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A Comparison of Maintenance Cost, Labor Demands, and System Performance for LID and Conventional Stormwater Management

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Abstract

The perception of the maintenance demands of Low Impact Development (LID) systems represents a significant barrier to the acceptance of LID technologies. Despite the increasing use of LID over the past two decades, stormwater managers still have minimal documentation in regards to the frequency, intensity, and costs associated with LID operations and maintenance. Due to increasing requirements for more effective treatment of runoff and the proliferation of total maximum daily load (TMDL) requirements, there is greater need for more documented maintenance information for planning and implementation of stormwater control measures (SCMs).

This study examined seven different types of SCMs for the first 2-4 years of operations and studied maintenance demands in the context of personnel hours, costs, and system pollutant removal. The systems were located at a field facility designed to distribute stormwater in parallel, in order to normalize watershed characteristics including pollutant loading, sizing, and rainfall. System maintenance demand was tracked for each system and included materials, labor, activities, maintenance type, and complexity. Annualized maintenance costs ranged from $2,280/ha/yr for a vegetated swale to $7830/ha/yr for a wet pond. In terms of mass pollutant load reductions, marginal maintenance costs ranged from $4-$8 per kg/yr TSS removed for porous asphalt, a vegetated swale, bioretention, and a subsurface gravel wetland, to $11-$21 per kg/yr TSS removed for a wet pond, a dry pond, and a sand filter system. When nutrients such as nitrogen and phosphorus were considered, maintenance costs per g/yr removed ranged from reasonable to cost prohibitive especially for systems with minimal to no nutrient removal. As such, SCMs designed for targeting these pollutants should be selected carefully. The results of this study indicate that generally, LID systems, as compared to conventional systems, have lower marginal maintenance burdens (as measured by cost and personnel hours) and higher water quality treatment capabilities as a function of pollutant removal performance. Cumulative amortized system maintenance expenditures equal the SCM capital construction costs (in constant dollars) in 5.2 years for wet ponds and in 24.6 years for the porous asphalt system. In general SCMs with higher percentages of periodic and predictive, or proactive maintenance activities have lower maintenance burdens than SCMs with incidences of reactive maintenance.

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Introduction

The misunderstanding of inspection and maintenance expectations for Low Impact Development (LID) systems have been one of the significant barriers to the acceptance of LID technologies. Most entities in charge of stormwater management systems over the past four decades generally have adopted maintenance plans or guidelines for conventional systems (curb, gutter, swale, and pond), yet there is little documentation in terms of the frequency, intensity, and costs associated with LID maintenance operations required to meet system design objectives. With increasing requirements for more efficient stormwater management designs and the proliferation of total maximum daily load (TMDL) requirements, a greater amount of documented maintenance information is necessary to facilitate the implementation of more

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effective stormwater management strategies. Increased attention to pollutant loads, numeric goals, and non-degradation requirements have also created the need for more emphasis on stormwater control measure (SCM) maintenance in order to meet permitting and reporting requirements (Erickson et al., 2010). Furthermore, as municipalities move to implement LID, managers need better information, resources and methods to estimate an LID technique's total costs, including maintenance. With more long-term LID maintenance costs available, cost estimations of this alternative will become easier to accomplish and more precise (Powell et al., 2005).

Traditionally, there has been significant resistance towards the acceptance and adoption of LID designs due to the perception that these systems have substantial maintenance requirements, representing a significant cost burden to developers and site owners. In contrast, proponents regard LID designs as lower in maintenance compared to conventional stormwater controls (MacMullan 2007; Powell et al., 2005; EPA 2000).

As an example of the available documentation directing LID maintenance protocols, the Prince George's County, Bioretention Manual (PGDER, 2007), recommends a frequency and time of year for the maintenance of plants, soil, and the organic layer of bioretention systems. Likewise, the Washington State University Pierce County Extension Maintenance of Low Impact Development Facilities (WSU, 2007) provides maintenance schedules for bioretention and permeable paving areas, listing general maintenance activity recommendations including objectives. However, while recommending specific activities and frequencies associated with LID maintenance, these documents, like others, do not cover costs and are not based on

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empirical data or referable evidence in terms of studied LID maintenance activities for ensuring system functionality. While many stormwater management manuals have stated the importance and estimated frequency of maintenance for SCMs, few have documented the actual frequency and intensity of maintenance required to maintain a desired level of performance and efficiency (Erickson et al., 2010).

Weiss et al. (2005), in a study comparing the cost and effectiveness of several common SCMs including LID designs (constructed wetlands, infiltration trenches, sand filters, bioinfiltration filters), found little data available that documented actual operation and maintenance (O&M) costs of existing SCMs. At best, the study found that available data consisted only of expected or predicted O&M costs of recently constructed SCM projects. Often times, estimated annual O&M costs are presented as a percentage of the total capital cost (Weiss et al., 2005) or as an annual percentage of capital costs (Narayanan and Pitt 2006). An example includes the USEPA's (1999) annual O&M costs for a range of typical SCMs, expressed as a percentage of the construction cost.

In a study for advancing short and long-term maintenance considerations so as to develop more realistic maintenance plans, Erickson et al. (2009) conducted a detailed municipal public works survey to identify and inventory stormwater SCM O&M efforts and costs. Results indicated that most cities (89%) perform routine maintenance once per year or less with staff-hours per year ranging from one to four hours for most stormwater SCMs, but significantly higher for rain gardens (one to sixteen hours per year) and wetlands (one to nine hours per year). In terms of costs, the study found that SCM maintenance expenses will roughly equal the construction cost (in constant dollars) after 10 years for a $10,000 installation (i.e. 10% of capital cost) and after 20 years for a $100,000 installation (i.e. 5% of capital cost in 2005 dollars).

In another effort towards better forecasting life-cycle project cost estimates of different stormwater control alternatives, Narayanan and Pitt (2006) utilized maintenance cost data from the Southeastern Wisconsin Regional Planning Commission (SWRPC), which documented maintenance costs for a range of SCMs, including LID. According to SWRPC figures, incremental average annual maintenance costs in 1989 dollars (over conventional pavement) for a permeable pavement parking lot was found to be $42/hectare ($17/acre) for vacuum cleaning, $20/hectare ($8/acre) for high-pressure jet hosing (which should likely only be used in isolated clogged areas), and $25 per inspection. Likewise, annual SWRPC maintenance costs for infiltration trenches was found to be $92/hectare ($37/acre) for buffer strip mowing, $9690/hectare ($3920/acre) for general buffer strip lawn care, and $25/inspection plus $50/trench for program administration.

The objective of this study is to develop quantified maintenance expendatures in the form of required personnel hours and economic costs expended for a broad range of SCMs. The University of New Hampshire Stormwater Center (UNHSC) has tested over 26 treatment strategies to date, logging all inspection hours and maintenance activities over the course of a 6-year study (2004-2010). For the purposes of this study, researchers compiled data from UNHSC testing efforts of seven different types of SCMs including conventional systems such as a wet pond, a dry pond, and a swale, as well as LID systems including bioretention, sand filter, subsurface gravel wetland, and a porous asphalt pavement. Manufactured treatment devices were omitted from this study as many vendors and product providers offer comprehensive and detailed O&M information pertaining to their systems.

Methodology

Site Design

The UNHSC site was designed to function as a series of uniformly sized, isolated, and parallel treatment systems with capacity for stormwater to be conveyed to each treatment device without significant transmission impacts from the distribution systems upon processes such as sedimentation. The watershed is a 4.5 ha commuter parking lot. Rainfall-runoff is evenly divided at the headworks of the facility in a distribution box, designed with an elevated floor that is slightly higher than the outlet invert which allows for scouring across the floor and into the pipe network. Effluent from all of the treatment systems flows into a sampling gallery where system sampling and flow monitoring are centralized. The parallel configuration normalizes the treatment processes for event and watershed-loading variations (all technologies receive the same influent hydrograph and water quality). This process and SCM design information are fully described in previous publications (Roseen, et al, 2009), and in Table 1.

The SCMs discussed in this paper include a vegetated swale, a wet pond, a dry pond, a sand filter, a subsurface gravel wetland, three bioretention systems (averaged), and a porous asphalt pavement. The treatment strategies are all uniformly sized to treat the same water quality flows and volumes, with equal capacity for conveying large flows. Design criteria were based on a rainfall frequency analysis to determine the 24-hour rainfall depth corresponding to a non-exceedance frequency of approximately 90%. For much of the northeast United States, 90% of the daily precipitation ranges from 2.0-3.3 cm (0.78 – 1.3 inches) in depth. The 90% criterion was selected by UNHSC researchers during site design for its increasingly widespread usage, ability to generate economical sizing, and because water quality treatment with this guideline accounts for more than 90% of the of the daily precipitation frequency. For Durham NH, 2.5 cm (one inch) or less rainfall depth in one day occurs 92% of the time on the days in which measurable precipitation occurs. These data were derived from a NOAA precipitation gauge with 76 years of record that is within 1 km (0.62 miles) of the site.

Tracking and Calculation of Maintenance Costs

Stormwater treatment system designs and selection were primarily based on manuals from New York (New York State Stormwater Management Design Manual, 2001), New Hampshire (New Hampshire Department of Environmental Services, 1996), and the Federal Highway Administration (Brown, 1996, FHWA, 2002). The New York State manual includes operation, maintenance, and management inspection checklists for several SCMs. The manual guidelines were utilized on a monthly basis to track observations and maintenance activities for all SCMs discussed in this paper

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except for the porous asphalt system. The routine use of these forms helped to establish a framework for development of annual maintenance strategies. The porous asphalt maintenance activities were developed by adjusting typical maintenance activities for standard asphalt surfaces and applying them to porous systems. Maintenance tracking consisted of initial observations using inspection checklists, written documentation in field books, photo documentation of issues, and research staff assessments. Maintenance activity documentation included SCM name, activity description, labor hours to complete task, materials, and name of staff members involved. Annual maintenance strategies were evaluated by quantifying hours spent, assessing difficulty of activities, and applying a standard cost structure. To better illustrate costs and anticipate maintenance burdens, activities were characterized into distinct categories. First, activities were assigned a maintenance complexity according to published criteria (Erickson et al 2010). Second a unit conversion with relative estimated hourly expenses according to each complexity category was added. This can easily be adapted according to local conditions, current economic climate, and regional cost variations, however scaled differences would likely produce similar unitless ratios.

- Minimal – $75/hr – stormwater professional or consultant is seldom needed.
- Simple – $95/hr – stormwater professional or consultant is occasionally needed.
- Moderate – $115/hr – stormwater professional or consultant is needed approximately half the time.

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- Complicated – $135/hr – stormwater professional or consultant is always needed.

These categories allow more accurate cost predictions and provide insight into the appropriate assignment of maintenance responsibilities. Minimal complexity activities can generally be performed by non-professionals and may include tasks such as mowing or slope seeding, whereas complicated activities may necessitate a design specification or the use of heavy equipment for requirements such as algae removal from a wet pond.

Secondly, activities were categorized with respect to a maintenance approach. The four basic maintenance approaches are found below (adapted from Debo and Reese 2003):

- Reactive – complaint or emergency driven.
- Periodic and Predictive – driven by inspections and standards embodied in an O&M plan; can be calendar driven, known, or schedulable activities.
- Proactive – adaptive and applied increasingly more as familiarity with the system develops.

Results and Discussion

Maintenance of stormwater management facilities is essential for ensuring that systems perform properly. This analysis relies on the assumption that routine maintenance and inspections of SCMs are performed as recommended. The

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development of an effective maintenance program takes time, and as with most systems it is not only specific to the individual SCM, but with many other variables including the overall design, system sizing, location, land use, and other watershed characteristics. In most cases, maintenance approaches are not static, but are instead adaptive as maintenance staff become familiar with the systems and are better able to plan for maintenance activities.

These research results indicate that maintenance activities are progressive: maintenance tasks often start out as reactive (the most expensive category of maintenance), but subsequently evolve into periodic and proactive approaches. Figure 1 (1a.-1g.) illustrates annual maintenance costs and personnel hours expended for each of the studied SCMs over time. Our research indicates that if maintenance activities are simple, then periodic and routine maintenance costs are kept at a minimum. Figure 2 illustrates that SCMs with higher percentages of periodic and predictive, or proactive maintenance activities have lower maintenance burdens than SCMs with incidences of reactive maintenance.

As depicted in Figures 1-2 and Table 2, maintenance burdens for vegetated filtration systems were generally less with respect to cost and personnel hours as compared to conventional SCMs such as ponds, with vegetated swales and sand filters as the exceptions. However, these results should be considered as conservative in that they document the most expensive period of maintenance that might be anticipated (the startup years). Barring unexpected maintenance issues or severe weather events that could occur beyond this study's timeframe, the maintenance activities, approaches, and expenditures examined in this study generally became less intensive and diminished over time as maintenance familiarity increased (Figures 1a. and 1f.). As an example, maintenance with respect to vegetated systems was found to require more attention during the first months and years of vegetation establishment. Additionally, while the activities associated with maintaining LID practices were found to be less expensive and more predictable than conventional systems, the scale, location, and nature of LID system maintenance requires different equipment (rakes and wheel barrels as opposed to vactor trucks) and will require new maintenance standards and strategies.

Staff Hours

Personnel hours dedicated to maintenance for the SCMs included in this study are displayed in Table 2. As shown, average annual staff-hours per SCM ranged from 14.8 to 70.4 hours per hectare of impervious cover (IC) treated per year (6 to 28.5 hours/acre/year). The sand filter system was found to require the most staff-hours, followed in declining sequence by the wet pond, dry pond, subsurface gravel wetland, bioretention, vegetated swale, and finally the porous asphalt pavement. These results were surprising as many of the conventional systems such as wet and dry ponds were found to carry the largest maintenance burdens. Maintenance routines for these systems required more tasks and included more reactive activities such as algae removal and outlet cleaning which tend to be more complex and incur higher costs. Also interesting to note is that although porous asphalt pavement is generally perceived as cost prohibitive because of high anticipated maintenance burdens, the porous asphalt system in this study was actually found to have the lowest maintenance burden overall in terms of personnel hours and the second lowest annual costs. Pavement vacuuming, which makes up the bulk of the costs associated with porous asphalt maintenance, is a service that is increasingly available in the private sector. This fact in combination with the small number of maintenance tasks, all ranging toward predictive and proactive activities (inspection and proactive sweeping), keeps overall maintenance burdens low.

Marginal Costs

Marginal costs for maintenance activities associated with total suspended solids (TSS), total phosphorus (TP) and total nitrogen (TN) removal were converted to annualized costs per system, per watershed area treated (Table 2), and annualized costs per system, per mass of pollutant removed (Table 3). Because TN removal efficiencies were not calculable for every SCM tested, dissolved inorganic nitrogen (NO_3, NO_2, NH_4) was instead used. Capital costs for SCMs are presented in terms of dollars per hectare of IC treated (real and constant dollars), and maintenance expenditures are presented as an annualized percentage of capital costs, a measure routinely used for projected SCM cost estimates.

Figure 1 illustrates costs associated with maintenance over the years of study per hectare of IC treated. Some systems such as the wet pond and the subsurface gravel wetland (Figure 1b. and 1e.) displayed cycling maintenance costs over the course of the study, while others, such as the vegetated swale, bioretention, and porous asphalt systems (Figures 1a., 1f., and 1g.), reached a steady state after the first few years of operation. Annualized data are summarized in Table 2 and Figure 2. In the majority of cases, costs and personnel hours for LID systems were lower in terms of per mass of pollutant removed as compared to conventional systems. While the vegetated swale is the least costly system in terms of maintenance, it is also the least effective in terms of annual pollutant load reductions. These data indicate that marginal costs and marginal pollutant load reductions for LID systems are less costly and require less effort to maintain but still achieve greater pollutant load reductions. Exceptions occur with respect to any LID or conventional SCM that does not have unit operations and processes that effectively target nutrients. Some SCM maintenance burdens, such as the sand filter may be controlled by reducing the hydraulic loading rate (HLR) and/or the watershed area to filter area ratio (WA/FA). The HLR is expressed as the ratio of the water quality flow, in cubic meters per second, divided by the surface area of the filter in square meters and expressed in meters per second. The WA/FA ratio is calculated by dividing the watershed area by the filter area, both in square meters and is expressed as a number or ratio. Both metrics are summarized for each system studied in Table 1. The porous asphalt pavement has the lowest WA/FA of 1.00 and one of the lowest maintenance costs. Alternatively, the sand filter has the second highest WA/FA of 272 and HLR of 6.57 m/s and one of the highest maintenance costs. The subsurface gravel wetland is the exception and illustrates limitations with these metrics for horizontal flow filters and systems throttled by orifice control rather than filter media permeability. These data indicate that adjustments to HLR and/or WA/FA for vertical filtration SCMs can lead

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to reductions in maintenance burdens with commensurate decreases in cost per mass of pollutant removed. However, in cases where costs per mass of pollutant trend toward unrealistic levels, alternative systems or treatment train approaches should be adopted as primary water quality management measures.

Maintenance as a Percent of Capital Cost

Maintenance costs are a substantial portion of the life-cycle costs of stormwater management practices. Estimates can vary and there may, or may not be economies of scale for larger systems. As illustrated in Table 2, annual maintenance expenses as a percentage of capital costs ranged from 4% to 19%. To calculate these values, all original capital construction costs were converted to constant 2012 dollars using consumer price index inflation rates (USDOL) and presented in Table 2. The amortized maintenance costs for the wet pond equaled total capital construction costs after only 5.2 years. LID systems, with the exception of the sand filter, had higher capital costs but lower annual maintenance costs as compared to the conventional pond systems. As shown in Table 2, the lowest SCM annualized maintenance costs expressed as a percentage of capital costs were porous asphalt (4%) followed by the vegetated swale (6%), the subsurface gravel wetland (8%), and the bioretention systems (8%). At these rates, annual LID system maintenance expenditures will equal total upfront capital costs after 24.6 years for the porous asphalt system, 15.9 years for the vegetated swale, 12.2 years for the subsurface gravel wetland system and 12.8 years for the bioretention system.

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Conclusions

Many communities are struggling to define stormwater SCM maintenance needs in the absence of clear documentation. As a step towards providing this information, maintenance activities and costs for a range of stormwater management strategies were calculated. Marginal costs, maintenance frequency, level of effort required, complexity, and pollutant load reductions were all factors that were considered. Annualized maintenance costs were lower for vegetated filter systems (bioretention and subsurface gravel wetland) and porous asphalt pavement and higher for wet and dry ponds. SCMs are increasingly selected for their water quality treatment potential. When TSS load reductions were considered, marginal maintenance costs per mass of pollutant removed were higher for conventional systems and lower for LID systems with vegetated swales and sand filters as the exceptions. When nutrients such as nitrogen and phosphorus were considered, marginal maintenance costs per mass removed ranged from reasonable to cost prohibitive especially for systems with no nutrient removal.

Examination of annual maintenance expenses as a function of capital construction costs indicate that annual maintenance costs for LID systems are not greater than conventional pond systems and in many instances have lower annual maintenance costs.

The results of this study indicate that generally, LID systems, as compared to conventional pond systems, do not have greater annual maintenance costs and in most cases have lower marginal maintenance burdens (as measured by cost and personnel hours) and higher water quality treatment capabilities as a function of pollutant removal performance. Although LID system maintenance will be different and may require additional training, it should not require unusual burdens for management. While maintenance expenses have been presented in this paper as a unit cost per year per area of impervious cover treated it is not clear that operation and maintenance costs are scalable. Research on scalability, costs with respect to temporal variations and costs associated with different land uses and location (urban vs. rural) will all play a factor in overall maintenance burden calculations and should be a focus of future research.

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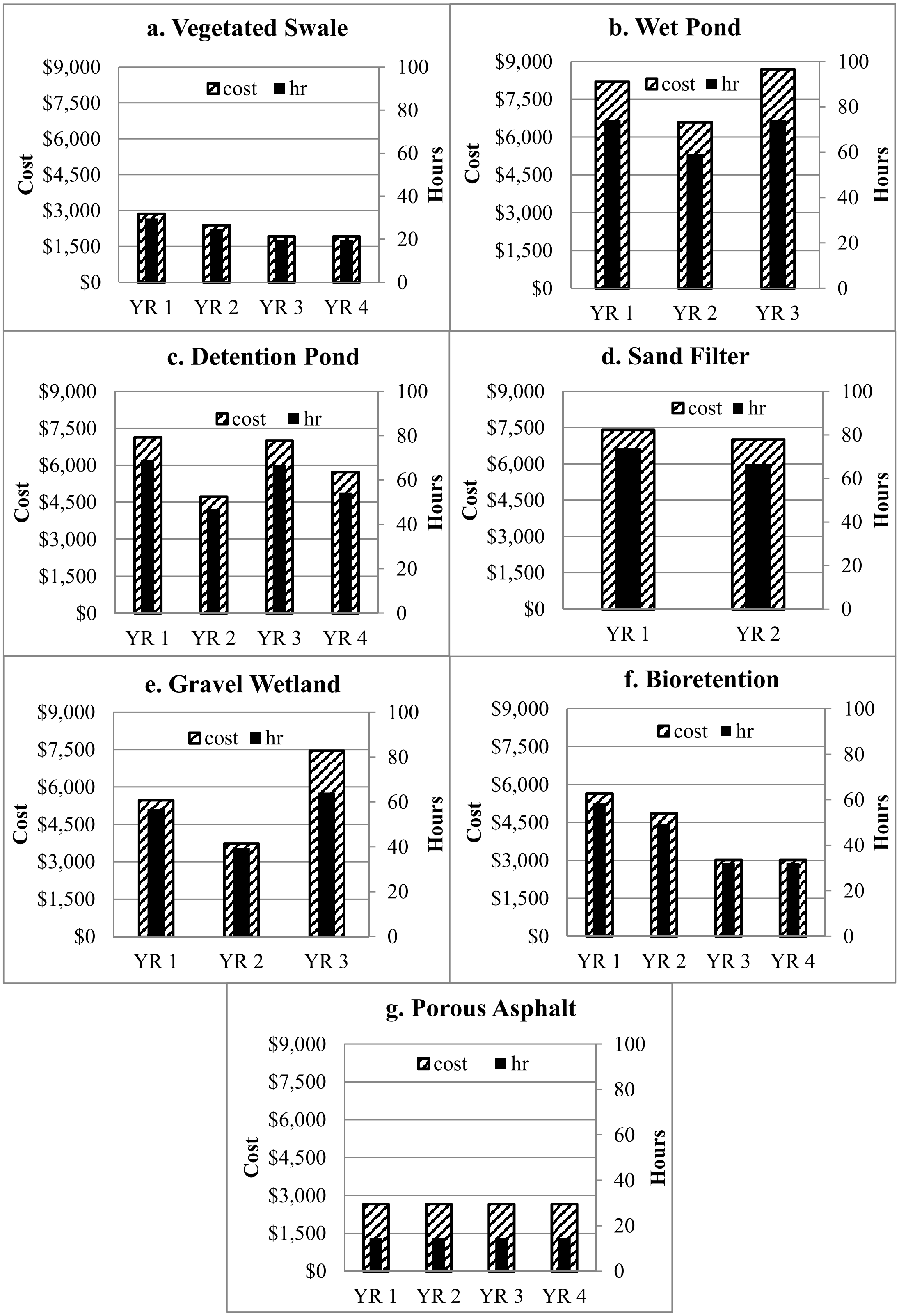

Figure 1: Annual maintenance costs and personnel hours tracked per system, per ha of IC treated, per year

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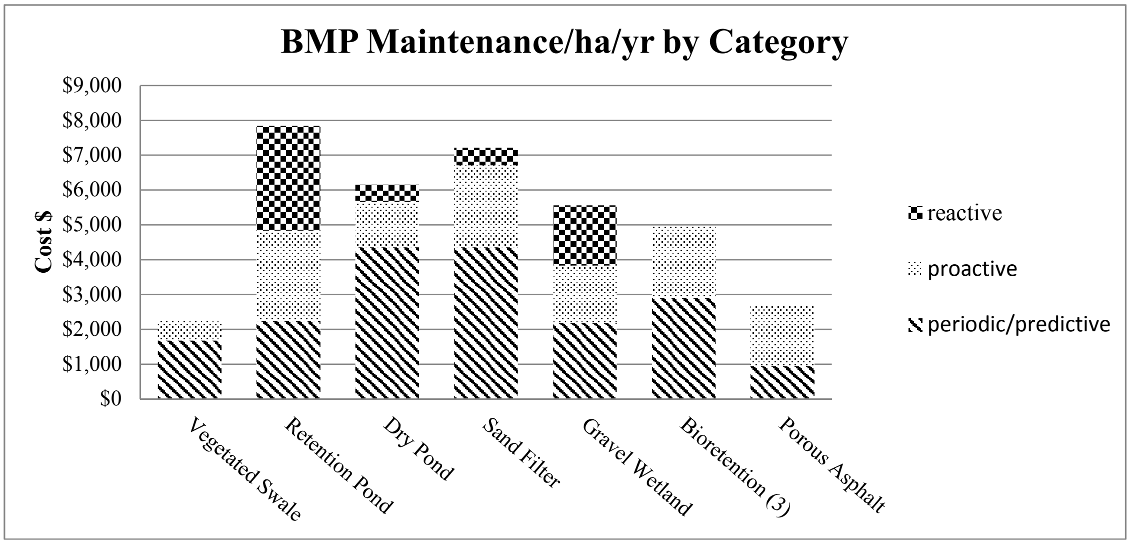

Figure 2: Annualized maintenance costs per system per hectare of IC treated per maintenance activity clasification

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Table 1: UNHSC SCM Design Data (SI Units)

Parameter	Vegetated Swale*	Wet Pond*	Dry Pond*	Sand Filter	Gravel Wetland	Bioretention #1	Bioretention #2 & #3	Porous Asphalt
Device Class	Conventional	Conventional	Conventional	LID	LID	LID	LID	LID
Filter Length (m)	85.3	21.3	21.3	6.1	15.8	20.4	10.4	26.8
Width (m)	3.0	14.0	14.0	2.4	11.3	10.7	2.4	19.5
Area (sq.m)	260	299	299	15	179	218	25	523
Depth (ft)	0.0	0.5	0.0	0.6	0.6	1.1	0.8	1.3
Ponding Depth (ft)	0.6	0.5	0.9	1.5	0.4	0.2	0.2	0.0
Catchment Area (ha)	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.05
Water Quality Volume (cu.m)	97.7	97.7	97.7	97.7	97.7	97.7	97.7	13.3
Water Quality Flow (cms)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	N/A
Watershed area/Filter area	N/A	N/A	N/A	272	22.6	18.6	160	1.00
HLR (m/s)	N/A	N/A	N/A	6.57	14.2	0.45	3.86	N/A

* HLR and FA/WA ratios are not calculated for non-filtration systems

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Table 2: UNHSC SCM installation and maintenance cost data, with normalization per hectare of IC treated *

Parameter	Vegetated Swale	Wet Pond	Dry Pond	Sand Filter	Gravel Wetland	Bioretention	Porous Asphalt
Original Capital Cost ($)	29,700	33,400	33,400	30,900	55,600	53,300	53,900
Inflated 2012 Capital Cost ($)	36,200	40,700	40,700	37,700	67,800	63,200	65,700
Maintenance-Capital Cost Comparison (yr) †	15.9	5.2	6.6	5.2	12.2	12.8	24.6
Personnel (hr/yr)	23.5	69.2	59.3	70.4	53.6	51.1	14.8
Personnel ($/yr)	2,030	7,560	5,880	6,940	5,280	4,670	939
Materials ($/yr)	247	272	272	272	272	272	0
Subcontractor Cost ($/yr)	0	0	0	0	0	0	1,730
Annual O&M Cost ($/yr)	2,280	7,830	6,150	7,210	5,550	4,940	2,670
Annual Maintenance/Capital Cost (%)	6	19	15	19	8	8	4

* Calculations based on original data with BGS units of $/acre and hr/acre

† Number of years at which amortized maintenance costs equal capital construction costs

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Table 3: Summary of removal performance and comparison per kg removed of TSS, and per g removed of TP, and TN as DIN

Parameter	Vegetated Swale	Wet Pond	Dry Pond	Sand Filter	Gravel Wetland	Bioretention	Porous Asphalt
Total Suspended Solids Performance - Annual Load of 689kg							
Removal Efficiency (%) †	58	68	79	51	96	92	99
Annual Mass Removed (kg)	399	468	544	351	662	632	682
Capital Cost Performance ($/kg)	91	87	75	107	102	100	96
Operational Cost ($/kg/yr)	6	17	11	21	8	8	4
Total Phosphorus Performance - Annual Load of 2,950 g*							
Removal Efficiency (%) †	0	0	0	33	58	27	60
Annual Mass Removed (g)	0	0	0	974	1700	799	1770
Capital Cost Performance ($/g)	NT	NT	NT	39	40	79	37
Operational Cost ($/g/yr)	NT	NT	NT	7	3	6	2
Dissolved Inorganic Nitrogen as Total Nitrogen Performance - Annual Load of 26,600 g*							
Removal Efficiency (%) †	0	33	25	0	75	29	0
Annual Mass Removed (g)	0	8,770	6,640	0	19,900	7,740	0
Capital Cost Performance ($/g)	NT	5	6	NT	3	8	NT
Operational Cost ($/g/yr)	NT	0.89	0.93	NT	0.28	0.64	NT

* Denotes change in unit mass from kg to g

† Values from (UNHSC, 2012)

NT – No Treatment, values are incalculable as lack of SCM pollutant treatment results in infinite costs