Cost and Pollutant Removal of Storm-Water Treatment Practices

Peter T. Weiss, M.ASCE[1]; John S. Gulliver, F.ASCE[2]; and Andrew J. Erickson, S.M.ASCE[3]

Abstract: Six storm-water best management practices (BMPs) for treating urban rainwater runoff were evaluated for cost and effectiveness in removing suspended sediments and total phosphorus. Construction and annual operating and maintenance (O and M) cost data were collected and analyzed for dry extended detention basins, wet basins, sand filters, constructed wetlands, bioretention filters, and infiltration trenches using literature that reported on existing storm-water BMP sites across the United States. After statistical analysis on historical values of inflation and bond yields, the annual O and M costs were converted to a present worth based on a 20-year life and added to the construction cost. The total present cost of each storm-water BMP with the 67% confidence interval was reported as a function of the water quality design volume, again with a 67% confidence interval. Finally, the mass of total suspended solids and total phosphorus removed over the 20-year life was estimated as a function of the water quality volume. For the six storm-water BMPs investigated, results show that, ignoring land costs, constructed wetlands have been the least expensive to construct and maintain if appropriate land is available. However, since wetlands typically require more land area to be effective, land acquisition costs may result in wetlands being significantly more expensive than other storm-water BMPs that require less area. The results can be used by planners and designers to estimate both the total cost of installing a storm-water BMP and the corresponding total suspended solids and total phosphorus removal.

DOI: 10.1061/(ASCE)0733-9496(2007)133:3(218)

CE Database subject headings: Construction costs; Economic factors; Maintenance costs; Operation costs; Precipitation; Runoff; Stormwater management; Water pollution.

Introduction

With the implementation of the United States Environmental Protection Agency's (USEPA) national pollution discharge elimination systems (NPDES) Phase I and II programs, much interest has developed in the area of water quality treatment of storm-water runoff. While little is known about the cost effectiveness of available storm-water treatment technologies, often called storm-water best management practices (BMPs), municipal and state agencies are now being required to meet certain pollutant removal criteria based on the USEPA requirements.

Of primary water quality concern are nutrients such as phosphorus (P). Excess nutrients can initiate large algae blooms that generate negative aesthetic and eutrophic conditions in receiving lakes and rivers. In inland water bodies, phosphorus is typically the limiting nutrient (Schindler 1977) and can be contributed to storm water from various sources such as fertilizers, leaves, grass clippings, etc. (USEPA 1999). Other pollutants of primary concern in storm water are dirt, sand, and other solid particles, which are commonly quantified by measuring the total suspended solids (TSS) of a water sample. TSS can severely and negatively impact an aquatic environment. The solids increase turbidity, inhibit plant growth and diversity, affect river biota, and reduce the number of aquatic species (Shammaa et al. 2002). Total suspended solids and phosphorus are primary concerns of most storm-water management plans, and little is known about the cost effectiveness of available storm-water treatment options.

This paper seeks to fill a need by developing both a cost comparison tool (based on total construction cost not including land acquisition) and an effectiveness comparison tool (based on mass of total suspended solids and total phosphorus removed) for common storm-water BMPs. Since, depending on conditions, some total phosphorus can become biologically available (Reynolds and Davies 2001), and since reported values of phosphorus and phosphorus removal are often given in terms of total phosphorus, this analysis included herein is based on total phosphorus values. The method is based on published, reliable information of existing storm-water BMPs relating to their construction and annual operating and maintenance (O and M) costs and their ability to remove TSS and total P from storm-water runoff. Six types of storm-water BMPs were chosen by the availability of this information. The goal is to provide planners and engineers with a prefeasibility tool that can be used to compare the costs and impact on water quality of available storm-water BMPs. First, a review and discussion of the storm-water BMPs with sufficient

---

[1] Associate Professor, Dept. of Civil Engineering, Valparaiso Univ., Valparaiso, IN 46383 (corresponding author). E-mail: Peter.Weiss@Valpo.edu

[2] Joseph T. and Rose S. Ling Professor and Head, Dept. of Civil Engineering, Univ. of Minnesota, Minneapolis, MN 55414. E-mail: gulli003@umn.edu

[3] Graduate Student, St. Anthony Falls Laboratory, Dept. of Civil Engineering, Univ. of Minnesota, 3rd Ave. SE, Minneapolis, MN 55414. E-mail: eric0706@tc.umn.edu

Note. Discussion open until October 1, 2007. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on June 7, 2005; approved on June 1, 2006. This paper is part of the ***Journal of Water Resources Planning and Management***, Vol. 133, No. 3, May 1, 2007. ©ASCE, ISSN 0733-9496/2007/3-218–229/$25.00.

credible data are presented below. It is assumed that all BMPs receive regular and sufficient maintenance such that they perform as designed. The cost of this regular maintenance will be incorporated into the analysis as described below.

Dry Extended Detention Basins

Dry extended detention basins are relatively shallow impoundments that typically detain storm water for no more than 48 h. These basins do not maintain a permanent pool of water between storm events, but do allow for settling of solids and removal of pollutants that are sorbed to the settled particles.

Dry extended detention basins also reduce the risk of flooding by attenuating the peak storm flow rate because they temporarily store the runoff and release it at a slower rate through designed outlet structures. Compared to other storm-water BMPs such as wet ponds and wetlands, dry extended detention ponds typically provide less water quality treatment. For example, while properly designed detention basins can remove large solid particles via settling, they often do not detain runoff long enough to allow finer particles to be removed. However, they can be a low-cost and effective method of removing a fraction of the pollutant load.

Wet/Retention Basins

"Retention systems capture a volume of runoff and retain that volume until it is displaced in part or in total by the next runoff event. Retention systems therefore maintain a significant permanent pool volume of water between runoff events" (USEPA 1999).

Also termed wet ponds in some contexts, these basins are similar to dry extended detention basins except the outlet structure is set at a higher elevation to create a permanent pool within the pond. Retention basins utilize gravity settling as the major removal mechanism, but nutrient and organic removal can be achieved through aquatic vegetation and microorganism uptake.

Limitations of these systems are typically related to retention time. During high flows, or freezing weather (when the permanent pool is frozen or covered with ice), influent runoff can short circuit through the retention system, which reduces the effectiveness of the sedimentation mechanism. Pond characteristics such as size, shape, and depth can also affect the removal efficiency. Changes in pH or hardness can alter the solubility of many contaminants and thus release them to the effluent (USEPA 1999).

Constructed Wetlands

"Constructed wetland systems are similar to retention and detention systems, except that a major portion of the storm-water BMP water surface area (in pond systems) or bottom (in meadow-type systems) contains wetland vegetation" (USEPA 1999).

Constructed wetlands are similar to dry extended detention basins in that they release water slowly. Although they are shallower, they also resemble wet basins in that they typically hold a permanent pool of water so that wetland vegetation can be maintained. Whereas dry extended detention basins are typically designed to release the entire storm-water inflow within 24–48 h, constructed wetlands can take several days or more to release runoff events.

Constructed wetlands allow for more removal mechanisms than detention basins and longer contact times than retention basins; therefore, they are capable of removing more pollutants such as nutrients and organics. Unlike dry extended detention basins, constructed wetlands, if designed properly, do not allow for resuspension of particles and contaminants. However, a major drawback of constructed wetlands is the large space they require. Constructed wetlands typically require large areas to allow for adequate storage volumes and long flow paths. As a result, wetlands are often impractical in urban and suburban areas where land costs are high.

As with any storm-water BMP, constructed wetlands require regular maintenance to remain effective. Faulkner and Richardson (1991) attributed a significant reduction in nutrient removal to the wetland vegetation reaching maximum density. Thus, wetland plants may have to be harvested to remove overabundant vegetation. Furthermore, overabundant and decaying vegetation can deposit large amounts of soluble and particulate phosphorus into the wetlands system; typically more than the living vegetation can uptake. This can result in an addition of phosphorus to the system. Also, it is questionable if harvesting plants will adequately remove phosphorus because in studies where vegetation has been harvested in an attempt to remove phosphorus, only minimal amounts of phosphorus have been recovered (Kadlec and Knight 1996). These factors may make it difficult for constructed wetlands to be a long-term cost-effective quality control technique without relatively frequent large-scale maintenance.

Infiltration Trenches

Infiltration trenches fall into the category of infiltration practices, which are defined by the USEPA (1999) as follows: "Infiltration systems capture a volume of runoff and infiltrate it into the ground." Any technique that does not discharge effluent to surface waters and/or reduces total discharge can be categorized as an infiltration practice. Infiltration practices encompass a number of techniques utilized for the treatment of storm-water runoff and most require some form of pretreatment and frequent maintenance to prevent blockage and ensure proper operation of the system.

The removal performance of infiltration practices has not been thoroughly reported. The difficulty in determining the quality of the effluent is most likely the chief reason for this lack of information. The data that are available regarding infiltration practices vary drastically due to many factors such as varying soil conditions, influent water quality, depth to water table, degree of pretreatment, maintenance protocols, etc.

Infiltration trenches can be thought of as constructed channels filled with filtration media or soil that allows for the infiltration of storm water. These trenches are often placed around the perimeter of parking lots or other structures to treat the runoff generated by the site. With sufficient sizing and properly designed flow regulators (typically, check dams), infiltration trenches can infiltrate a large portion of the runoff, although peak flow reduction is typically not substantial. Thus, additional benefits (which are not investigated in this study) of any infiltration device are that of runoff volume reduction and groundwater recharge.

Bioretention Systems

While not specifically defined by the USEPA, bioretention systems may be classified as an infiltration practice and are essentially landscaped depressions to which storm-water runoff is diverted and stored. Once in the depression, the trees, shrubs, and other vegetation help to remove the water through uptake, while the runoff infiltrates into the soil. The underlying soil may consist of the original soil, but is more typically a non-native soil such as sand that is installed during construction. Also, depending on the permeability of the soil, a bioretention system may include a perforated underdrain that collects and removes infiltrated water.

Bioretention systems are rapidly gaining in popularity because it is assumed they incorporate the best of vegetative systems and filtration systems. However, their impact on water quality is neither well known nor documented. The area of bioretention systems that would be required for substantial peak flow reduction would also be greater than normally used.

Sand Filtration

Sand filtration systems utilize granular media to filter storm-water runoff that is collected and discharged as effluent to other treatment systems or directly to receiving waters. Those called "Austin" sand filters appear much like a dry detention basin, but include built-in sand-filled areas that filter the water and release it to an underdrain. The "Delaware" sand filters are usually smaller, low-retention filters that can be placed underground in concrete chambers and are typically designed to capture and treat only the first portion of most runoff events. Peak flow reduction is not a primary objective of most sand filtration systems, but peak flow reduction occurs for nonoverflow conditions.

Cost Estimation

Based on published cost data of actual storm-water BMPs, the method that is described below was developed to enable designers and planners to make estimates of the total present cost of various storm-water BMPs if the size of the system is known. Herein, the total present cost is defined as the present worth of the total construction cost of the project (not including land acquisition costs) plus the present worth of 20 years of annual O and M costs. The values reported do not include costs of pretreatment units (which may be required), design or engineering fees, permit fees, land costs, contingencies, etc. The costs of storm-water BMPs are usually reported along with the corresponding watershed size and/or the water quality volume (WQV) for which the storm-water BMP was designed. The water quality volume is often defined as the volume of runoff that the storm-water BMP is designed to store and/or treat, which is often based on a design precipitation depth or depth of runoff. Water quality volume will be discussed in more detail below.

Total Construction Costs

Values of total construction costs of storm-water BMPs throughout the United States were collected from published literature. The data originating from Brown and Schueler (1997) were read graphically, whereas the values from SWRPC (1991), Caltrans (2004), and ASCE (2004) were given in tabular form. Also, the data from Caltrans (2004) were collected by means of a survey distributed by Caltrans to other agencies throughout the country. It should be noted that the total construction costs of storm-water BMPs installed by Caltrans were also available, but these values were omitted from this analysis because their costs were typically about one order higher than similarly sized projects constructed by other agencies. Caltrans attributed these high costs to the fact that their projects were retrofits and were not installed as part of larger construction projects.

Although data were collected on many storm-water BMPs, sufficient data to perform a cost analysis could be found for only dry extended detention basins, wet/retention basins, constructed wetlands, infiltration trenches, bioretention filters, and sand filters. By means of "regional cost adjustment factors" as reported by the United States Environmental Protection Agency, all data were adjusted to reflect costs in Rainfall Zone 1 of the United States (USEPA 1999). Rainfall Zone 1 covers the northeast and north-central United States and includes Maine, New Jersey, Pennsylvania, Michigan, Wisconsin, Iowa, Minnesota, and the northern portions of Indiana, Illinois, and Ohio. Based on this method first employed by the American Public Works Administration (APWA 1992), construction costs in Rainfall Zone 1 are estimated to be 12% higher than the "Twenty Cities Average" in the United States. Costs were also adjusted to year 2005 dollars using an annual inflation rate of 3%. A value of 3% was chosen after an analysis of building cost indexes for the past 11 years (Turner Construction 2004) and revealed that the average annual inflation was 3.26% with a range from 0.3 to 5.4%.

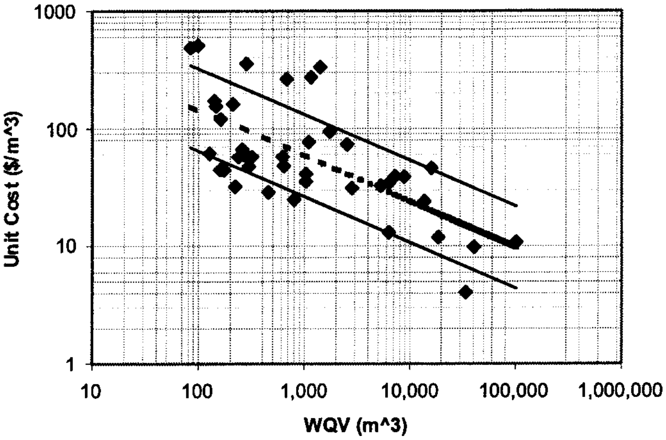

Fig. 1. Unit construction costs of dry extended detention basins

The cost data collected were usually reported in conjunction with the watershed area and/or the water quality volume for which the particular storm-water BMP was designed. When comparing unit cost data based on watershed area and WQV, the data based on WQV were, in most cases, observed to have less scatter. Thus, in order to provide for as much consistency as possible while minimizing scatter overall, WQV based unit construction costs were selected for use over watershed area based unit construction costs.

Figs. 1–6 show the analyzed unit construction cost data in graphical form. Also shown is the dashed, best-fit line through the data and the 67% confidence interval as shown by solid lines on either side of the best-fit line. When the cost data were converted to unit construction costs, defined as the total construction cost per hectare of watershed or per cubic meter of WQV, the data, in all cases except for bioretention filters, exhibited an "economy of scale." In other words, when the unit construction cost was plotted versus the size i.e., watershed area or WQV, the unit cost tended to decrease as the size increased. As mentioned, the only exception to this trend was bioretention filters, which exhibited a slight increase in unit cost with increasing size.

Of the data collected for sand filters, some contained information on the type of sand filter (e.g., Austin or Delaware) while other data included no such description. When analyzing the sand filter data for unit costs, there was essentially the same amount of scatter when the data of each sand filter type were analyzed alone as there was when all sand filter data were combined and ana-

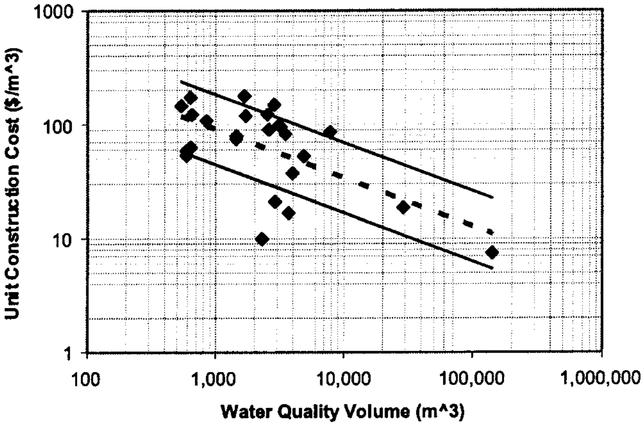

Fig. 2. Unit construction costs of wet basins

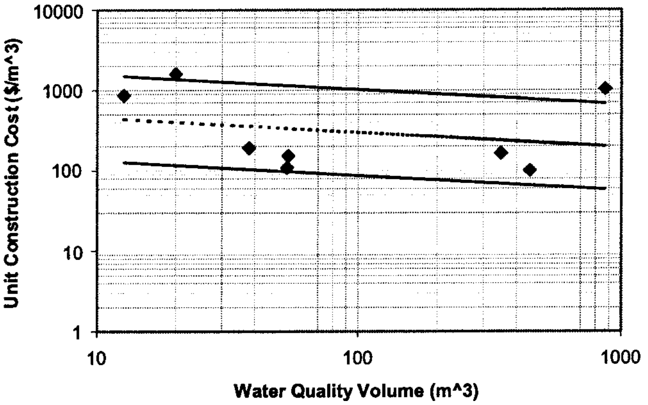

Fig. 4. Unit construction costs of infiltration trenches

lyzed together. This suggests that sand filter unit construction costs are independent of the type of filter. Fig. 6 does differentiate between the Austin, Delaware, and undefined data by the data marker, but since no trend was observed for individual filter types, the best-fit line is drawn through the combined data.

The uncertainty observed in the data for all storm-water BMPs is most likely due to several factors such as design parameters, regulation requirements, soil conditions, site specifics, etc. For example, variable design parameters that would affect the total construction cost include pond side slopes, depth and free board on ponds, total wet pond volume, outlet structures, the need for retaining walls, etc. Site-specific variables include clearing and grubbing costs, fencing around the storm-water BMP, etc. Due to the wide number of undocumented variables that affect the cost, this scatter would be difficult to minimize.

Land Area Requirements

An important cost of any storm-water BMP is that of the land area on which the storm-water BMP will be located. For urban areas, in which land is typically at a premium, this cost can be relatively large. On the contrary, in more open, rural areas, land costs might be a very small percentage of the total project costs. Due to the extreme range of land costs and variability from site to site, no attempt was made to incorporate this cost into the total present cost analysis. However, the land area requirements, and therefore the associated land costs of each storm-water BMP, can vary dramatically and would, in many scenarios, have a significant impact on the total cost of a project.

Given the variability of land costs and the variety of potential storm-water BMPs that could be used, the impact of land costs must be done on an individual, case-by-case basis. Table 1, which lists typical storm-water BMP land area requirements for effective treatment, is presented to assist designers and planners in making such a comparison. Values reported in Table 1 by Claytor and Schueler (1996) are for the general category of storm-water BMP system and may include more than one specific type of storm-water BMP. For example, their pond category may include both wet and dry ponds. If the land costs in the locale of a particular project are known, these costs can be combined with the information presented in the Table 1 to estimate a range of possible land area costs associated with each storm-water BMP under consideration. This information is intended to give only a typical range of land areas. For more accurate land area estimates, a preliminary storm-water BMP design should be performed.

Operating and Maintenance Costs

Over the lifetime of a storm-water BMP the operating and maintenance costs can be a significant expense that must be considered when selecting a treatment method. However, no data were found that documented actual O and M costs of existing storm-water

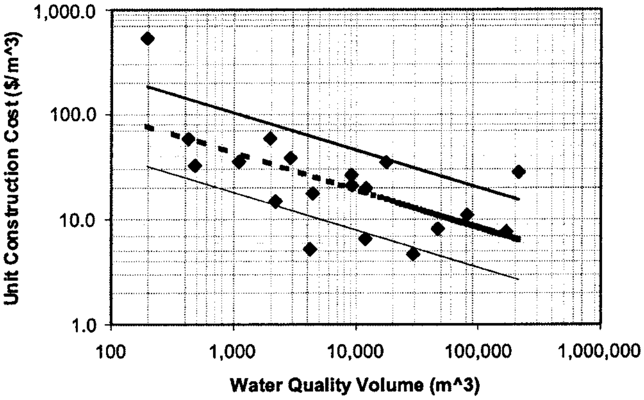

Fig. 3. Unit construction costs of constructed wetlands

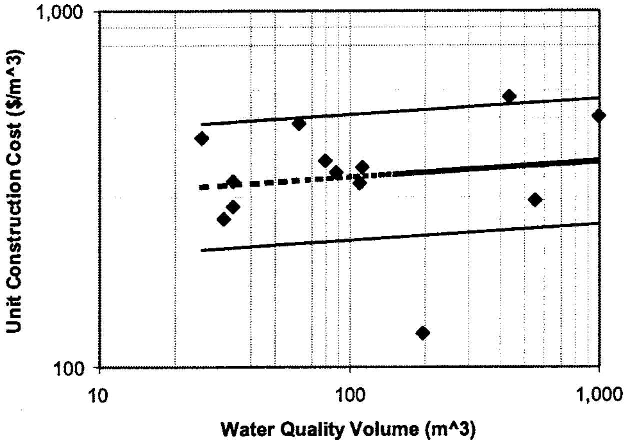

Fig. 5. Unit construction costs of bioretention filters

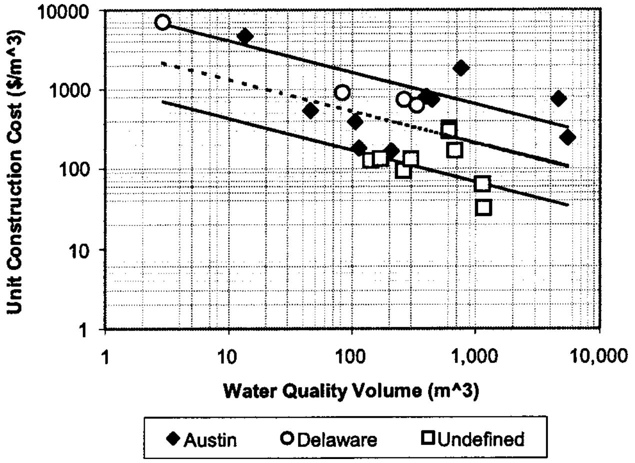

Fig. 6. Unit construction costs of sand filters

BMPs. At best, available data consisted only of expected O and M costs of recently constructed storm-water BMP projects. Often times, general guidelines of estimated annual O and M costs were presented as a percentage of the total construction cost. For example, the USEPA (1999) gives a summary of typical storm-water BMP annual O and M costs as shown in the middle column of Table 2. Also included in the right column of Table 2 is the range of the writers, collection of predicted O and M costs (SWRPC 1991; Landphair et al. 2000; Caltrans 2004; Moran and Hunt 2004).

When analyzing the data, a trend was observed for all storm-water BMPs except infiltration trenches, in which the annual O and M cost as a percentage of the construction cost decreased with increasing construction cost. The annual O and M cost data for all stormwater BMPs except infiltration trenches are shown as log–log plots in Figs. 7–11. Infiltration trench data are not included because four of the six data points obtained for this storm-water BMP were over 100% of the total construction cost, which is high compared to the 5–20% range reported by the USEPA (1999). Therefore, these data were not used in this analysis and a different approach, which will be described below, was used when analyzing infiltration trenches. As with the construction cost data, the best-fit line through the data and the 67% confidence interval are shown. In the following section the annual O and M costs will be combined with the unit construction costs to develop an estimate for the total present cost of each storm-water BMP as a function of WQV.

Table 1. Reported Best Management Practices Land Area Requirements for Effective Treatment

Best management practice	Best management practice area (% of impervious watershed)[a]	Best management practice area (% of watershed)[b]
Bioretention	5	—
Wetland	3–5	3–5
Wet/retention basin	2–3	—
Sand filter	0–3	—
Dry DET Basin	—	0.5–2.0[c]
Infiltration trench	2–3	—
Filter strips	100	—
Swales	10–20	—
Pond	—	2–3
Infiltration	—	2–3
Filter	—	2–7

Note: DET=Detrital valley groundwater.

[a] USEPA (1999).

[b] Claytor and Schueler (1996).

[c] UDFCD (1992).

Table 2. Typical Annual Operation and Maintenance Costs of Best Management Practices

Best management practices	Summary of typical annual O and M costs (% of construction cost)[a]	Collected cost data: estimated annual O and M costs (% of construction cost)
Retention basins and constructed wetlands	3–6%	—
Detention basins	<1%	1.8–2.7%
Constructed wetlands	2%	4–14.1%
Infiltration trench	5–20%	5.1–126%
Infiltration basin	1–3%, 5–10%	2.8–4.9%
Sand filters	11–13%	0.9–9.5%
Swales	5–7%	4.0–178%
Bioretention	5–7%	0.7–10.9%
Filter strips	$320/acre (maintained)	—
wet basins	Not reported	1.9–10.2%

[a] USEPA (1999).

Total Present Cost

If an estimate of the total construction cost of a storm-water BMP were desired, the data presented in Figs. 1–6 could be used in a stand-alone manner simply by multiplying the unit construction cost (dollars/m^3) by WQV (m^3). However, a more useful estimate is that of the total costs needed to not only construct, but also to maintain and operate the storm-water BMP. Rather than provide one estimate for total construction cost and another estimate for annual O and M expenditures, the data will be combined in order to estimate the total present cost of each storm-water BMP as a function of water quality volume. As previously defined, the total present cost is the sum of the total construction cost and the equivalent present cost of 20 years of annual O and M expenses. In this estimate, the annual O and M costs are converted to an

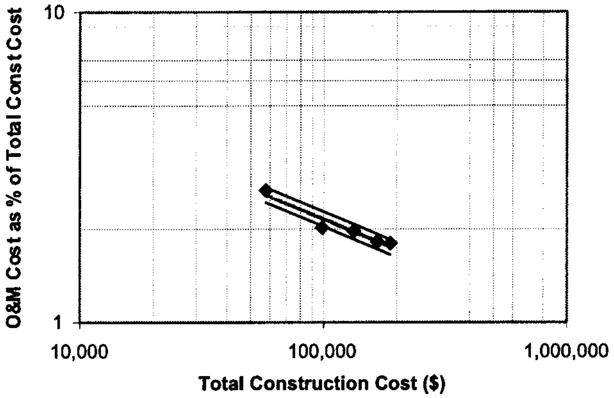

Fig. 7. Annual operating and maintenance costs of dry extended detention basins

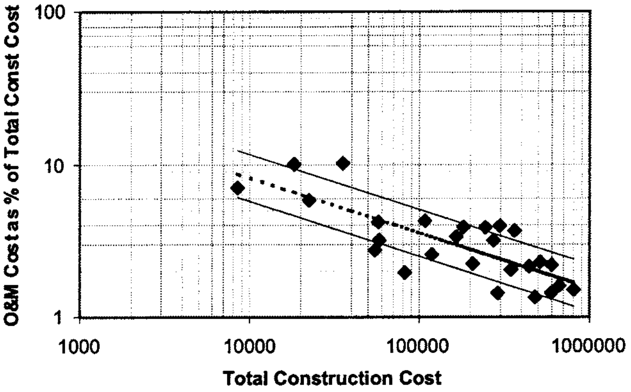

Fig. 8. Annual operating and management costs of wet basins

equivalent present cost using historical data on the rates of municipal bond yields and inflation. The analysis method and the results for each of the six storm-water BMPs are presented below.

In order to estimate the total present cost of each storm-water BMP the total construction cost was calculated as a function of WQV by multiplying the corresponding unit construction cost, given in Figs. 1–6, by WQV. For all storm-water BMPs, except infiltration trenches, the annual O and M cost, as a percent of construction cost, was estimated for each WQV from Figs. 7–11. Next, the annual O and M costs were estimated by multiplying each percentage by the corresponding total construction cost. Finally, the annual O and M costs were converted to an equivalent present cost for a 20-year period and added to the total construction cost.

Before the conversion of the annual O and M costs to an equivalent present cost is described, the analysis method used for infiltration trenches must be discussed. For infiltration trenches an average value of the annual O and M cost (as percent of total construction cost) based on the USEPA summary shown in Table 2 was assumed. Thus, annual O and M costs for infiltration trenches were not determined from the best-fit line through the data of Fig. 10, but rather assumed to be 12% (+/−7%). Other than this assumption, the total present cost analysis for this storm-water BMP was identical to the others.

Having obtained an annual O and M cost estimate, it was assumed that these costs would be incurred for 20 years. The 20 years of annual O and M costs were converted to an equivalent present O and M cost using the time value of money and historical values of interest and inflation rates. Given an interest rate and inflation rate, the equivalent present cost of the 20-year annual O and M costs can be computed by equations modified from Collier and Ledbetter (1988)

$$P_C = C_{\mathrm{OM}}[E] \qquad (1)$$

$$E = \left[\frac{\left(\frac{1+r}{1+i}\right)^n - 1}{r-i} \right] \qquad (2)$$

where P_C=equivalent present cost of 20 years of annual O and M costs; C_{OM}=annual O and M cost; r=inflation rate; i=interest rate; and n=number of years (i.e., 20).

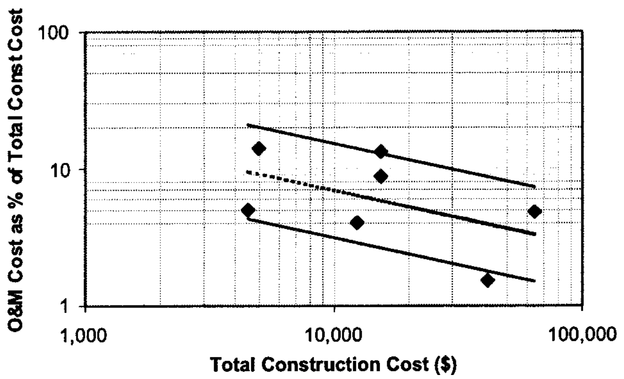

Fig. 9. Annual operating and management costs of constructed wetlands

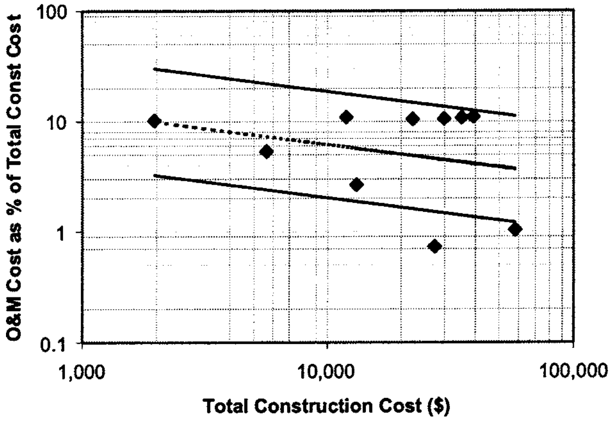

Fig. 10. Annual operating and management costs of bioretention filters

Using average annual "Aaa" municipal bond yield rates (Mergent 2003) for interest rate values and historical consumer price index (CPI) based inflation rates (Fintrend 2004), the value of E was calculated for each year from 1944 to 2002. Since this analysis is based on a 20-year time span, the running 20-year average value of E was calculated for each year from 1963 to 2002. The running 20-year average values resulted in an overall average value of 18.68+/−2.29 (67% confidence interval). Using a value of 18.68 for E, the present equivalent costs of 20 years of annual O and M expenses were calculated over the range of WQVs and added to the corresponding total construction cost to give the total present cost in 2005 dollars as a function of WQV. The uncertainties associated with the 67% confidence intervals of

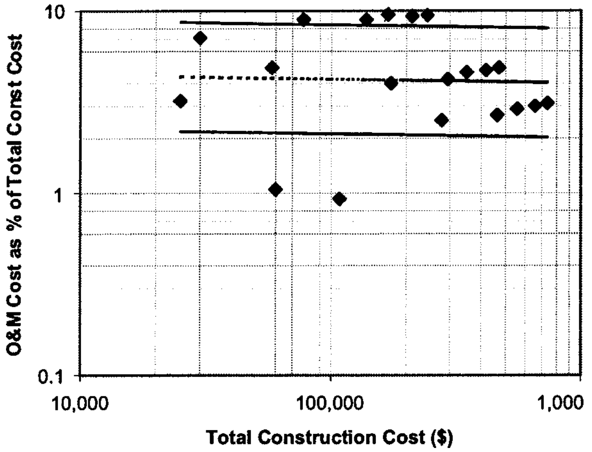

Fig. 11. Annual operating and management costs of sand filters

Table 3. Eq. (5) Constants for Total Present Cost

Best management practice	Average total present cost		Upper confidence interval		Lower confidence interval		Water quality volume range (m^3)
	β_0	β_1	β_0	β_1	β_0	β_1	
Dry basins	1,281	0.634	2,024	0.671	1,055	0.585	85–101,000
Wet basins	4,398	0.512	6,119	0.536	3,592	0.484	410–215,000
Sand filters	6,153	0.594	13,618	0.596	3,495	0.592	3–5,500
Bioretention filters	1,542	0.776	3,838	0.723	897	0.802	26–990
Construction wetlands	1,515	0.565	2,579	0.585	1,076	0.537	200–215,000
Infiltration trenches	2,237	0.817	4,039	0.817	1,418	0.817	13–870

the unit construction costs, annual O and M costs as a percent of the construction cost, and inflation and interest rates (i.e., E) were incorporated into the total present cost using the first-order, second-moment analysis described by Kline (1985).

The resulting total present cost (with 67% confidence interval), excluding land costs, of each storm-water BMP can be described (fit) in equation form as

$$\mathrm{TPC} = \beta_0(\mathrm{WQV})^{\beta_1} \tag{3}$$

where: TPC=total present cost (2005 U.S. Rainfall Zone 1 dollars); WQV=water quality volume (m^3); and β_0 and β_1=constants.

For each storm-water BMP the values of β_0 and β_1 for the average TPC, the values of β_0 and β_1 for the upper and lower 67% confidence intervals, and the range of WQV for which data were collected are given in Table 3. A comparison of the average total present cost of all six storm-water BMPs is given in Fig. 12. It must be noted that Fig. 12 presents average values and, for sake of clarity, does not include the associated confidence intervals. One must keep in mind that if confidence intervals were included there would be some overlap between the confidence intervals. Investigation of Fig. 12 reveals that, based on the collected data and in terms of average total present cost, wetlands are the least expensive storm-water BMP for the range of WQVs listed, assuming that land suitable for wetland development was available. This finding is somewhat similar to that of Wossink and Hunt (2003) who concluded that, in terms of construction costs, wetlands were the least expensive of four storm-water BMPs (wet ponds, constructed wetlands, sand filters, and bioretention basins) for watersheds larger than 10 acres in sandy soils. Contrary to the previous conclusions, the California storm-water Quality Association (CSQA) (2003) states that wetlands are relatively inexpensive, but are typically 25% more expensive than storm-water ponds of equivalent volume. As will be demonstrated with an example later in this paper, one must also remember that since wetlands generally require more land area, any savings in total present cost may potentially be offset by larger land acquisition costs.

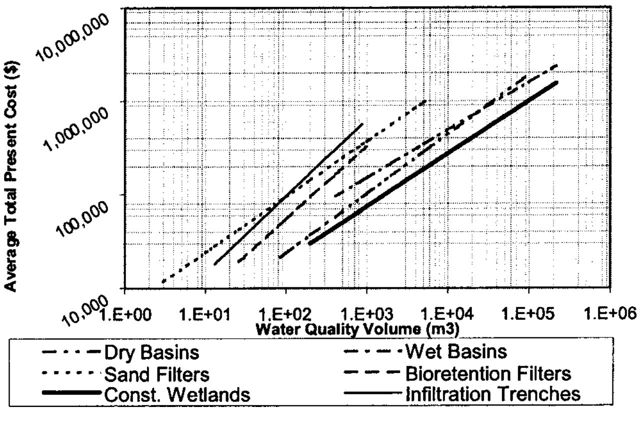

Fig. 12. Average total present cost of six best management practices versus water quality volume

Effectiveness of Contaminant Removal

An estimate of the total cost of a storm-water BMP can be a valuable aid during the planning and selection process. However, an inexpensive storm-water BMP that has minimal impact on water quality would be of little value for water quality improvement. Thus, knowledge of the impact or effectiveness a particular storm-water BMP will have on water quality is just as important as the cost. In an effort to provide this information, an analysis was performed in which the total amount of TSS and phosphorus removed over a 20-year span was estimated as a function of water quality volume. In this analysis the amount of TSS and P removed is considered to be a function of the fraction of storm-water runoff that will be treated by the storm-water BMP, the pollutant load that reaches the storm-water BMP, and the removal performance of the storm-water BMP itself. Of course, some of these parameters depend on other variables such as watershed area, impervious area, rainfall amounts, etc. All of these variables and the analytical method that was used to incorporate them into the estimate of total pollutant load removal are described and discussed below.

Runoff Fraction Treated

Most storm-water BMPs are designed for a particular rainfall depth that is used to estimate a water quality volume or a peak flow rate to size the storm-water BMP. WQV is usually defined on the basis of a prescribed runoff depth over the entire watershed or designed for a particular rainfall depth.

If using the latter method, a modified relationship used by Claytor and Schueler (1996) can be used to calculate the WQV (m^3) for a particular precipitation amount

$$\mathrm{WQV} = 100 * P * R_V * A \tag{4}$$

where P=design rainfall precipitation depth (cm); R_V=ratio of runoff to rainfall in the watershed; and A=watershed area (ha).

The ratio of runoff to rainfall, R_V, has the most uncertainty of the parameters in Eq. (4). For this analysis, a relatively simple relationship was used (Claytor and Schueler 1996)

$$R_V = 0.05 + 0.009 * (\mathrm{I}) \quad (5)$$

where I=percent (0–100) of the watershed that is impervious. Eq. (5) indicates that, for a 100% impervious watershed, 95% of the rainfall becomes runoff and for 0% impervious, 5% of the rainfall becomes runoff.

Since a storm-water BMP is designed for a finite value of rainfall and/or runoff, there is always the chance that a given storm will produce more runoff than the unit was designed to store and/or treat. When that happens, a portion of the runoff bypasses the storm-water BMP or is discharged from the storm-water BMP via an overflow outlet and receives no treatment. In order to account for this untreated fraction of runoff, a statistical analysis should be performed on historical rainfall data. Given the design rainfall depth, the process, as described below, can be used to estimate the fraction of storm-water runoff that will be bypassed or exit the storm-water BMP without treatment.

1. Since design recommendations for storm-water BMPs typically state that the devices should be designed to drain in two days, combine rainfall amounts over every 2-day span to calculate the 2-day running sum precipitation amounts.
2. Using the combined data, generate a 2-day running sum (R_S) histogram and a percent exceedance corresponding to each precipitation depth.
3. Determine the design precipitation depth of the storm-water BMP, the corresponding percent exceedance, and an estimate of the fraction of runoff that will bypass or exit the storm-water BMP without treatment.

For example, if a storm-water BMP were designed for a precipitation depth of 3.7 cm, the exceedance graph area that is both under the plotted curve *and* below the horizontal line that corresponds to an abscissa value of 3.7 cm divided by the total area under the curve, equals the fraction of the 2-day summed precipitation amounts that were below the 3.7 cm design storm depth. For the Minneapolis/St. Paul metro region a design depth of 3.7 cm, which, in this analysis may occur over a span of up to 2 days, is also the depth of the 3-month 24-h storm (Huff and Angel 1992). By analysis of the exceedance graph, a depth of 3.7 cm corresponds to approximately 93% of all storm-water runoff being treated over time. This value is similar to that obtained in Maryland in which storm-water BMPs designed for the 3-month storm depth were estimated to treat a minimum of 92% of the annual runoff (Claytor and Schueler 1996). For precipitation events larger than 3.7 cm, this method assumes that the runoff from the first 3.7 cm is treated by the BMP. Further details of the analysis method described herein are available in Weiss et al. (2005).

Based on the above analysis, when estimating the total amount of TSS and P removed over 20 years it was assumed that 7% of all runoff in the Minneapolis/St. Paul region would receive no treatment. With this estimate, the total suspended sediment and phosphorus removal are given by

$$\%\text{total removal} = 0.93 * (\%\text{removal by storm-water BMP}) \quad (6)$$

where the percent removal by storm-water BMP=removal based on inflow and treated outflow concentrations and does not consider overflow conditions. Overflow and/or bypass conditions are accounted for by multiplying percent removal by storm-water BMP by 0.93 as shown in Eq. (6). This method assumes that the total phosphorus and suspended solids concentrations in the runoff are distributed evenly over time. If initial concentrations are higher than the concentrations in the bypassed fraction this assumption will result in conservative estimates of pollutant load removed.

It must be noted that this estimate of percent total removal is conservative in that it assumes any runoff volume larger than the amount for which the storm-water BMP was designed will not be treated. Because all the runoff does not arrive at the BMP at once, this may not be an accurate assumption. Since arrival of the runoff volume at the storm-water BMP may occur over several hours (or days), some runoff will have already passed through the BMP early in the event, which will allow additional volume to be treated during the latter stages of the runoff event.

Pollutant Loading

Several methods with a wide degree of complexity are available to estimate storm-water pollutant loads. For example, the storm-water management model (SWMM) can be used to model single storm events or watershed basins over time. Additional methods described by Young et al. (1995) include regional United States Geological Survey (USGS) equations for estimation of storm loads, runoff volumes, and event mean concentrations. A simplified, but less accurate set of USGS regression equations is also available and can be used to estimate storm runoff loads and volumes. The Federal Highway Administration (FHwA) has also developed a method to estimate pollutant loading from highway runoff (Driscoll et al. 1990).

The methods mentioned above require a level of detail that is beyond what is necessary for the comparative purposes of this study. Thus, a modified version of a less involved but widely accepted method, the simple method (Schueler 1987), was selected to estimate pollutant loads. The modified simple method used in this paper is also used by the Lower Colorado River Authority (LCRA 1998) and has been recommended for use by the State of Texas, Department of Transportation (Landphair et al. 2000)

$$L = (0.10) * A * R_F * R_V * C \quad (7)$$

where L=annual pollutant load (kg); A=watershed area (ha); R_F=average annual rainfall (cm); R_V=average annual runoff: rainfall ratio as defined in Eq. (2); and C=average annual contaminant (i.e., TSS and P) concentration (mg/L), which may be thought of as an annual "event" mean concentration.

In order to coincide with the 20-year time span used to estimate the total present cost, the pollutant loading must also be estimated for 20 years. To accomplish this, Eq. (7) must be multiplied by 20. Also, the variable R_F, must no longer be defined as the average annual rainfall, but rather the 20-year running average of annual rainfall. Incorporating these changes, Eq. (7) is converted to estimate the TSS and P loading over a 20-year span

$$L_{20} = 2.0 * A * R_{F20} * R_V * C \quad (8)$$

where L_{20}=estimated pollutant load over 20 years (kg); and R_{F20}=20-year running average of annual rainfall (cm). For the purposes of this paper it was assumed that watershed area A, percent impervious I, and therefore runoff coefficient R_V, would be measured without significant uncertainty.

In order to determine estimates of the average annual concentration of TSS and P in storm-water runoff (C), data were compiled on event mean concentrations from several studies and dozens of sites (Moxness 1986, 1987, 1988; Driscoll et al. 1990; Oberts 1994; Barrett et al. 1995; Stanley 1996; Wu et al. 1996; Sansalone and Buchberger 1997; Barrett et al. 1998;

Anderle 1999; Legret and Colandini 1999; Waschbusch et al. 1999; Carleton et al. 2000; Drapper et al. 2000; Brezonik and Stadelmann 2002; Harper et al. 1999). Data analysis revealed that the average values of storm-water event mean concentrations of TSS and P from sites located in Minneapolis and St. Paul, Minn., were similar to average values of all other sites located throughout the United States and Australia. Since the data were similar, the overall average values of 131+/−77 mg/L (67% confidence interval) for TSS and 0.55+/−0.41 mg/L (67% confidence interval) for total P were used. With values for C estimated, the total pollutant load for TSS and P over a 20-year time frame, as estimated by Eq. (8), becomes a function of only three variables; the 20-year running average of annual rainfall, watershed area, and with the use of Eq. (2), the percent of the watershed area that is impervious.

Two of these variables that determine the 20-year pollutant loads (i.e., watershed area and percent impervious) are also the same two variables that determine the WQV. Thus, in any given rainfall region for a watershed of known area and percent impervious, both the WQV and the TSS and P loads over 20 years can be estimated. In other words, for a given watershed, each value of WQV corresponds to a unique value of 20-year TSS and P loads. The pollutant loads will be used to estimate the mass of TSS and phosphorus removed by each storm-water BMP over 20 years as a function of WQV.

Fraction of Contaminants Removed

With the fraction of runoff treated and the total 20-year pollutant load estimated, the remaining variable that must be estimated is the fraction of TSS and P removed by each storm-water BMP. Once the removal rate of each storm-water BMP has been estimated, the total mass of TSS and P removed over the 20-year span may be estimated by multiplying the 20-year pollutant load by both the fraction of runoff treated (i.e., 93%) and the fraction of pollutant removed by the storm-water BMP. The fraction of TSS and P removed is usually reported in one of two ways; as a percent change between influent and effluent concentrations or as the percent change between the total mass load entering the storm-water BMP and the mass load exiting the storm-water BMP. Most of the removal data obtained were based on concentrations, however, some values of reported removal rates were not clearly defined.

Published data on the performance of the various types of storm-water BMPs analyzed in this study were collected and only data from actual sites that were field tested were included. When a single site was monitored over time and had more than one removal rate reported, only the average value of the data for that site was included in the analysis. Removal rates based on mass load removed were combined with removal rates based on the percent change in contaminant concentration between inflow to the storm-water BMP and treated outflow from the storm-water BMP. For each type of storm-water BMP the average percent removal of the combined data (with 67% confidence interval) was calculated and assumed to be the average percent of mass load removed.

The results are summarized in Table 4 and the raw data are available in Weiss et al. (2005). Sufficient amounts of reliable data needed to estimate the TSS removal rate of bioretention filters and TSS and phosphorus removal rates of infiltration trenches were not available. As denoted by the asterisks in Table 4, values of 85 and 95% for TSS removal as reported by the National Pollutant Removal Performance Database (Winer 2000) were used. Also assumed was the National Pollutant Removal Database value for infiltration trench phosphorus removal of 65%. The assumed values for TSS removal were either in agreement with other reported typical ranges of effectiveness, or conservative as Caltrans (2004) assumed infiltration trenches and basins remove 100% of TSS. Some literature, such as Caltrans (2004), have reasoned that since water entering these storm-water BMPs is removed from the surface water, these storm-water BMPs achieve 100% removal of TSS and P. However, some dissolved contaminants may potentially reach the groundwater (MPCA 2000) and could reenter as surface water at a later time. The 67% confidence intervals for these storm-water BMPs were also assumed as denoted by an asterisk in Table 4.

Table 4. Average Percent Removal Rates of Best Management Practice with Corresponding Confidence Interval

Best management practices	Total suspended solids removal (%)	Total suspended solids (67% Cl)	Total phosphorus removal (%)	Total phosphorus (67% Cl)
Dry extended detention pond	53	±28	25	±15
Wet basins	65	±32	52	±23
Storm-water wetland	68	±25	42	±26
Bioretention filter	85*	±10*	72	±11
Sand filter	82	±14	46	±31
Infiltration trench	95*	±5*	65*	±35

Note: * = assumed value.

The values presented in Table 4 are, more or less, in agreement with the typical removal rate values reported in the National Pollutant Removal Performance Database (Winer 2000). For example, this manual lists the percent of total phosphorus removal of both wetlands and ponds to be 40% For filtration practices (i.e., and filters) the percent removal of total phosphorus is listed at 50% and that of TSS as 85%.

The values shown in Table 4 correspond to storm water treated by the storm-water BMP and do not account for any portion of the flow that bypasses the storm-water BMP or exits through an overflow outlet. Also, as stated previously, the values reported for phosphorus removal are based on data collected from existing storm-water BMPs. If the studies that generated these data were not collected over a long enough time span (months or years), the values in Table 4 may not reflect the possibility that phosphorus bound to the soil and sediment may, depending on pH and other water characteristics, become soluble and be exported from the BMP. Finally, the confidence intervals reported in Table 4 reveal a large amount of uncertainty in the reported data, which is likely due to variations in design, pretreatment, maintenance, and other factors.

The total amount of TSS or phosphorus removed by each storm-water BMP was estimated by multiplying the 20-year total load by 93% (i.e., estimated percent of runoff treated) and by the corresponding removal rate as found in Table 4.

Example Application

Storm-water BMPs under prefeasibility consideration for a 20-ha watershed in the Minneapolis/St. Paul metro region that is 80% impervious include a dry extended detention basin and a constructed wetland. The storm-water BMP is to be designed

Table 5. Slopes of Total Suspended Solids Removal as a Function of Water Quality Volume

Best management practices	Slope TSS removed (average kg)	Upper confidence interval	Lower confidence interval
Dry basins	27.49	45.43	9.55
Wet basins	33.67	54.61	12.73
Sand filters	42.40	59.96	24.85
Bioretention filters	44.19	61.59	26.78
Constructed wetlands	35.27	53.74	16.79
Infiltration trenches	49.39	68.13	30.64

for a 3.7 cm precipitation depth and a comparison of the cost and effectiveness of both storm-water BMPs is desired.

Using Eqs. (1) and (2), the WQV can be determined as follows:

$$WQV = 100 * 3.7 * (0.05 + 0.009(80)) * 20$$

$$WQV \approx 5{,}670 \text{ m}^3$$

From Table 3, the total present cost of an average dry extended detention basin of this size is $307,000 with a 67% confidence interval range of about $166,000–$668,000. A similarly sized average wetland would cost approximately $200,000 with a 67% confidence interval range of $112,000–$405,000.

To obtain an estimate of R_{F20}, a statistical analysis on historical precipitation data in Minneapolis and St. Paul from 1950 to 2003 was performed. The results showed that the 20-year running average precipitation depth is 28.44+/−1.80 in. (67% confidence interval).

When load removed is plotted as a function of WQV the result is a linear function with an intercept of zero. For each storm-water BMP, the slope of the average value of TSS removed (kg) as a function of WQV (m^3), along with the 67% confidence interval slopes, are given in Table 5. Thus, to estimate the average TSS removed (kg) over 20 years for a particular storm-water BMP, the slope value given in Table 5 can be multiplied by the WQV (m^3). Similarly, the slopes of phosphorus removal (kg) as a function of WQV and the corresponding 67% confidence intervals are given in Table 6.

Over 20 years the estimated TSS removal and 67% confidence interval for the dry extended detention basin can be, with the use of Table 5, estimated to be 155,870 kg with a 67% confidence interval range of 54,150−257,590 kg. The corresponding wetland TSS removal based on Table 5 is estimated to be 199,980 kg with a range of 95,200−304,710 kg.

The phosphorus removed over 20 years can be estimated in a similar manner using Table 6. For the dry extended detention basin the average P removal is approximately 290 kg with a range of 36−535 kg (67% confidence interval). The wetland average P removal is about 472 kg with a range from 45 to 898 kg. Thus, for this watershed and design depth, the wetland, on average, would cost less to construct (not including land costs) and it would also remove more TSS and phosphorus. However, up to this point land costs have not been considered.

Focusing on associated land costs of each storm-water BMP under consideration, Table 1 can be used to estimate the approximate required land area required for each storm-water BMP. Using the values based on total watershed area and selecting the high end of each range, the dry extended detention basin would require 2.0% of the total watershed area, which corresponds to a required land area of 0.4 ha. Similarly, the wetland would require 5.0% of 20 or 1.0 ha. If land costs are known, the land areas can be used to estimate land costs associated with each storm-water BMP. For example, if land costs were $25,000 per hectare, acquiring the land for the detention basin would cost an additional $10,000 and the land for the wetland would cost $25,000. The resulting average total cost (now including land acquisition) for the detention basin and wetland are $317,000 and $225,000, respectively. Thus, in this relatively low land cost scenario, the wetland would still be cheaper and more effective, on average. However, if land costs in the vicinity of the project were $625,000 per hectare, an average dry extended detention basin would, including land, have an estimated total cost of $557,000 and the wetland under consideration would have a total cost of $825,000. Thus, with more expensive land, wetlands are no longer the less-expensive option. However, wetlands are still estimated to remove more TSS and phosphorus, meaning that the parties involved would have to weigh the increased cost of the wetland against its added benefit (i.e., more contaminant removal). In addition, at the higher land cost there may be more cost-effective options than either the constructed wetland or the dry extended detention basin. The cost estimates are preliminary, of course, and could be used to compare the experience in the United States to more site-specific feasibility options.

Table 6. Slopes of Phosphorus Removal as a Function of Water Quality Volume

Best management practice	Slope Total phosphorus removed (average kg)	Upper confidence interval	Lower confidence interval
Dry basins	0.0512	0.0944	0.0064
Wet basins	0.1040	0.1856	0.0224
Sand filters	0.0912	0.1648	0.0192
Bioretention filters	0.1792	0.2960	0.0624
Construction wetlands	0.0832	0.1584	0.0080
Infiltration trenches	0.1297	0.2385	0.0208

Conclusion

Historical data have been used to compare the cost and effectiveness in suspended sediment and phosphorus removal of several common storm-water best management practices including dry extended detention basins, wet detention basins, constructed wetlands, infiltration trenches, bioretention filters, and sand filters. Effectiveness in reducing runoff volume or peak flow discharge were not considered. Data on construction costs and annual O and M costs have been combined to estimate the total present cost of the storm-water BMPs in 2005 dollars as a function of water quality volume. The total present cost is based on 20 years of annual O and M costs that have been converted to a present value based on historical values of inflation and municipal bond yield rates.

The pollutant-removal effectiveness of the storm-water BMPs as a function of WQV have been assessed by estimating the total amount of total suspended solids and phosphorus removed over a 20-year time period. Also, in order to help the user incorporate land costs, typical land area requirements for each storm-water BMP as a function of watershed area are presented.

Both the cost and effectiveness (i.e., amount of TSS and P removed) estimates are presented with 67% confidence intervals. Due to the wide scatter in the original data, the confidence intervals associated with each estimate also exhibit a relatively wide range.

For the six storm-water BMPs investigated, results show that, ignoring land costs, constructed wetlands have been the least expensive to construct and maintain if appropriate land is available. This result indicates that, when suitable land is available, constructed wetlands have been a cost-effective means of removing suspended sediment and phosphorus from storm-water runoff. However, since wetlands typically require more land area to be effective, land acquisition costs may result in wetlands being significantly more expensive than other storm-water BMPs that require less area. Also, the long-term capability of wetlands to remove phosphorus has been questioned by other authors.

The original data exhibited a wide amount of scatter that resulted in large 67% confidence intervals for the estimates of both the total present costs and mass of contaminants removed. Even with the scatter, the results can be used as a preliminary tool to compare storm-water BMPs in the categories of cost and impact on water quality, which are under consideration for a given project.

Acknowledgments

This work was funded by the Minnesota Local Road Research Board through the Center for Transportation Studies at the University of Minnesota.

Notation

The following symbols are used in this paper:

A = watershed area;
C = average annual contaminant concentration;
C_{OM} = annual operating and maintenance cost;
I = percent impervious in watershed;
L = annual pollutant load;
L_{20} = pollutant load over 20 years;
P = precipitation depth;
P_C = equivalent present cost;
R_F = average annual rainfall;
R_{F20} = 20-year running average annual rainfall;
R_V = ratio of runoff to rainfall;
WQV = water quality volume;
i = interest rate;
r = inflation rate;
β_0 = fitted constant; and
β_1 = fitted constant.

References

American Public Works Association (APWA). (1992). "A study of nationwide costs to implement municipal storm water best management practices." *Rep.*, Southern California Chapter, Water Resource Committee, APWA, Washington, D.C.

Anderle, T. A. (1999). "Analysis of stormwater runoff and lake water quality for the Twin Cities metropolitan area." MS thesis, Univ. of Minnesota, Twin Cities, Minn.

ASCE. (2004). "International stormwater best management practices (SBMP) database." ⟨http://www.bmpdatabase.org/⟩.

Barrett, M. E., Malina, J. F., Jr., Charbeneau, R. J., and Ward, G. H. (1995). "Characterization of highway runoff in the Austin, Texas, area." Center for Research in Water Resources Univ. of Texas, Austin, Tex.

Barrett, M. E., Walsh, P. M., Malina, J. F. Jr., and Charbeneau, R. J. (1998). "Performance of vegetative controls for treating highway runoff." *J. Environ. Eng.*, 124(11), 1121–1128.

Brezonik, T. H., and Stadelmann, P. L. (2002). "Analysis and predictive models of stormwater runoff volumes, loads, and pollutant concentrations from watersheds in the Twin Cities metropolitan area, Minnesota, USA." *Water Res.*, 36(7), 1743–1757.

Brown, W., and Schueler, T. (1997). "The economics of stormwater BMPs in the mid-atlantic region." *Final Rep.*, Center for Watershed Protection, Silver Spring, Md.

California Stormwater Quality Association (CSQA). (2003). "California stormwater BMP handbook—New development and redevelopment." Menlo Park, Calif., ⟨http://www.cabmphandbooks.com/Documents/Development/TC-21.pdf⟩ (January 2005).

California Department of Transportation (Caltrans). (2004). "BMP retrofit pilot program—Appendix C3." *Final Rep.*, Division of Environmental Analysis, Caltrans, Sacramento, Calif.

Carleton, J. N., Grizzard, T. J., Godrej, A. N., Post, H. E., Lampe, I., and Kenel, P. P. (2000). "Performance of a constructed wetlands in treating urban stormwater runoff." *Water Environ. Res.*, 72(3), 295–304.

Claytor, R. A., and Schueler, T. R. (1996). *Design of stormwater filtering systems*, Center for Watershed Protection, Silver Spring, Md.

Collier, C. A., and Ledbetter, W. B. (1988). *Engineering economic and cost analysis*, 2nd Ed., Harper and Row, New York.

Drapper, D., Tomlinson, R., and Williams, P. (2000). "Pollutant concentrations in road runoff: Southeast Queensland case study." *J. Environ. Eng.*, 126(4), 313–320.

Driscoll, E., Shelley, P. E., and Strecker, E. W. (1990). *Pollutant loadings and impacts from highway stormwater runoff*, Vol. I–IV, U.S. Dept. of Transportation, Federal Highway Administration, Washington, D.C.

Faulkner, S., and Richardson, C. (1991). "Physical and chemical characteristics of freshwater wetlands soils." *Constructed wetlands for wastewater treatment*, D. Hammer, ed., CRC, Boca Raton, Fla.

Fintrend (2004). "Historical CPI inflation values." Fintrend.com, Richmond, Va., ⟨http://www.inflationdata.com/inflation/Inflation-Rate/HistoricalInflation.aspx⟩ (October, 2004).

Harper, H. H., Herr, J. L., and Livingston, E. H. (1999). "Alum treatment of stormwater runoff—An innovative BMP for urban runoff problems." *Proc., 6th Biennial Stormwater Research and Watershed Management Conf.*, U.S. Environmental Protection Agency, Washington, D.C.

Huff, F. A., and Angel, J. R. (1992). *Rainfall frequency atlas of the Midwest*, State Water Survey Div., State of Illinois, Champaign, Ill.

Kline, S. J. (1985). "The purposes of uncertainty analysis." *J. Fluids Eng.*, 107, 153–160.

Kadlec, R. H., and Knight, R. L. (1996). *Treatment wetlands*, CRC, Boca Raton, Fla.

Landphair, H. C., McFalls, J. A., and Thompson, D. (2000). *Design methods, selections, and cost-effectiveness of stormwater quality structures*, Texas Transportation Institute, Texas A&M Univ. System, College Station, Tex.

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

Lower Colorado River Authority (LCRA). (1998). *Nonpoint source pollution control technical manual*, 3rd Ed., LCRA, Austin, Tex.

Mergent. (2003). *Mergent municipal and government manual*, Mergent, Inc., New York.

Minnesota Pollution Control Agency (MPCA). (2000). *Protecting water quality in urban areas—Best management practices for dealing with stormwater runoff from urban, suburban, and developing areas of Minnesota*, MPCA, St. Paul, Minn.

Moran, A., and Hunt, B. (2004). *BMP cost estimate study*, North Carolina State Univ., Raleigh, N.C.

Moxness. (1986). *Characteristics of urban freeway runoff. Phase I*, Water Quality Unit, Environmental Services Section, Office of Technical Support, Minnesota Dept. of Transportation, St. Paul, Minn.

Moxness. (1987). *Characteristics of urban freeway runoff. Phase II*, Water Quality Unit, Environmental Services Section, Office of Technical Support, Minnesota Dept. of Transportation, St. Paul, Minn.

Moxness. (1988). *Characteristics of urban freeway runoff. Phase III*, Water Quality Unit, Environmental Services Section, Office of Technical Support, Minnesota Dept. of Transportation, St. Paul, Minn.

Oberts, G. (1994). "Influence of snowmelt dynamics on stormwater runoff quality." *Watershed protection techniques*, Center for Watershed Protection, Elliott City, Md.

Reynolds, C. S., and Davies, P. S. (2001). "Source and bioavailability of phosphorus fractions in freshwaters: A British perspective." *Biol. Rev. Cambridge Philos. Soc.*, 76(1), 27–64.

Sansalone, J. J., and Buchberger, S. G. (1997). "Partitioning and first flush of metals in urban roadway stormwater." *J. Environ. Eng.*, 123(2), 134–143.

Schindler, D. W. (1977). "Evolution of phosphorus limitation in lakes." *Science*, 195(4275), 260–262.

Schueler, T. R. (1987). *Controlling urban runoff: A practical manual for planning and designing urban BMPs*, Dept. of Environmental Programs, Metropolitan Council of Governments, Washington, D.C.

Shammaa, Y., Zhu, D. Z., Gyurek, L. L., and Labatiuk, C. W. (2002). "Effectiveness of dry ponds for stormwater total suspended solids removal." *Can. J. Civ. Eng.*, 29(2), 316–324.

Southeastern Wisconsin Regional Planning Commission (SWRPC). (1991). *Costs of urban nonpoint source water pollution control measures*, SWRPC, Waukesha, Wis.

Stanley, D. W. (1996). "Pollutant removal by a stormwater dry detention pond." *Water Environ. Res.*, 68(6), 1076–1083.

Turner Construction. (2004). "Building cost index, 2004 fourth quarter forecast." Turner Construction, New York, ⟨http://www.turnerconstruction.com/corporate/content.asp?d=20⟩ (January 2005).

Urban Drainage Flood Control District (UDFCD). (1992). "Best management practices." *Urban storm drainage criteria manual*, Vol. 3, UDFCD, Denver.

U.S. Environmental Protection Agency (USEPA). (1999). "Preliminary data summary of urban stormwater best management practices." *EPA-821-R-99-012*, Washington, D.C.

Waschbusch, R. J., Selbig, W. R., and Bannerman, R. T. (1999). "Sources of phosphorus in stormwater and street dirt from two urban residential basins in Madison, Wisc., 1994–95." *USGS Water-Resources Investigations Rep. 99-4021*, U.S. Geological Survey, Reston, Va.

Weiss, P. T., Gulliver, J. S., and Erickson, A. J. (2005). "The cost and effectiveness of stormwater management practices." Minnesota Dept. of Transportation, St. Paul, Minn., ⟨http://www.rrb.org/pdf/200523.pdf⟩ (December 2005).

Winer, R. (2000). *National pollutant removal performance database for stormwater treatment practices*, 2nd Ed., Office of Science and Technology, Center for Watershed Protection. Ellicott City, Md.

Wossink, A., and Hunt, B. (2003). "The economics of structural stormwater BMPs in North Carolina." *Water Resources Research Institute Rep. No. UNC-WRRI-2003-344*, Univ. of North Carolina, Raleigh, N.C.

Wu, J. S., Holman, R. E., and Dorney, J. R. (1996). "Systematic evaluation of pollutant removal by urban wet detention ponds." *J. Environ. Eng.*, 122(11), 983–988.

Young, G. K., Stein, S., Cole, P., Kammer, T., Graziano, F., and Bank, F. (1995). "Evaluation and management of highway runoff water quality." *FHWA-PD-96-032*, Federal Highway Administration, U.S. Dept. of Transportation, Washington, D.C.