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Review

The Challenge of Maintaining Stormwater Control Measures: A Synthesis of Recent Research and Practitioner Experience

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Abstract: The methods for properly executing inspection and maintenance of stormwater control measures are often ambiguous and inconsistently applied. This paper presents specific guidelines for inspecting and maintaining stormwater practices involving media filtration, infiltration, ponds, and permeable pavements because these tend to be widely implemented and often unsatisfactorily maintained. Guidelines and examples are based on recent scientific research and practitioner experience. Of special note are new assessment and maintenance methods, such as testing enhanced filtration media that targets dissolved constituents, maintaining proper vegetation coverage in infiltration practices, assessing phosphorus release from pond sediments, and the development of compressed impermeable regions in permeable pavements and their implications for runoff. Inspection and maintenance examples provided in this paper are drawn from practical examples in Northern Midwest USA, but most of the maintenance recommendations do not depend on regional characteristics, and guidance from around the world has been reviewed and cited herein.

Keywords: maintenance; stormwater; treatment; assessment; stormwater control measure; sustainable drainage system; best management practice; green infrastructure; filtration; infiltration; retention pond; permeable pavement

1. Introduction

As urbanized areas around the world wrestle with growing pains and shifting ideologies on urban planning, stormwater control measures (SCMs) and green infrastructure are becoming increasingly popular for managing urban hydrology and stormwater. However effective newly-constructed SCMs and newly-installed proprietary devices may be, none can be expected to continue functioning effectively without regular and well-informed maintenance and inspections [1]. These efforts are best conducted by individuals experienced in stormwater management, which requires designating and training a dedicated stormwater work crew or contracting a stormwater engineer for consultations [2]. Even if the need is not immediately obvious (primarily because it is underground or under water), maintenance may still be required and can be identified with timely and thorough inspections. The frequency with which maintenance is needed can only be informed by periodic inspections but should occur at least once per year [1]. Additionally, properly budgeting and assigning responsibility for these activities is paramount for them to occur [3–5], especially considering that the total cost of maintenance for SCMs typically approximates the original construction cost over its designed lifetime [6]. Additional maintenance may be necessary to sustain site-specific performance criteria, such as managing erosion due to landslide concerns, managing vegetation due to wildfire concerns, or managing water quality to protect sensitive fisheries [5].

A regular inspection begins with visual observations and ends with detailed documentation. Excessive sedimentation, bank destabilization and erosion, invasive vegetation, or problematic wildlife could all lead to costly maintenance if left unresolved [1]. Any evidence of illicit discharges should be carefully noted, and other problems beyond the normal loading conditions of the watershed should be documented [3]. Steps should be taken to raise public awareness of stormwater infrastructure and its connections to water bodies rather than to sewage treatment facilities, a common misconception [7,8]. While previous work has set base guidelines for the maintenance of common stormwater control measures, the purpose of this paper is to address new and emerging challenges faced by stormwater professionals. Thus, scientific research is combined with practitioner experience to develop guidelines for the proper maintenance of high-priority SCMs, including media filtration practices, infiltration practices, stormwater wet ponds, and permeable pavements. These four SCM types were selected because they are in widespread use and are often inadequately maintained. While the observations are drawn from practical examples in Northern Midwest USA, most of the maintenance recommendations do not depend on regional characteristics and guidance from around the world has been reviewed and cited herein whenever possible. This information is intended to serve as a supplement to currently-available assessment and maintenance manuals (e.g., [1]) that have been developed globally, including the Pacific Northwest USA [7,9–11], New England USA [8,12–16], Mid-Atlantic USA [17–20], South Central USA [21–23], Southwest USA [5,24–27], Canada [28,29], New Zealand [30], the United Kingdom [31], Australia [32–35], Malaysia [36], Singapore [37,38], and South Korea [39], among others.

2. Media Filtration

Media filtration is the process by which particles suspended in stormwater are removed while water is passing through granular media [1]. The design of media filtration for stormwater treatment is simple and well-defined [40], and the maintenance of these filters has been similarly studied and documented [1]. The greatest need of stormwater professionals maintaining media filtration practices arises from the development of new additives, which are added to filtration media to capture soluble reactive pollutants, such as phosphate [41,42], nitrate [43], metals [44,45], bacteria [46], and others [47]. Primarily, stormwater professionals are unsure of how to determine when to maintain the additives within media filtration practices because there is a lack of visual indicators of when additives are no longer functional. To overcome these challenges, stormwater professionals must adopt more advanced assessment methods and rigorous documentation.

Visual inspection is a simple assessment method that can be used to identify poor performance within an SCM, assess the cause of the poor performance, and determine the necessary maintenance to restore the practice to proper functionality [1]. An example for filtration is slow drainage (poor performance indicator), which is often caused by clogged media as a result of accumulation of stormwater sediment or erosion from misaligned inlet and outlet structures and/or around the exterior of the filtration practice (cause of poor performance). Corrective maintenance involves removing the accumulated sediment and restoring the hydraulic conductivity of the media surface. Visual inspection, however, typically cannot identify poorly functioning additives because the additives are commonly mixed into or installed within the media itself, and thus are not visible from the surface of the filtration practice. To properly assess the performance of media filtration additives, more intense assessment, such as capacity or synthetic runoff testing [1] or monitoring, may be necessary. These methods can be expensive, and thus cost-prohibitive, to deploy throughout a municipality or other jurisdiction with tens, hundreds, or even thousands of SCMs. Annual maintenance cost estimates for media filtration practices range from 1–10% of the original construction cost [1]. However, these assessment methods can be modified to simplify the process, reduce costs, and specifically assess media filtration practices with additives.

Capacity testing is an assessment method that measures the capacity of an SCM to perform its intended function [1]. Typically employed to measure sedimentation or infiltration, capacity testing can be modified to incorporate a batch jar test and directly measure the capacity of media filtration additives to capture their target pollutants. Measuring the sorption capacity of media filtration additives will provide a snapshot of the remaining capacity, which can be used to estimate when additives need to be replaced. Optionally, this procedure can be performed prior to installation of the filtration media and additive(s) to determine a 'baseline' by which subsequent tests can be compared to determine the rate of degradation. A sample protocol of such batch tests is described in the following steps:

Step 1 Collect a representative sample of the filtration media, including additive(s), with a known volume and mass. It is important to know the mass of media, including the mass of sand (if applicable) and each additive individually, to determine the ratio of these masses to the pollutant(s) captured in subsequent steps. In addition, the (bulk) volume of the sample can be used to expand the results to the full-scale media filtration practice.

Step 2 Place the filtration media in a container of clean water with a known concentration of pollutant(s) that the additive is intended to capture. The mass ratio of water to additive should be approximately 100:1, and the mass ratio of pollutant(s) to additives should be approximately equal to the capacity of the additives to capture that pollutant. For example, a 10 g sample is collected of a mixed filtration media comprising sand (8 g) and a commercial adsorbent media (2 g). The capacity of the commercial additive to capture arsenic (As) is reported to be 12 mg As per kg sorbent. Thus, 2 g of additive within the sample can be expected to capture 24 μg of As. Using a mass ratio of water to additive of 100:1, the mass of water should be 200 g, which is approximately 0.2 L. The mass of As (24 μg) in this volume of water yields an As concentration of 120 μg/L.

Step 3 Thoroughly mix the additive in the water for at least a length of time equal to the contact time between the additive and the pollutant in the full-scale SCM, or up to 24 hours. Selecting a shorter mixing time will often result in less pollutant(s) capture and thus a more conservative measure of remaining sorption capacity.

Step 4 Collect samples from the water and measure pollutant concentration. This should be performed at the beginning of the test to verify the initial pollutant concentration, and at the end of Step 3 to confirm performance. This step can be performed throughout the duration of Step 3 to measure the change in concentration as a function of time, which can be used to estimate the relative rate of removal. Pollutant concentration can be measured following Standard Methods [48], other approved laboratory methods, using analytical laboratory services, or by chemical analysis kits that can be purchased online.

Step 5 Determine the pollutant capture ratio as the ratio of captured pollutant mass to additive mass. For example, if the mass of As in solution is reduced by 10 μg, then the remaining capacity of the additive to capture As is 14 μg As per 2 g of additive, or 7 mg per kg. Thus, the capacity has been reduced from 12 mg per kg to 7 mg per kg.

Table 1 provides a list of base guidelines for the maintenance of media filtration practices, including those with additives for enhanced performance.

Table 1. Maintenance recommendations for media filtration practices [1,13,17,21,22,30,32].

Task	Frequency	Notes
Inspection	Annually or after every two-year storm	
Remove trash and debris	Annually	Increase frequency, if needed
Remove obstructions to outlet structures and underdrain systems	As needed	Cleanouts can simplify obstruction removal from underdrain systems and should be included in all filtration designs
Remove vegetation from filter surface, if applicable	Once per year	Increase frequency, if needed

Table 1. *Cont.*

Task	Frequency	Notes
Perform testing to determine filtration rates	Whenever visual inspection identifies the need	
Remove retained sediment, typically the top 5–20 cm of discolored surface media	Variable (once every five to ten years is typical in stable watersheds)	In unstable watersheds (i.e., those with active construction), the frequency is typically once per year
Effluent sampling and analysis of enhanced media	Annually, or when amendment performance is in question as needed	
Capacity testing for pollutant capture by additives	As needed, when effluent samples suggest reduced pollutant capture capacity	

3. Infiltration Practices

Infiltration practices capture stormwater runoff and allow it to flow into the ground rather than into a collection system [1]. Infiltration practices vary in design and appearance and include practices such as infiltration basins, trenches, and rain gardens (bioretention, bioinfiltration), among others. Visual inspection will identify poor performance in a manner similar to filtration practices. In addition, capacity testing of the infiltration rate is often conducted on infiltration practices through measurement with field infiltrometers. It has been found that the infiltration rate (as indicated by saturated hydraulic conductivity) will vary substantially over most infiltration practices, even with engineered soil [49,50]. A representative infiltration rate for the whole practice can be determined with the appropriate mean value of hydraulic conductivity [51].

Many of these infiltration practices rely on vegetation to support infiltration through the soil surface [52], evapotranspiration, pollutant capture [47,53,54], and microbial breakdown of captured pollutants [55]. Thus, managing proper vegetation is one of the greatest challenges for stormwater professionals. The aspects of managing proper vegetation in infiltration practices include maintaining proper coverage and species and also ground cover management because it affects the health and diversity of vegetation. Proper vegetation coverage is important because a lack of vegetation results in open and exposed soils, which are susceptible to erosion and weed germination. In addition, fine sediment removed from the stormwater runoff often clogs the soil surface of an infiltration basin. Healthy vegetation in SCMs can create macropores by which stormwater can pass through a clogged soil surface [52]. Thus, a lack of proper vegetation coverage can reduce infiltration, which subsequently increases the amount of time that water is stored within an infiltration basin. This periodic inundation can further impact vegetation, beginning a cycle of reduced vegetation coverage, reduced infiltration, and increased ponding time until the infiltration practice completely fails.

Vegetation coverage can also be over-abundant, which potentially limits access for inspection and corresponding maintenance. The most common cause of over-abundant vegetation is a lack of vegetation management, often resulting in undesirable vegetation species (e.g., invasive weeds) that can quickly outcompete and dominate native or selected vegetation species. In fact, a major challenge in managing infiltration practices is maintaining the proper vegetation diversity. Native plants are typically better-suited to their environment and will require less fertilizer to become established [19].Working with local partners can facilitate the selection of appropriate species [33]. Infiltration practices are often designed with between one and ten different vegetation species, ranging from native prairie grasses and sedges to wildflowers and pollinator-supporting plant species in the upper Midwest USA [56], to forbs, rushes, and trees in Australia [57,58], and to succulents and forbs in drier climates [25,26]. Maintaining a plant species palette requires knowledge in plant species identification to ensure that non-design species are removed and design species are healthy and present. Some plants may also require specialized care such as limited pruning to minimize stress and maximize health [23]. In appropriate regions, desert vegetation may require little maintenance [26]. Vegetation management for aesthetics will depend on site characteristics. In some cases, a more natural appearance can be desirable, while a manicured landscape is preferable in others [19]. In applications where longer vegetation is desired, it can be cut back just enough to show that it is being maintained [39]; the appearance of maintenance is important to discourage littering and vandalism. Site-specific safety considerations regarding overgrown vegetation should also be considered (e.g., blocking vehicle lines-of-sight or allowing individuals to hide) [19].

Proper ground cover (e.g., mulch) management can also limit an over-abundance of design vegetation and invasion of undesirable species. Ground cover includes mulch, landscaping stone, rock, and recycled materials, such as shredded tires. These materials provide aesthetic benefits, but when properly selected, designed, and maintained, can also limit erosion, weed germination, and vegetation overabundance. Proper inspection frequency and effectiveness can identify issues related to poor vegetation cover, poor species diversity, and improper ground cover management. Annual maintenance cost estimates for infiltration practices range from 3–5% of the original construction cost [1]. Table 2 provides a list of base guidelines for the maintenance of infiltration practices.

Table 2. Maintenance recommendations for infiltration practices [1,12,17,21,30,31].

Task	Frequency
Remove sediment and oil/grease from pretreatment devices and overflow structures	As Needed
Mow and remove litter and debris	As Needed
Stabilize eroded banks, repair undercut and eroded areas at inflow and outflow structure	As Needed
Inspect pretreatment devices and diversion structures for signs of sediment buildup and structural damage	Semi-Annual Inspection
If dead or dying grass is evident at the bottom or the basin/trench, check to ensure water infiltrates within two days following significant rain events	Semi-Annual Inspection
Disc or otherwise aerate bottom	As Needed
De-thatch basin bottom	Annually
Provide an extended dry period, if bypass capability is available, to regain or increase the infiltration rate in the short term	Five-year Maintenance

4. Ponds

Despite being one of the most abundant SCMs, many stormwater ponds (also known as retention ponds, wet detention ponds, or wet ponds) are seldom maintained [29]. First and foremost, a stormwater pond must be designed with maintenance in mind. This includes everything from having an easily-accessible sedimentation forebay or other pretreatment practice, to budgeting for and scheduling both routine and non-routine maintenance activities. Annual maintenance cost estimates for ponds range from 2–10% of the original construction cost [1]. A standardized inspection schedule may not be appropriate for all ponds because watershed and even pond characteristics vary greatly, and the frequency with which maintenance is needed may change as the watershed becomes more developed [59]. For example, poor upstream erosion control can drastically shorten a pond's lifespan due to increased sediment loads, requiring more frequent maintenance [60]. As physical changes to the pond or watershed occur, or water quality treatment goals intensify, the need may arise to increase the hydraulic residence time by adding screens or flow-lengthening baffles [59].

The design of a pond must be suited to a specific purpose, and performance goals must be appropriate for the given watershed and site constraints. Whether a pond addresses volume control, water quality, ornamental purposes, or a combination of these, other priorities will determine how an optimally functional system should look and how it needs to be maintained. Water features often provide ecosystem services in addition to their hydraulic and hydrologic functions. Aside from bringing open green spaces to urban environments, which can provide socioeconomic benefits [20,29,61], ponds can contribute to carbon sequestration, biodiversity, and cultural services. The first two of these are facilitated by the presence of a littoral shelf, which must be maintained to promote non-invasive, emergent vegetation that provides habitat for various species, including predators of mosquitos [62]; where mosquitos are a particular threat, regular inspections and treatments may be necessary [5,20,38]. The abundance and general variability of stormwater ponds further magnify their potential benefits to biodiversity [63,64]. Cultural services, such as recreation and education, will depend on accessibility, proper landscape management, and the maintenance of trails, infrastructure, and signage [62], in addition to public understanding and aesthetic preferences, which will vary and must be determined locally [65,66]. It is therefore important to educate the public on the function of stormwater ponds and safety concerns related to coming into contact with the water [29,38].

When tasked with performing such a broad range of functions, ponds may need additional improvements and enhancements. Stormwater ponds are effectively sacrificial water bodies aimed at protecting downstream waters; however, residents and other stakeholders will often expect to use ponds for ornamental or recreational purposes, which can cause concern when water clarity decreases and nuisance vegetation or algae begin to take over [59,60,66,67]. Deriving additional benefits from stormwater ponds may therefore necessitate providing additional pretreatment for the ponds in the form of pretreatment sumps (potentially including sediment separation devices). In some cases, direct treatment of the undesired symptoms, such as algae growth, may become necessary by means of mechanical or chemical methods [67]. Because of the complex functions and roles expected of stormwater ponds by the public, it is important that all stakeholders be given a voice regarding large-scale maintenance or construction activities [33]. Residents around stormwater ponds tend to view them as natural water bodies and may even resist maintenance efforts that could be seen as destroying 'natural' habitats [29].

The baseline for any SCM should come from the as-built condition. A thorough assessment following construction can help trace future problems back to issues with the design, construction, operation, and/or maintenance [5]. The sooner deviations from designs are discovered, the easier it will be to have the construction contractor rectify them [3]. Clearly communicating to contractors the intricacies and special considerations involved in constructing SCMs is paramount to minimizing such design deviations [34]. As-built drawings are usually not available for ponds that were constructed by retrofitting existing wetlands with poorly-defined elevations [4]. A follow-up assessment two years after construction or the most recent dredging can help estimate targeted characteristics, such as the sedimentation rate, to approximate when dredging will need to occur (often at 50% sediment accumulation [35]), which is particularly important because it can take a year or more for the excavation to occur once the need for it has been established [68]. Most, if not all, municipal separate storm sewer system (MS4) permits require regular outfall inspections (approximately every five years), at which time the bathymetry of the pond can be recorded to update models and keep track of sediment deltas [60]. Knowing the volume of sediment to be removed also allows the number of trucks necessary to haul the dredged material, and therefore the number of days required, to be estimated [4].

Most stormwater pond maintenance efforts evaluate 'success' as removing particulates to restore volume [2,4], and many stormwater ponds have water quality goals that include phosphorus removal associated with these solids. However, a portion of the phosphorus in the sediments is bound to be redox-sensitive ions, which means that oxygen must be present in the water to keep phosphorus in its particulate form. When dissolved oxygen (DO) drops below 1 mg/L, the pond is considered anoxic and redox-sensitive phosphorus will be released into the water column as soluble reactive phosphorus (also called orthophosphorus, ortho-P, or phosphate, ${PO_4}^{-3}$). This is particularly problematic because this is the most bio-available form of phosphorus and can lead to harmful algal blooms of blue-green algae (cyanobacteria) in addition to contributing to eutrophication and other water quality problems. Cyanobacterial growth rates will depend on water temperatures and pond residence time, so it is recommended that residence times in warmer regions be reduced according to the average summer water temperature to minimize harmful algal blooms [35]. Blooms can also be suppressed by applying beneficial bacteria, aerators, or specific chemicals [20,67].

Stormwater ponds that release ortho-P from the sediments will appear to capture less phosphorus overall and could be a net source of phosphorus to the receiving water body. To keep ponds from becoming anoxic, early design recommendations from the National Urban Runoff Program (NURP) called for stormwater ponds to be between 1 and 8 m in depth [69]; current design standards typically specify a depth of approximately 1 to 3 m [70–72]. This depth was assumed to allow for settling of suspended sediments containing particulate phosphorus, while remaining shallow enough to be fully-mixed by wind and storm events and therefore remain oxic [69]. However, periodic and sometimes regular and persistent thermal stratification has been observed during summer months, even in ponds less than 1 or 2 m in depth [72,73]. Thermal stratification can be especially problematic in warmer climates [36]. It is recommended that DO and temperature profiles be measured during regular inspections to evaluate which ponds are experiencing anoxic conditions that may trigger phosphorus release from the sediments [74]. Sheltering from wind (see Figure 1) by trees can prevent destratification, so vegetative growth around stormwater ponds should be controlled when possible [75]. In addition, conductivity profiles should also be measured in colder regions because road salt applications from winter deicing operations can accumulate in stormwater ponds and contribute to stratification [76]. Alum treatment [77] or iron treatment [78] can be used to fix phosphate in the sediments. In certain cases, aeration systems could be used to avoid stratification, although these systems must be run continuously and must aerate across as much of the pond area as possible to be effective.

(**a**) (**b**)

Figure 1. A well-sheltered stormwater pond (**a**) and a poorly-sheltered stormwater pond (**b**).

The worst-performing ponds usually get maintained first, but a cost-effectiveness approach looking at pounds of phosphorus removed per dollar spent within a given watershed would allow funds to be spent more efficiently on a greater number of ponds [60]. Additionally, there may be times where maintaining one pond over another is necessary because of connectedness to downstream protected water bodies or water bodies of interest [4,5].

With any maintenance strategy, careful coordination and planning is integral to success. Maintenance access along the edge of the pond and through easements must be maintained over time, both to facilitate access and to keep the easements identifiable. It is also important to inform residents of maintenance/access agreements whenever property changes ownership. Any long-term plan must clearly hold specific individuals and entities responsible so that the required tasks occur as intended [3–5]. Poorly maintained easements are occasionally unintentionally annexed by residents who may place permanent structures or plant trees that block the path of larger equipment. Often, these may have special sentimental value to the residents, composing the 'human dimension' of challenges [4]. In such cases, opposition can be circumvented by working with residents to enable the establishment of temporary easements to minimize disruptions to their yards. If trees must be felled, an offer can be made, for example, to replace them at a ratio of 2:1, potentially even allowing residents to select the species and placement of the new trees [3]. However, care must be taken that tree roots are not at risk of destabilizing banks [35] or infiltrating pipes [20].

The timing of maintenance activities can also be optimized. Retrofit projects to meet increasing needs and standards can be used as opportunities to improve performance and increase the time until the next maintenance activity [60]. Different settings will require activities to be conducted at different times of day to minimize traffic and noise disruptions. In climates that have a season where frozen soil is common, full-pond dredging is often done in the winter because soils are hard; this will make heavy equipment movements simpler and minimize undesirable impacts to surrounding soils [60,68]. Ponds can also be more easily dewatered with lower liquid precipitation in winter [68]. Otherwise, special care should be taken to ensure that dewatering operations do not cause erosion downstream of the pond [79]. If dewatering is not necessary and only the sediment delta is being removed from the forebay, a temporary silt screen can be deployed to minimize suspended sediment dispersal and impacts to the rest of the pond. However, this dredging will typically be limited to the sediment that can be reached from the shore by an excavator [3]. Adverse impacts to fish and wildlife should also be considered. Special requirements and permitting may also be required for wetlands that were converted from natural wetlands. In this case, permit applications should specify that only non-natural materials are being removed [3].

Forebay dredging can occur at any time of year. For summer operations, temporary shield plates can be placed over grass and soft soils to minimize impacts. For sediment delta dredging, sediments can be deposited into a vacuum dredge box (a metal trough to which a vacuum hose can be connected, as shown in Figure 2) and be collected by a vacuum truck rather than having to be transferred directly from excavators to dump trucks [2]. This method can minimalize 'human dimension' challenges by greatly reducing impacts to yards and lawns via reducing vehicular traffic through the easement and the width of easement that is required [4]. Efforts made to minimize impact and disruptions also simplify and shorten restoration efforts following maintenance operations, which can make up approximately 30–50% of total costs. Communication is also crucial in this phase to make sure that all parties involved understand what is expected of them so that any new sod or replacement trees are adequately watered until roots can become established [2,4,18]. In wetter regions, drainage may be necessary to keep seeds from drowning, and in all cases, plantings should occur at the appropriate time of the year for vegetation to properly establish [35]. The potential for herbivory must also be considered [18].

(**a**) (**b**)

Figure 2. Dredged sediment being deposited into a vacuum dredge box (**a**) and vacuumed away to a truck on the street (**b**). Photos copyright of the City of Eden Prairie, MN, USA.

During dredging, junk materials from illicit dumping are often discovered and may complicate dredging, depending on the sizes of the materials. It may also be discovered that as-built drawings are inaccurate and not representative of the conditions encountered at the site. An inaccurately-defined pond bottom coupled with unexpected underlying pervious soils can lead to groundwater impacts and the unintended, and perhaps undesirable, conversion of a stormwater pond into an infiltration basin [4]. Placing a hard surface as a reference point (e.g., concrete or rocks at the bottom of the forebay) can facilitate identifying the bottom of the pond during dredging [35].

After dredging, sediments should be dewatered to reduce the mass that must be transported [29,35]. Sediments can be reused or disposed of according to concentrations of various contaminants, such as heavy metals [29,80]. The contaminants of concern in pond sediments are polycyclic aromatic hydrocarbons (PAHs), which are carcinogenic products of incomplete combustion, primarily originating from coal tar sealants and vehicular combustion [81]. Different PAHs vary in carcinogenic risk and bioavailability, but typically must be disposed of in confined disposal facilities due to their perceived danger [80]. This alone can triple the cost of dredging a pond [82]. In some cases, the cost of dredging ponds can become so high that it becomes preferable to reroute stormwater to an entirely new pond and abandon the original pond [4]. When handling potentially hazardous materials, appropriate personal protective equipment (PPE) should be worn. In this case, soils should not be handled or disturbed until laboratory results have been received. If soils are determined to be hazardous, only professionals trained to safely and properly handle the soils should do so [19].

Ultimately, the most effective pond maintenance technique is proactive load reduction. Vocal residents may tend to call stormwater pond managers with questions and concerns regarding a pond's appearance. These are opportunities for energetic residents to be activated to raise awareness about how stormwater ponds function and promote watershed management for nutrient load reduction [60]. Table 3 provides a list of base guidelines for maintenance of stormwater ponds.

Table 3. Maintenance recommendations for ponds [1,17].

Task	Frequency	Notes
Inspection	Annually or after every two-year storm	
Monitor sediment depth in forebay and deep pools	Once per year	Can be performed with capacity testing
Measure pond bathymetry	After construction/dredging and then every five years	Calculate sedimentation rates to estimate dredging timeline
Inspect outlet structures	Annually or after every 2-year storm	Follow visual inspection guidelines
Remove trash and debris	Annually	Increase frequency, if needed
Remove vegetation from dam top and faces, if applicable	Once per year	Increase frequency, if needed
Mow wet pond perimeter	As needed	
Remove burrowing animals and beavers, if present	As needed	Destroy burrow holes whenever present; contact a professional trapper to remove beavers; nuisance animals may return after removal
Measure dissolved oxygen, temperature, and conductivity profiles	As frequently as possible	Frequency can be increased or decreased once trends are observed
Collect total phosphorus surface water samples	As frequently as possible	Frequency can be increased or decreased once trends are observed
Remove all sediment from forebay and deep pool (dredging)	Variable (Once every five to ten years is typical in stable watersheds)	In unstable watersheds (i.e., those with active construction), the frequency is typically once per year
Treat phosphorus release with alum or iron filings	As needed	Harmful algal blooms resulting from high phosphorus may have to be treated directly with beneficial bacteria, aeration, or chemicals
Maintain easements accessible	Annually	Maintaining a regular presence can discourage homeowners from obstructing passage

5. Permeable Pavements

Permeable pavements are an alternative to conventional asphalt or concrete pavement material where the porosity of the pavement is increased to allow transport of water from the surface through the pavement to the materials below. Permeable pavements include asphalt, concrete, and modular permeable block systems, where the water passes either through or between the blocks. Permeable pavements are often designed with up to 90 cm of large gravel below the pavement to temporarily store water that infiltrates through the permeable pavement.

A major challenge in the maintenance of permeable pavements is the development of depressed areas where vehicle tires commonly impact the pavement surface. In some cases, the cause of this depression is poor pavement strength because of poor design or construction, resulting in pore space collapse and reduced infiltration capacity. In addition, particles from vehicle tires and wheel wells tend to be deposited within these depressed areas, and water preferentially accumulates and infiltrates into these depressed areas, causing an accumulation of particles that can clog the permeable pavement surface. In permeable pavements that do not develop depressed areas, sediment from vehicles can still clog the pavement surface preferentially in the areas in which tires impact the pavement surface. As a result of collapsed pore space and/or accumulated sediment, the infiltration capacity can be substantially reduced. Because depressed areas are lower in elevation than the surrounding permeable pavement, these linear channels can become surface conveyances and create runoff from an area intended for infiltration.

Simple methods have been developed to determine whether collapsed pores or sediment accumulation have reduced infiltration rates through permeable pavements [83]. Maintenance activities for permeable pavements have been shown to restore up to 90% of the original infiltration capacity [84]. In a comparison of mechanical street sweeping, regenerative-air street sweeping, vacuum street sweeping, hand-held vacuuming, high-pressure washing, and milling of porous asphalt, the most successful methods were milling 2.5 cm from the surface and vacuum street sweeping [84]. In some areas with high debris loading, multiple passes with a vacuum street sweeper were needed to increase surface infiltration rates above acceptable thresholds [84]. While vacuum street sweeping can remove sediment, none of the surface cleaning maintenance methods can restore infiltration capacity in collapsed pores. If the collapsed pores are only near the surface, milling may be the only maintenance activity that will restore infiltration capacity. Milling as a maintenance activity on permeable pavement requires some additional research, though, to determine how clean pavement can be added to the surface or whether pavement sections can be designed such that milled pavement can be removed without replacement. Table 4 provides a list of base guidelines for the maintenance of permeable pavements.

Table 4. Maintenance recommendations for permeable pavements [1,17,84].

Task	Frequency	Notes
Inspection	Annually or after every two-year storm	
Vacuum street sweeping	Variable (three to four times per year recommended)	More frequent cleanings may be required in watersheds with large debris loads
Measure surface infiltration rate	As needed, when inspections indicate reduced infiltration rate (i.e., surface ponding)	
Milling the top 1–2.5 cm	As needed, when vacuum sweeping does not restore infiltration capacity	
Where areas of paving settle, lift blocks, re-level bedding material, and lay blocks at new level	As needed	
Do not sand or salt during the winter	Annually	
Maintain landscaped areas that may run-on to pavement; reseed bare areas	As needed; inspect annually	

6. Future Research

As the above review suggests, recent research has found new methods for improving how engineers maintain SCMs. New research is continually expanding the types of SCMs available to engineers and improving the performance of existing SCM designs. As new mechanisms are added to existing practices and new practices are developed, still more research is needed to determine the best maintenance methods and the frequency, effort, and costs associated with the maintenance. In addition, more research is needed to better understand the relationship between the performance of a practice (e.g., runoff volume reduction, pollutant capture) and maintenance activities. While this has been done for a select few practices and maintenance activities (e.g., [84]), more research like this for more practices and more maintenance activities is needed to better understand the cost-effectiveness of maintenance throughout the life-cycle of an SCM.

7. Summary and Conclusions

The function of a stormwater control measure (SCM) needs to be maintained and should not be ignored in determining life-cycle costs. A rule-of-thumb is that the maintenance of a SCM throughout its life will cost as much in current currency as the construction cost of the practice. As the treatment of stormwater becomes more complex, new concerns for SCM assessment emerge, such as the capacity of media filtration additives targeting specific dissolved pollutants and the implications of permeable pavement compression for runoff. There are also older stormwater practices that have developed new problems, such as retention ponds that are sheltered by large trees and can therefore stratify and develop low dissolved oxygen concentrations at the bottom, which can in turn lead to phosphate release from the sediments that can flow into receiving water bodies. The maintenance of an SCM is therefore a continuous adaptation to changes in the practices and condition of the practices.

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