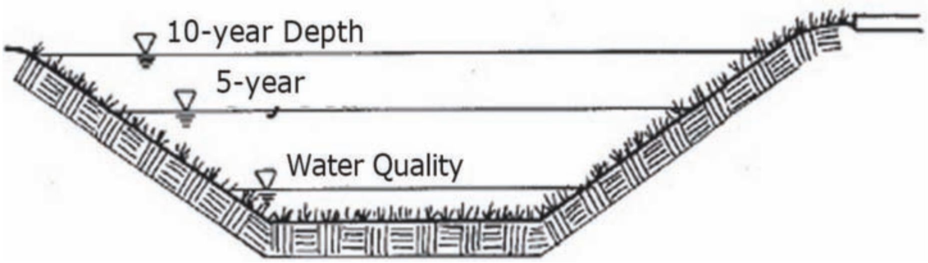


Figure A.10 Grassed channel profile design view (AMEC, 2008).

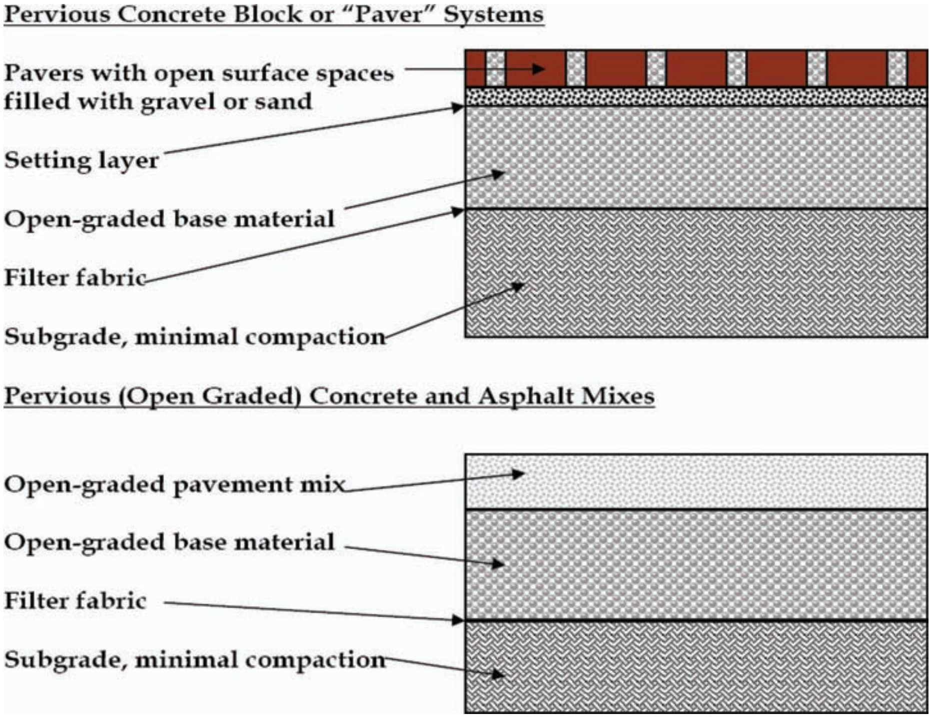


Figure A.11 Two pervious pavement system profile design views (AES, 2006).

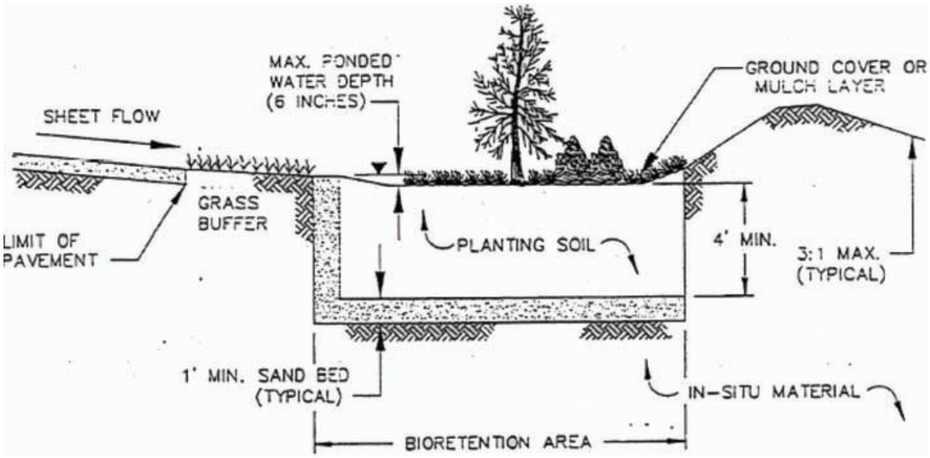


Figure A.12 Bioretention system profile design view (AES, 2006).

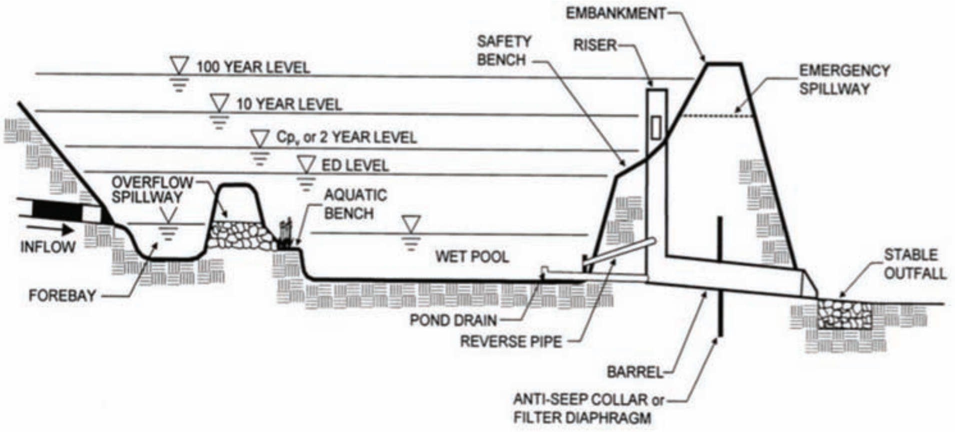


Figure A.13 Wet detention pond profile design view (PADEP, 2006).

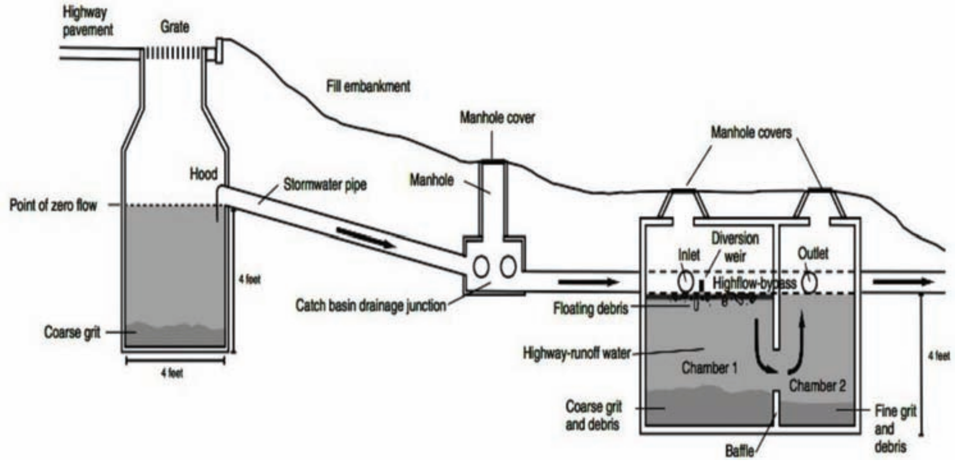


Figure A.14 Oil-grit separator profile design view (Smith, 2002).

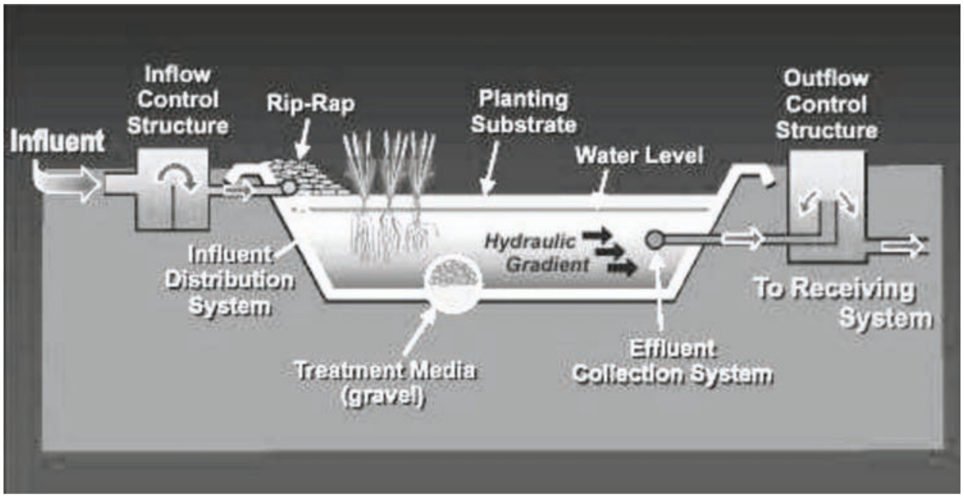
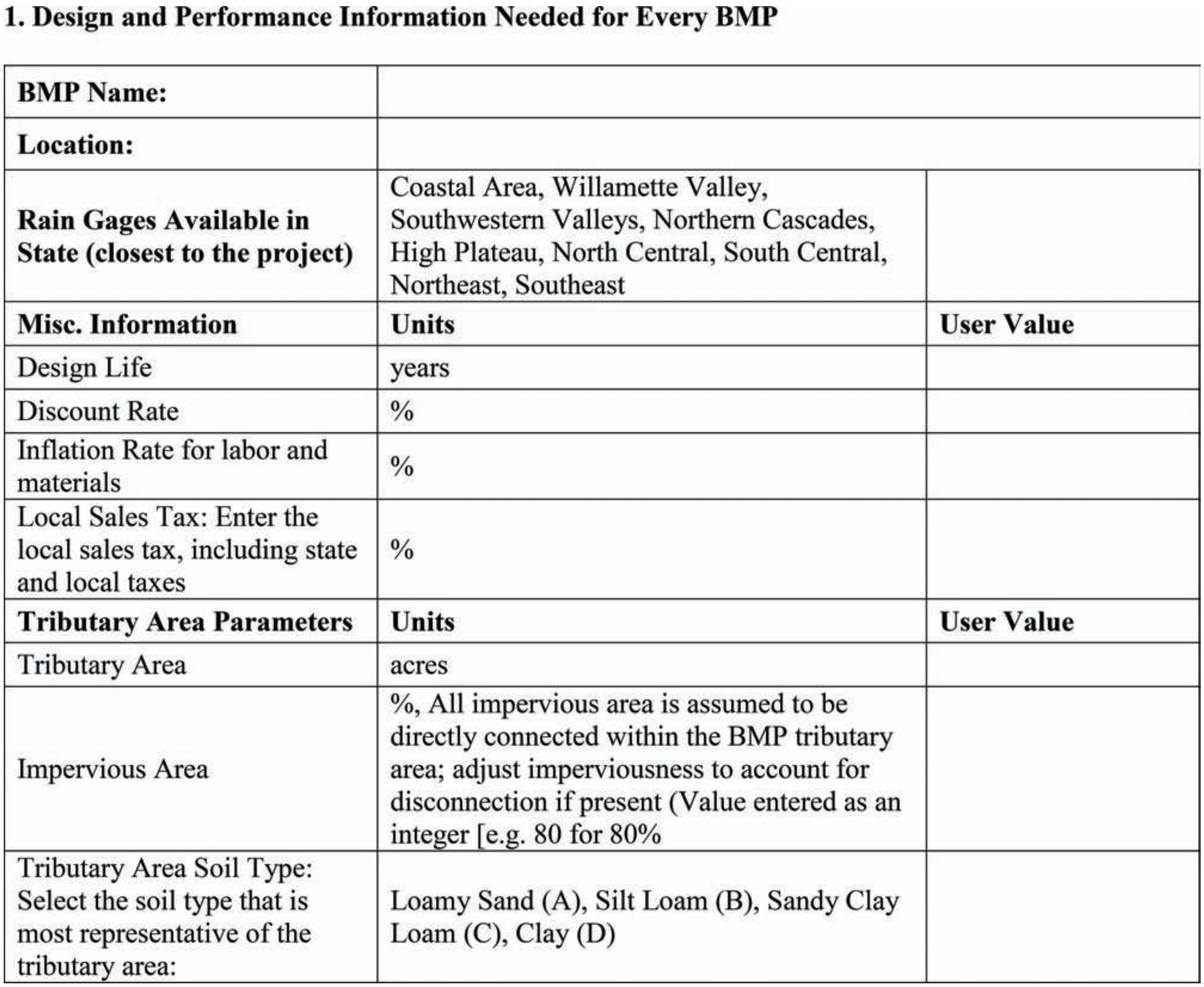


Figure A.15 Submerged gravel wetland (AMEC, 2008).

APPENDIX B: NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM (NCHRP) DATA COLLECTION SCRIPT FOR POST-CONSTRUCTION BMPS



1. Design and Performance Information Needed for Every BMP

BMP Name:		
Location:		
Rain Gages Available in State (closest to the project)	Coastal Area, Willamette Valley, Southwestern Valleys, Northern Cascades, High Plateau, North Central, South Central, Northeast, Southeast	
Misc. Information	**Units**	**User Value**
Design Life	years	
Discount Rate	%	
Inflation Rate for labor and materials	%	
Local Sales Tax: Enter the local sales tax, including state and local taxes	%	
Tributary Area Parameters	**Units**	**User Value**
Tributary Area	acres	
Impervious Area	%, All impervious area is assumed to be directly connected within the BMP tributary area; adjust imperviousness to account for disconnection if present (Value entered as an integer [e.g. 80 for 80%	
Tributary Area Soil Type: Select the soil type that is most representative of the tributary area:	Loamy Sand (A), Silt Loam (B), Sandy Clay Loam (C), Clay (D)	

2. Design Parameters Needed for Each BMP Type

Swale		
Design Parameters	**Units**	**User Value**
Water Quality Design Flow: The flow through the swale required to achieve the desired water quality performance	cfs	
Bottom length: The length of the conveyance/swale feature in the direction of flow	ft	
Effective amended soil depth: Select from available options. Represents depth of soil and/or gravel sump that is actively available for soil soaking and drying. Pick value from 0″, 3″, 6″, 12″, 24″	inches	
Fraction of runoff as lateral inflow: The fraction of runoff that enters the swale laterally (from the sides). This fraction is treated as a filter strip	%	
Longitudinal slope: The average slope in the direction of flow	ft/ft	
Time of concentration: User specified, time of concentration based on the water quality design flow, pick value from 5, 10, 15, 20, 30, 60	min	
Manning's friction coefficient: User specified, manning's friction coefficient based on vegetation and surface of swale	unitless	
Bottom width, ft: The width of the approximately flat section at the bottom of the conveyance/swale feature	–	Calculated value, not input value
Calculated pervious area, ft^2: Estimate footprint area for volume reduction calculations	–	Calculated value, not input value
Ratio of pervious area to impervious area: Calculated based on user inputs; fundamental indicator of volume reduction performance	–	Calculated value, not input value
Wetland area, ft^2: Calculated based on previous inputs for water quality estimation only	–	Calculated value, not input value
Wetland perimeter, ft: Calculated based on previous inputs for water quality estimation only	–	Calculated value, not input value
Hydraulic radius, ft: Calculated based on previous inputs for water quality estimation only	–	Calculated value, not input value
Calculated design intensity, in/hr: Calculated based on previous inputs for water quality estimation only	–	Calculated value, not input value
Hydraulic residence time, min: Calculated based on the water quality flow and the swale bottom length	–	Calculated value, not input value

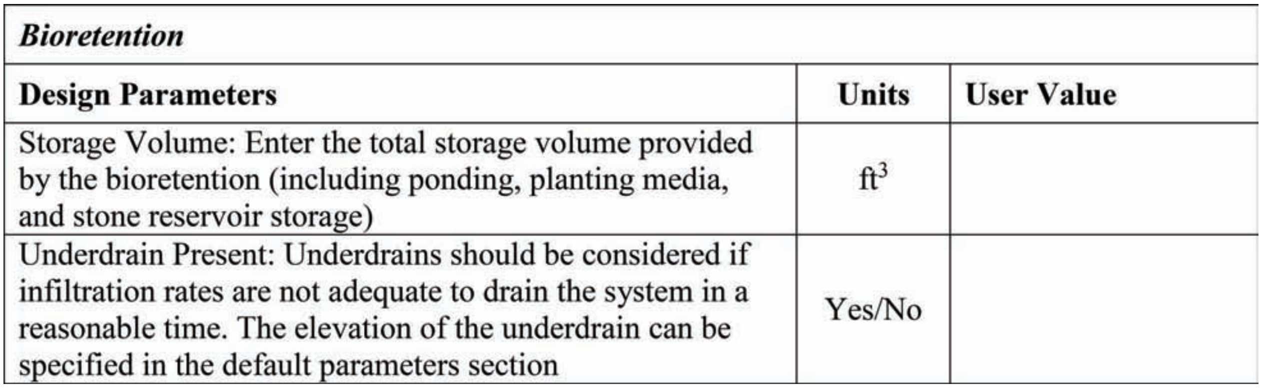
Filter Strip		
Design Parameters	**Units**	**User Value**
Water Quality Flow: The flow over the filter strip desired to meet the water quality design requirements. Used to compute residence time, which is for informational purposes to assist with proper sizing	cfs	
Length: The length of the filter strip perpendicular to the flow	ft	
Underling Soil Design Infiltration Rate: A default infiltration rate has been provided based on the soil type selected for the tributary. If a localized site infiltration rate is available, it should override this default data	in/hr	
Effective Amended Soil Depth: Pick value from 0″, 3″, 6″, 12″, 24″	inches	
Overland Flow Width: The width of the filter strip in the direction of the flow	ft	
Longitudinal Slope: The average slope in the direction of flow	ft/ft	
Manning's Friction Coefficient: User specified, manning's friction coefficient based on vegetation and surface of filter strip	unitless	
Water Quality Flow Depth, in: The design depth, below which the majority of flow is assumed to be conveyed and above which treatment processes begin to decline. If this value is greater than 2/3 the height of the grass, the filter strip is undersized	–	Calculated value, not input value
Hydraulic residence time, minutes: Calculated based on the water quality flow and the filter strip dimensions. If this is less than 9 minutes, consider a longer overland flow width or shallower slope	–	Calculated value, not input value
Calculated pervious area, ft^2: Estimated footprint area	–	Calculated value, not input value
Rate of pervious area to impervious area: Calculated based on user inputs; fundamental indicator of volume reduction performance	–	Calculated value, not input value

Permeable Friction Course (PFC)		
Design Parameters	**Units**	**User Value**
Permeable Friction Course Surface Area: Enter the total surface area of the permeable friction course overlay. In most cases this should equal the tributary area converted to ft^2	ft^2	
Permeable Friction Course Depth: Enter the total depth of the permeable friction course overlay. This parameter only affects capital costs	in	

Wet Pond		
Design Parameters	**Units**	**User Value**
Total Storage Volume: Enter the total storage volume provided by the extended detention basin up to the primary overflow	ft^3	
Surcharge Depth: The surcharge depth is equal to the depth from the permanent pool elevation up to the overflow elevation. The surcharge volume, which is a function of this depth, must always be smaller than the permanent pool volume	ft	
Permanent Pool Depth: The permanent pool depth represents the outlet offset from the bottom of the pond. The permanent pool volume, which is a function of this depth, must always be greater than the surcharge volume	ft	
Surcharge Volume Drawdown Time: Enter the surcharge volume minimum drawdown time required to achieve full treatment	hr	
Minimum Residence Time in the Permanent Pool: The target residence time of a parcel of water at the water quality design flow rate	hr	

Sand Filter		
Design Parameters	**Units**	**User Value**
Storage Volume: Enter the total storage volume provided by the ponding depth	ft^3	
Max Ponding Depth: Ponding depth is equal to the elevation of the overflow above the surface of the media	ft	
Media Thickness: The thickness of the sand or media layer provided	ft	
Media Filtration Rate: The rate at which water will infiltrate through the sand or media	in/hr	
Calculated footprint area, ft^2: This footprint calculated as the storage volume divided by the ponding depth; actual dimensions may vary	–	Calculated value, not input value
Calculated drawdown time, hr: The drawdown time is calculated based on the storage volume and the media filtration rate. Adjust the design parameters to increase or decrease the drawdown time	–	Calculated value, not input value

Dry Detention		
Design Parameters	**Units**	**User Value**
Storage Volume: Enter the total storage volume provided by the extended detention basin up to the primary overflow	ft^3	
Impermeable liner present? If incidental infiltration is not required or the underlying soil is not suitable, an impermeable liner may be applied	Yes/No	
Water Quality Depth: Water quality depth is equal to the elevation of the primary overflow above the surface of the planting media	ft	
Design Drawdown Time: Enter the design drawdown time or residence time that represents the treatment required	hr	
Approximate area of basin, ft^2: This footprint represents the surface area of basin at water quality depth, assuming a rectangular shape; actual dimensions may vary	–	Calculated value, not input value
Calculated outlet flow, cfs: The outlet flow is calculated based on the storage volume and the design drawdown time, also accounting for the presence of an impermeable liner	–	Calculated value, not input value
Approximate area of basin bottom, ft^2: The basin bottom area is calculated based on the ponding depth, the BMP length/width ratio, and the horizontal/vertical slope ratio. This area is used in determining the quantity of design infiltration	–	Calculated value, not input value



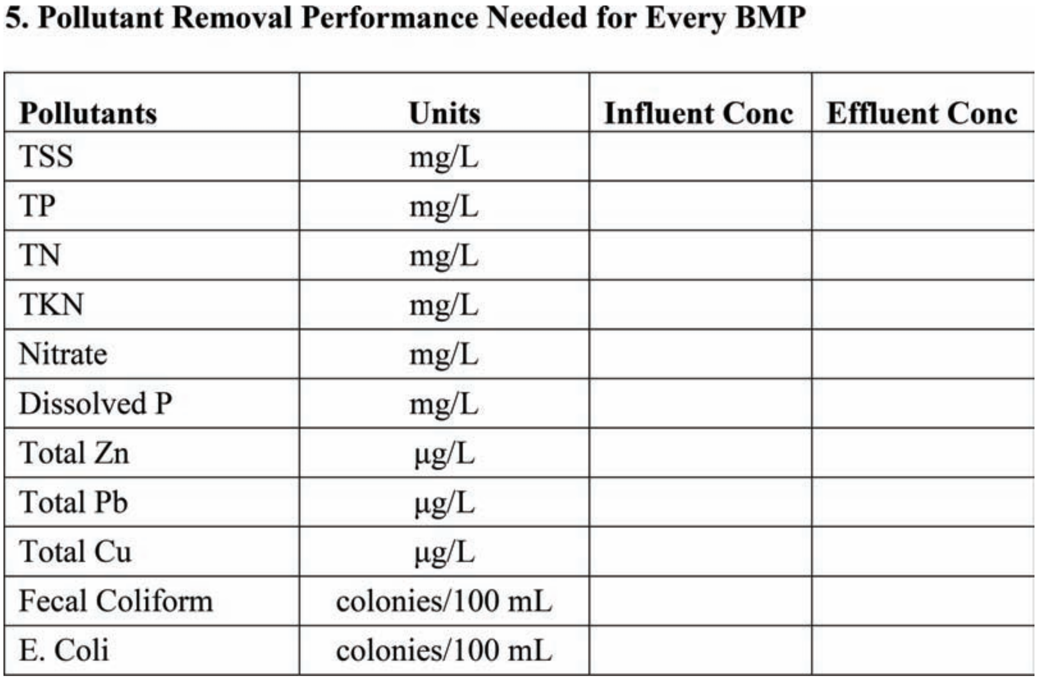
Bioretention		
Design Parameters	**Units**	**User Value**
Storage Volume: Enter the total storage volume provided by the bioretention (including ponding, planting media, and stone reservoir storage)	ft^3	
Underdrain Present: Underdrains should be considered if infiltration rates are not adequate to drain the system in a reasonable time. The elevation of the underdrain can be specified in the default parameters section	Yes/No	

3. Capital Cost Information Needed for Every BMP

Capital Costs	Base Unit	User Value	Quantity
Mobilization	$		
Clearing and Grubbing	yd^2		
Excavation/Grading	yd^3		
Dewatering	days		
Haul/Dispose of Excavated Material	yd^3		
Inflow Structures	$		
Overflow Structure [concrete or rock riprap]	yd^3		
Hydroseed/Erosion Control	ft^2		
Metal Beam Guard Rail	linear ft		
Signage, Public Education Materials, etc.	$		
Project Management	$		
Engineering (preliminary)	$		
Engineering (final design)	$		
Topographic Survey	$		
Geotechnical	$		
Landscape Design	$		
Land Acquisition (site, easements, etc.)	$		
Utility Relocation	$		
Legal Services	$		
Permitting and Construction Inspection	$		
Sales Tax (if known for specific project)	$		
Contingency	$		

4. Maintenance Cost Information Needed for Every BMP

Maintenance Costs	Frequency	Hours per Event	Average Labor Crew Size	Average Pro-Rated Labor Rate per Hour	Machinery Cost per Hour	Materials and Incidental Cost
Routine Maintenance						
Inspection, Reporting & Information Management						
Vegetation Management with Trash and Minor Debris Removal						
Additional Activities						
Corrective/Infrequent Maintenance						
Corrective Maintenance						
Additional Activities						



5. Pollutant Removal Performance Needed for Every BMP

Pollutants	Units	Influent Conc	Effluent Conc
TSS	mg/L		
TP	mg/L		
TN	mg/L		
TKN	mg/L		
Nitrate	mg/L		
Dissolved P	mg/L		
Total Zn	µg/L		
Total Pb	µg/L		
Total Cu	µg/L		
Fecal Coliform	colonies/100 mL		
E. Coli	colonies/100 mL		

APPENDIX C: COST, OPERATIONS, AND MAINTENANCE COMPARISON OF THREE BMPS EXAMINED IN THE COST-BENEFIT ANALYSIS

Treatment Device	Model Name	Purchase Cost ($)	Maintenance Cost ($)	Installation Cost ($)
BaySeparator	½K	7000	800–1500	3000
	1K	9000	800–1500	3000
	3K	14000	800–1500	3000
	5K	19300	800–1500	3000
	10K	28500	800–1500	3000
Downstream Defender	4-ft	11000	800–1000	No data
	6-ft	16,000	800–1000	No data
	8-ft	24,000	800–1000	No data
	10-ft	41,000	800–1000	No data
	12-ft	62,000	800–1000	No data

The Costs of BaySeparator and Downstream Defender with Different Models.

BaysSparator. Cost per maintenance (once a year).

- Installation cost depends on size of device, and site conditions.
- Service life of 100 yr.
- Reported by manufacturer.

Downstream Defender. Cost per maintenance (once a year, depends on the area that runoff is formed).

- Installation cost depends on size of device, and site conditions.
- Service life of 30 yr.
- Reported by manufacturer.

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,500 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at: http://docs.lib.purdue.edu/jtrp

Further information about JTRP and its current research program is available at: http://www.purdue.edu/jtrp

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