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# Tracking the Cost of Maintaining Stormwater Best Management Practice Facilities: the Role of Database Design and Data Entry Best Practices

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## ABSTRACT

Best management practices (BMPs) are widely used to mitigate non-point source pollution from stormwater discharges. However, long-term operation and maintenance of stormwater BMPs have been an afterthought before the compliance requirement detailed in the Municipal Separate Storm Sewer Systems (MS4) permit. As a result, there is limited information available on the actual cost of maintaining BMPs. The objective of this research is to analyze the stormwater maintenance tracking database created by the Virginia Department of Transportation (VDOT) to (1) complete a preliminary cost analysis of routine and non-routine maintenance with respect to VDOT district or practice type and to (2) identify challenges encountered when processing the data for analysis and provide potential solutions relevant to other entities tracking BMP maintenance costs. The cost analyses presented in this study are preliminary based on the currently available data; however, they

show insightful trends among the data collected by VDOT from 2018 to 2020. Namely, preventative maintenance actions appeared to greatly lower the need for non-routine or major repairs within the Virginia districts. Routine and non-routine maintenance costs were, on average, $375 per task and $812 per task, respectively. The cost of major repairs was approximately $63,000 per case. The most expensive routine maintenance tasks were Basin BMPs (constructed wetlands, wet ponds, extended detention, and ponds), averaging $400 per task. The most expensive non-routine maintenance tasks were Infiltration BMPs (permeable pavement, infiltration practices, and bioretention), averaging $1,123 per task. The Basin BMPs had the largest annual upkeep at $1,100 per year. Approaches for extending the current database design used by VDOT are discussed to address challenges identified through the analysis including data incompleteness, overloaded work orders, and the lack of controlled vocabulary. These lessons learned regarding database design can be useful to other agencies seeking to track and analyze stormwater maintenance activities and associated costs.

## PRACTICAL APPLICATIONS

The tracking of stormwater best management practice (BMP) operation and maintenance (O&M) practices can help reduce the costs associated with stormwater permit compliance. A key factor in the O&M tracking process is the database design, which governs the collection, storage, accessibility, and analysis of the O&M data. However, the database design for BMP O&M tracking is not well documented. An analysis of the Virginia Department of Transportation's (VDOT) O&M collection process and database design indicates that a many-to-many relationship exists between work orders and the BMP assets, hindering the cost analysis of the maintenance work. Other challenges observed were a lack of controlled vocabulary when reporting the maintenance activities, assigning maintenance tasks associated with multiple BMPs to a single BMP, and the presence of incomplete work orders. The access to detailed BMP maintenance information can be used to calculate the approximate costs of routine and non-routine maintenance with respect to district or practice type, to determine estimates for BMP inspection frequencies, and to assess the level of effort needed to maintain certain BMPs. A design extension of the VDOT stormwater O&M tracking database is proposed that can inform the design for other states' and communities' stormwater BMP O&M tracking databases.

## INTRODUCTION

The U.S. Environmental Protection Agency (USEPA) lists stormwater runoff from urbanized areas as one of the top sources of water quality impairments to surveyed estuaries and lakes (USEPA 2009). Since the passing of the 1987 amendments to the Clean Water Act that authorized the USEPA to begin regulating non-point source pollution from stormwater discharges, the field of stormwater management has arguably experienced more innovation than any other environmental discipline (Flynn et al. 2012). The implementation of stormwater best management practices (BMPs) is one of the most widely accepted measures used to control surface runoff volume and reduce pollutant loads (Li 2015; Hoss et al. 2016). Unlike common sources of point-source pollution (e.g., municipal wastewater treatment plants), stormwater management lacks detailed and agreed-upon guidelines concerning the ongoing maintenance of BMPs (Barbosa et al. 2012; Blecken et al. 2017). As a result, stormwater BMPs were consequently neglected or assumed to function indefinitely after their construction (Blecken et al. 2017). Furthermore, Roy et al. (2008) concluded that there were seven major obstacles to sustainable urban stormwater management: (1) uncertainties in performance and cost, (2) insufficient engineering standards and guidelines, (3) fragmented responsibilities, (4) lack of institutional capacity, (5) lack of legislative mandate, (6) lack of funding and effective market incentives, and (7) resistance to change.

The USEPA requires all Municipal Separate Storm Sewer Systems (MS4) permit holders to inspect their respective BMPs annually and perform all needed maintenance within the same permit year to help those facilities maintain a desired level of performance and efficiency (VDOT 2021). However, very few studies have documented the actual maintenance activity, frequency, and cost required to ensure the designed functionality and efficacy of BMPs (Houle et al. 2013; Nobles et al. 2017). A case study on the current stormwater program identified common maintenance issues found for green stormwater infrastructure (GSI) in Fairfax County, Virginia (DelGrosso et al. 2019). This study compared public and private facilities with GSIs by reviewing inspection data, typical maintenance problems, and the frequency of said maintenance problems. The bulk of the issues reported in the evaluations was due to site conditions as well as the frequency of the routine maintenance performed (DelGrosso et al. 2019). One of their final recommendations was that a thorough record and tracking of construction and post-construction inspection items are needed to improve the facilities' longevity and aid in the decision-making efforts regarding GSI construction and placement (DelGrosso et al. 2019). This research shows the value of consolidating maintenance data into a database to help identify trends in deficiencies for specific facilities, as well as BMP types.

Many stormwater permittees, regulators, and other interested parties found it challenging to weigh the costs and benefits of a chosen practice since BMP cost is typically discussed in terms of initial construction cost instead of the life-cycle cost that includes expenses over long-term O&M. This is quite problematic for stormwater BMP managers who are in charge of BMP infrastructure decision-making assessments (Roy et al. 2008). A few preliminary studies have been performed to address this problem. One such study created a highly customizable Excel-based life-cycle cost tool to help managers evaluate stormwater control measures (SCMs) by estimating the cost of materials, labor, equipment, energy, and environmental costs (Krieger and Grubert 2021). There is still a large uncertainty associated with their proposed tool due to the BMP design choice and regional and temporal variability. Furthermore, the life-cycle cost is influenced by many other factors including: is the labor subcontracted or internal; is the equipment rented or owned; what is the minimum unit of equipment usage; will this be a high, medium, or low-cost estimate; and how often is maintenance performed? (Krieger and Grubert 2021). The information gap remains clear: there is a lack of detailed maintenance cost data describing BMP performance that could be used to provide guidance on BMP management (Qiao et al. 2018; Roy et al. 2008).

To remain in compliance with the MS4 permit, to more efficiently plan and document stormwater maintenance events, and to collect data on BMP O&M cost in the hope of estimating the whole-life costs of various types of BMPs, certain state departments, local governments, and nonprofit technical and educational organizations have become deeply invested in building their own stormwater maintenance tracking databases (Qiao et al. 2018; Smith et al. 2023; Blecken et al.

2017). These BMP maintenance tracking databases must be purposefully managed by the staff so that trends can be identified and educated decisions regarding BMP design and selection can be made. A robust database should give an indication of the following: frequency and schedule of inspection and maintenance, level of effort needed for routine maintenance, BMP deterioration factors, and reasonable cost estimates for routine and non-routine BMP maintenance.

The International Stormwater Best Management Practices Database (BMP Database) is one large systematic database that allows access to BMP data from organizations all around the world (Smith et al. 2023). The goal of the BMP Database is to help municipalities select the best BMP for their area and increase the performance and longevity of BMPs (Clary et al. 2018). Currently, there are six different publicly available databases: Urban Stormwater BMP Database, DOT Portal to BMP Database, Urban BMP Cost Database, National Stormwater Quality Database, Agricultural BMP Database, and Stream Restoration Database (Smith et al. 2023). Requests from the International Stormwater BMP Database range from a multitude of criteria: general site information (location, climate characteristics, etc.), watershed information (soil type, land use, imperviousness, etc.), general BMP information (cost data, date of installation, maintenance and rehabilitation types and frequencies, etc.), monitored events, stations, and results (precipitation, runoff, water quality, etc.), and many more (Clary et al. 2011). Even though the BMP Database offers an abundance of BMP O&M information and data, it does not have the capability for individual municipalities to assess and manage their data on an internal level (Smith et al. 2023). Furthermore, the analysis of the downloaded data is quite difficult due to inadequate data records, unique format, and inconsistent vocabulary (Smith et al. 2023).

Smith et al. (2023) proposed a relational data model to aid in BMP management that has a similar format to the Consortium of Universities for the Advancement of Hydrologic Sciences, Inc. (CUAHSI)'s observations data model 1 (ODM1). Their data model structure enables stormwater-specific data to be managed efficiently so that performance and function are effectively monitored over time to give insight into BMP planning and management. The model has the potential for powerful data analysis considering each data point has an associated spatial and temporal value. The unification of BMP data allows for a holistic analysis of the system's performance and function over time. According to Smith et al. (2023), there are a few important requirements for a successful relational database model: controlled vocabulary to limit confusion, efficient processing (in terms of uploading, storing, and retrieving data), quality control to ensure that the data uploaded is accurate, data reuse to identify potential discrepancies, and analysis across traditional data barriers to aid in the comparisons of BMPs.

The Virginia Department of Transportation (VDOT) started digitally tracking stormwater maintenance in October 2012. In 2018, the agency transitioned to an updated database within its newly designed asset and work order management system named the Highway Maintenance Management System (HMMS). The agency is highly interested in finding the type(s) of stormwater practices that are more costly to maintain in the long run and eventually using the estimated life-cycle costs to prioritize BMP options currently approved by the Virginia Stormwater BMP Clearinghouse.

The current approach to BMP maintenance tracking is disjointed; therefore, there is a need to create a more sustainable data-informed maintenance program that allows municipalities a more systematic view to help with future decision-making (Qiao et al. 2018; Smith et al. 2023; Blecken et al. 2017). A uniform format for tracking BMP items among municipalities would go a long way to help design, regulate, and manage BMPs (Smith et al. 2023). Furthermore, this study seeks to address the need for a comprehensive database for BMP maintenance that includes an emphasis on controlled language in the collected data to increase the efficiency of data queries. In summary, the objectives of this study are to assess the maintenance records stored within VDOT's HMMS to (1) approximate the costs of routine and non-routine maintenance with respect to VDOT district or practice type and to (2) identify challenges encountered when processing the data for analysis and provide potential solutions, both relevant to VDOT and other entities seeking to track BMP O&M costs, to address the issues.

## METHODS

## Data and the Current Database Design

For the purposes of this study, VDOT supplied data from two sub-databases within the HMMS database: (1) the stormwater BMP work orders and (2) the stormwater BMPs. The former consisted of over 4,000 stormwater work orders created from October 2018 to September 2020. A portion of these work orders was created by internal staff and employees to keep track of inspections and maintenance tasks conducted on stormwater BMPs, while the others were citizens' drainage complaints or stormwater-related service requests submitted through VDOT's customer service center and its online service portal. The BMP database comprised attributes for over 2,600 stormwater BMPs built by VDOT across Virginia from 1977 to 2020. These BMPs were categorized into nine general BMP types, namely Basins, Filtration, Infiltration, Conveyance, Miscellaneous, Underground Manufactured Filtering (UMF), Underground Manufactured Hydrodynamic (UMH), and OU (Other Underground Practices) based on their specific practice types (see Table 1)

The work order data mainly includes information on the current status, date created (and date completed, if available), cost, and description of work performed or cause for complaint. The BMP data includes facility-specific information such as inventory date, comments on the site and design, and BMP type. In addition, both contain details regarding jurisdiction and location. The complete lists of attributes used to define the two datasets can be found in Fig. 1. The "ID" and the "Asset ID" columns are designated as the primary keys for the work order entity and the BMP entity, respectively. The work order entity also uses an attribute named "SWM ID" (which is essentially a duplicate column of "Asset ID") as the foreign key to create a link between the two entities, and a many-to-many relationship currently exists between them.

A few distinct entities appear when reviewing the data. First, a BMP maintenance task (BMT) can be defined as a single maintenance event conducted at one and only one BMP site at a given time. Work orders without any BMTs are referred to as non-BMP work orders, whereas work orders that consist of a single BMT are referred to as single-task BMP work orders, and those overloaded with multiple BMTs are named bulk BMP work orders. Example 1 from Fig. 2 represents a typical non-BMP work order with no "SWM ID" entered. Its description field shows that some kind of shrub is growing out of the curb inlet at this location, which is not a maintenance issue related to any BMP facility. For this reason, the work order does not relate to any BMP entity. Example 2, however, involves repair work done to the rip rap area of a stormwater pond. This work order is, therefore, considered a single-task BMP work order, and it is associated with one and only one BMP entity through its "SWM ID" attribute. Lastly, the third example shows a bulk BMP work order that consists of 71 separate inspections of 71 different BMPs. In this case, the work order is related to many different BMP entities and each record in the work order dataset can potentially have zero, one, or more than one related records in the BMP database. From the BMP perspective, a facility may be maintained one or more times, or may not have been visited by any maintenance crew during the two-year window. This means each BMP record can also be associated with zero, one, or more than one work order record. This ultimately creates a many-to-many relationship between BMPs and BMTs, which presents problems for the cost analysis, as described more fully later.

## Data Preparation

Records from the BMP dataset were joined to records from the work order dataset on the "SWM ID" key. For work orders that had valid entries in the "SWM ID" field, the combined table could directly show the type of stormwater BMP being maintained. With all pertinent data in a single table, the data-cleaning process could proceed.

### *Associating SWM IDs with Work Orders*

VDOT's stormwater work order entity was designed to track all stormwater-related operations and maintenance (O&M) events. For this reason, work orders created for non-BMP-related jobs, such as culvert cleaning and sinkhole repairs, were also logged in the system. Ideally, these non-BMP related jobs would have a null value for their "SWM ID", and maintenance work conducted on structural BMP facilities would be differentiated with a non-null value for the "SWM ID". That way, BMP work orders should be easily separated by selecting those with non-null values in the "SWM ID" field. However, some inputs for the "SWM ID" for the BMP-related jobs were occasionally omitted. As a result, no information on the BMP type could be added from the join, i.e., those incomplete records would have to be excluded from the average maintenance cost calculation in regard to that BMP type.

To correct this omission and include as many work orders in the analysis as possible, a spatial join operation was performed using a geographic information system (GIS) to associate "SWM IDs" of the closest BMP facilities for work orders with missing "SWM IDs". The searching radius of the operation was determined by first calculating the geodesic distance between each identified BMP work order and its respective BMP facility using the latitude and longitude coordinates provided by the newly joined table from above. The mean, median, and standard deviation of these distances were found to be 197.69 m, 5.32 m, and 1501.96 m, respectively. The statistics pointed to a highly right-skewed distribution, and for this reason, the Interquartile Range Rule (Eq. 1, Eq. 2, and Eq. 3) was applied to identify outliers:

$$IQR = Q_3 - Q_1 \tag{1}$$

$$Lower\ Bound = Q_1 - 1.5 \times IQR \tag{2}$$

$$Upper\ Bound = Q_3 + 1.5 \times IQR \tag{3}$$

Any distances that were less than the lower bound (the lower bound value was set to zero since distance cannot be negative) or higher than the upper bound (86.29 m) were treated as outliers and subsequently excluded from the calculation. Ultimately, distance values from 738 existing BMP work orders were used, and the mean and standard deviation were 14.61 m and 20.56 m, respectively. To be conservative with the association procedure, the search radius was chosen to be two standard deviations away from the mean, which was 55.73 m. For any "unclaimed" work order generated without a SWM ID, if there was a BMP site located within 55.73 m of where the work order was documented to be performed (per the latitude and longitude coordinates of the work order), such BMP facility's SWM ID would be assigned to that work order. When multiple BMP sites met such a condition, the closest BMP's SWM ID was used. The spatial join operation successfully associated SWM IDs for 577 work orders, which were thought to be BMP work orders due to their spatial proximity to a BMP but had missing SWM ID values.

*Searching for Additional BMP Work Orders*

Some BMP work orders were still not identified after the spatial join process. In an attempt to address this issue, a string-searching algorithm in Python was developed to iterate through the "Description" fields of work orders that were still missing SWM IDs after the spatial join operation to look for keyword(s) that signify BMP maintenance activities. Through trial and error, the following strings were used to find additional BMP work orders: "routine maintenance", "annual maintenance", "annual inspection", "annual assessment", "storm pond", "storm basin", "bmp", "storm water basin", "storm water management basin", "corrective maintenance", "mowing", "swb", and "cleaning of pond". If a match was found, the work order would be considered to be a BMP work order even though its affiliated BMP facilities could not be determined. Note that if the description field of a work order contained the word "test", the record was skipped because these were presumably created for testing purposes when the HMMS was first launched. An additional 83 BMP work orders were found through this process. These work orders were only used in district-level analysis and were excluded from analysis associated with the practice type due to the missing SWM ID values.

After the initial steps of data cleaning, a total of 2,136 BMP work order records were identified. To simplify future selections when calculating the maintenance task counts and maintenance costs, a new attribute column named "BMP Work Order" was created. Work orders that initially had SWM IDs were given a value of "Y1" in their "BMP Work Order" field; those found through a spatial join were given a value of "Y2"; lastly, BMP work orders identified by the keyword search algorithm were given a value of "Y3".

*Categorizing Maintenance Work Orders*

BMP work orders were next passed through another string-searching algorithm implemented in Python to determine the maintenance type of each record and the specific maintenance task(s) carried out. Maintenance for stormwater BMPs consists of routine, non-routine, and major operations. According to Erickson et al. (2010), routine maintenance typically includes annual inspection, vegetation and ground cover management, and litter removal, while non-routine maintenance covers tasks such as structural repairs, erosion repairs, and sediment and debris removal. Major maintenance often refers to full-fledged corrective repairs (i.e., restoration, rehabilitation, and rebuild) (Erickson et al. 2010).

Found by trial and error, the different lists of strings used to identify specific maintenance activities are summarized in Table 2. Certain VDOT districts preferred grouping some of the routine maintenance activities together, which led to various combinations of maintenance activities. In order for a maintenance record to be recognized by the algorithm as "M&C" (mowing and clean-up) work order, its work description must meet the following three conditions: (1) contains the string "mow", (2) contains the string "trash" or "clean", and (3) does not contain any of the strings on the following list: "weed", "spray", "trim", and "contractors".

Once the BMP work orders were classified based on the maintenance activities carried out, the BMP maintenance type (routine, non-routine, or major) to which they belonged could be easily determined. Ultimately, 14 types of work orders were categorized as routine maintenance, three were found to be non-routine maintenance, and one as major maintenance (see Table 2). Out of the 2,136 BMP work orders, 739 (34.6%) were uncategorizable. Those records either had no work description logged or the content of the description was too vague to automatically ascertain the tasks performed using the keyword searching algorithm. For this reason, their BMP Maintenance Type field was marked as "Unknown". See Fig. 3 for a schematic diagram summarizing these data preparation steps.

*Calculating the Unit Cost of Work Orders*

VDOT divides Virginia into nine districts that oversee the maintenance of the stormwater BMPs in each of their areas. When logging the maintenance operations into the HMMS, the district offices would occasionally create bulk BMP work orders, which were used to record the same type of maintenance task completed over two or more separate BMP facilities. Moreover, certain district offices with large BMP inventories opted to hire contractors to help with addressing the maintenance needs in a timely manner. Those contracted jobs appeared to be entered into the database as bulk BMP work orders on an invoice-by-invoice basis. The bulk work orders were typically reflected in the "Actual Total Cost" category where the entry was the sum of all the costs (e.g., labor, equipment, etc.). One significant drawback of this approach is that the costs provided represented the total invoice amount instead of the unit maintenance cost per facility.

Staff from VDOT typically used an attribute called "Quantity" to indicate the exact number of BMPs that received the maintenance under each work order. Ideally, the unit cost should be derived by dividing the total cost by the quantity. However, there were cases that the Quantity field was used for other purposes, such as specifying the number of working hours spent on performing a task. To remedy such an issue, an "Adjusted Quantity" and a "Unit Cost" column were created through this project. The "Adjusted Quantity" column started off as a duplicate copy of the Quantity column, but 105 records were manually adjusted based on the information provided in the work description. For example, one of the work orders whose quantity value was "1" was described as "Spraying of 12 basins in Henry County." As a result, the value for its Adjusted Quantity field was changed to 12. Values of the "Unit Cost" column were then calculated by dividing each total cost by the Adjusted Quantity value.

*Counting the Number of BMP Maintenance Tasks*

After manually adjusting some of the quantity values, a total of 186 bulk BMP work orders were found, many of which consisted of jobs across multiple types of BMPs. To provide a more accurate estimate on the total number of maintenance events conducted per BMP type, a "Maintenance Count" column was created for each of the eight general BMP types from VDOT, and the values were manually entered after carefully reviewing every "Description" field. For a single-task BMP work order performed on a grass swale, its "Conveyance Count" field would receive a value of "1"; for a bulk BMP work order that serviced eight bioretention facilities and three hydrodynamic separators, its "Infiltration Count" field and the "Underground Manufactured Hydrodynamic Count" field were given values of "8" and "3", respectively.

*Calculating the Average Maintenance Frequency of BMP Maintenance Tasks and Annual Costs*

The estimated maintenance frequencies for various practice types are displayed as "Average Task Count Per BMP Per Year". Those maintenance frequencies were found by dividing the number of maintenance tasks by (1) the number of unique BMP maintained and (2) the number of years of data used for the analysis (two years). The average annual costs can then be calculated by multiplying the "Average Cost Per Task" by the average maintenance frequencies.

### Data Analysis

The 2,136 BMP work orders identified, through the previously described data cleansing steps, were first grouped together based on the BMP maintenance types to find the average cost for the entire collection of routine, non-routine, or major maintenance operations during the two-year study period. Next, routine work orders and non-routine work orders were in turn divided up by VDOT district to show how the maintenance cost varies from district to district. Lastly, the maintenance costs for various BMP types were computed by splitting the work orders up by the eight general practice types recognized by VDOT.

## RESULTS

### Overall Work Order Count and Maintenance Task Count

Results of work order and maintenance task counts for various BMP maintenance categories are summarized in Table 3. As defined earlier, a BMP maintenance task (BMT) is a single maintenance event conducted at one and only one BMP site at a given time. Multiple BMTs were sometimes compiled into a single BMP work order; this BMP work order is referred to as a bulk BMP work order. For this reason, the number of BMTs conducted from 2018 to 2020 is more than the number of BMP work orders identified in the database. Results from the analysis show that routine maintenance records accounted for over half of the BMP work orders and 80% of the total maintenance task count. In total, 158 non-routine maintenance work orders were found in the database, which accounted for 182 BMTs performed. Major maintenance work was only recorded 22 times during this two-year period. This study also found 186 bulk BMP maintenance records, which were primarily used to combine routine maintenance tasks conducted over two or more BMPs. Lastly, over a third of work orders were indeterminable because their description fields contained null values or insufficient details (i.e., not found by an algorithm search).

## Maintenance Task Count by District or Practice Type

Both Tables 4 and 5 focus on the number of BMTs performed over the two-year period. Table 4 summarizes the results by VDOT district while Table 5 displays the statistics by BMP type. For example, out of the nine VDOT districts, the Northern Virginia district invested a tremendous amount of time and effort into the upkeep of its BMP assets, completing, on average, 4.54 routine maintenance tasks per BMP in two years. These preventative maintenance actions appeared to greatly lower the need for non-routine or major repairs within the district. Mowing services were the only routine maintenance work performed in the Bristol district. Roughly half of Salem district's work orders were well documented in the database. Those work orders not only listed individual maintenance activities completed in the Description field but also used the word "routine" at the front to signify routine maintenance. Major maintenance events conducted in the Lynchburg district exceeded the other districts combined. This suggests some inconsistencies across district data entry practices. In fact, only two VDOT districts, Lynchburg and Northern VA created major maintenance work orders during the time frame. It is possible that some districts decided to defer major maintenance work orders during the time frame; however, it is also possible that certain districts did not enter them into the database since BMP restoration, rehabilitation, or rebuild work is typically contracted out to consultants. With a portion of the BMP maintenance records noted as "Contractor BMP Maintenance Tracking," the Richmond district appeared to engage an outside contractor to do part of the routine maintenance work. Only a very small number of the BMP work orders were found to be from the Hampton Roads district, and an overwhelming majority of them came without a work description. The most common BMP work orders in the Fredericksburg district were labeled as "Routine Maintenance," but the exact maintenance activities performed were not identified. Culpeper district's semiannual routine mowing work was typically grouped together by county. In addition, details on the maintenance issues revealed by its annual inspections seemed to be summarized and stored elsewhere (i.e., they were not found in the dataset provided). BMP maintenance jobs from the Staunton district primarily involved routine ground management (i.e., mowing and trimming) and non-routine sediment or debris removal.

The maintenance categories of roughly 16% of the BMP work orders could not be determined due to missing descriptions of work performed. Overall, the top three general BMP types that were most frequently maintained during the study period were Conveyance (1.93 counts of maintenance tasks per facility over two years), Basin (1.85), and Underground Manufactured Hydrodynamic (1.75). If only routine maintenance records were considered, Underground Manufactured Hydrodynamic (1.71) on average required the most maintenance and attention, followed by Conveyance (1.56) and Basin (1.45).

### Overall Maintenance Cost by Maintenance Type

Table 6 presents the overall maintenance costs with respect to BMP maintenance type. The percentage of routine, non-routine, and major work orders without any cost information was found to be 10%, 23%, and 14%, respectively. Results from this 2018-2020 dataset show that, on average, routine and non-routine BMP maintenance costs per facility were $375 and $812, respectively. The average cost of the 22 major repairs was approximately $63,000. Furthermore, the average cost of those work orders whose maintenance type could not be ascertained was almost the same as that of routine maintenance. Therefore, the majority of the work orders that were missing work descriptions likely belonged to the routine maintenance category.

### Average Maintenance Cost Per BMT by District

Cost results of routine and non-routine maintenance tasks for the nine VDOT districts are shown in Tables 7 and 8, respectively. As mentioned earlier, the only routine maintenance task description found from the Bristol district was mowing. Therefore, Bristol district's per facility cost of $213 was a great representation of the average cost of routine mowing. Salem district's BMP routine maintenance was evaluated to be $385 on average, and this district also saw the highest average non-routine maintenance cost at $1,672, which was largely attributed to an expensive tree removal work order that cost $11,679.70. By removing the tree removal work order, the average non-routine maintenance for Salem was found to be $560.43, almost a third of the average maintenance cost. Despite mowing and trimming activities making up its most common routine work orders, the Lynchburg district had the highest average routine maintenance cost of over $1,500 per task. The Richmond district's contractor-accomplished routine maintenance tasks did not provide any cost information. The remaining routine work orders mainly included mowing-only jobs or services of multiple activities featuring mowing, trimming, spraying, and clean-up, and the average cost of these routine operations was valued at $299. As discussed before, work orders from the Hampton Roads district typically lacked work descriptions. As a result, very limited work orders were categorized and used to calculate the costs. Routine maintenance tasks from the Fredericksburg district were evaluated at $59 on average, the lowest among the nine districts. With an average cost of $775, its non-routine maintenance primarily consisted of unspecified repairs and post-repair BMP re-inspections. Since 50% of the routine maintenance records and 48% of the non-routine records from the Culpeper district were missing cost information, its average cost of routine maintenance largely covered BMP mowing and clean-up jobs, while that of non-routine maintenance represented the expenses for addressing unidentified maintenance issues upon the completion of annual inspections. The lowest average cost of non-routine maintenance was observed from the Staunton district at $431 per BMT; however, such cost information was estimated based on sediment, debris, or shrub removal work orders because no repair records were found. Lastly, for the Northern Virginia district, the average cost for performing inspections and other routine maintenance activities was assessed to be $700 per task.

**Average Maintenance Cost Per BMT by Practice Type**

Table 9 and Table 10 compare the maintenance costs among different BMP types; Table 9 summarizes routine maintenance costs, while Table 10 presents non-routine maintenance costs. Note that the costs of some BMP types were generated from less than 10 counts of maintenance tasks. Hence, those results may not truly reflect the costs of maintaining certain BMP assets.

For stormwater basins, the average cost of routine maintenance was estimated to be $400 per maintenance task, the highest among the eight general practice types recognized by VDOT.

Basin BMPs are considered to be easy and inexpensive to maintain, so it was interesting that this estimated maintenance cost was so high. However, many of VDOT's basins are aging and require more maintenance. Furthermore, 70% of the BMPs are basins (i.e., more maintenance tasks done; larger sample size leads to higher average), and basins are better studied and well understood by the crew when it comes to their upkeep. As a result, the maintenance effort and the associated cost are likely to be recorded more accurately. Conveyance channels (e.g., grass swales) saw an average cost of $357 per task for routine maintenance jobs. For infiltration practices and BMPs of miscellaneous type (i.e., level spreaders), the routine maintenance generally costs less, ranging from $100 to $250 per site. Routine maintenance operations on manufactured devices were found to cost less than $100 per task on average. The high standard deviation value for the Basin type ($690) suggests that some bulk BMP orders conducted on the basins were mislabeled by the staff as single-task work orders. Therefore, the average cost per task for stormwater basins was likely higher than the actual cost. Due to the limited number of non-routine maintenance records found in the database (see Table 5), the average costs for only three of the eight BMP types have the potential to be used as references. Infiltration BMPs had the highest non-routine maintenance cost (on average $1,123 per task); Basin BMPs had non-routine maintenance average costs of $911. Lastly, each non-routine maintenance task for Filterras, Stormfilters, and other types of underground manufactured filtering devices cost around $313 on average.

### Total Annual Cost By General BMP Type

The estimated total annual costs that cover both the routine maintenance and the non-routine maintenance tasks for different types of BMPs are shown in Table 11. The maintenance conducted on Basin BMP types was the most expensive at $1,100 annually. The second most expensive BMP practice was infiltration, which cost about $775 to maintain per year. The least expensive BMPs were the proprietary devices that cost less than $214 per year.

## DISCUSSION

## Challenges Caused by Current Database Design and Data Entry Practices

*Data Completeness*

The accuracy and reliability of the BMP O&M costs represented in this study are affected by data completeness, which refers to the comprehensiveness or wholeness of the data. Attribute fields that were significant to our study and that were often left blank were "SWM ID", "Actual Total Cost", and "Description". Out of the 2,136 potential BMP work orders, nearly 31% were missing SWM IDs, 11% had no cost information, and roughly 34% were generated without a helpful work description (the field was either left blank or only contained a facility ID number).

It is possible that the large amount of incomplete data presented in the database was due to the staff's unfamiliarity with the available attributes and/or their failure to understand the importance of data entry. For example, not only did the "SWM ID" serve as a foreign key that links the work order entity and the BMP entity, but it also was the only attribute for differentiating BMP work orders from non-BMP work orders, since this is an overall O&M database for VDOT. Although it is possible that employees were simply not aware of the existence of the "SWM ID" column (which helped explain why some of those missing facility IDs were added to the "Description" field instead), it is also possible that the staff entered all pertinent information that requires a manual entry in the "Description" field out of convenience. Moreover, it is also possible that the crew found it redundant to attach the SWM IDs since the work orders' latitude and longitude coordinates would suggest their affiliations to the BMP sites.

It is possible that there is a breakdown in communication between the management team implementing the database and the maintenance staff entering data into the database. This miscommunication and the lack of controlled vocabulary standards contribute to data incompleteness. VDOT's BMP Inspection and Maintenance Manual stated that in order to stay in compliance with the agency's MS4 permit, all BMPs must be inspected and all necessary maintenance must be conducted within the same permit year (VDOT 2021). Additionally, to prepare for periodic audits from the Virginia Department of Environmental Quality (VDEQ) and USEPA, sufficient inspection and maintenance records must be retained in the database (VDOT 2021). Even though the motivations behind implementing the database were well explained in the manual, the essential components (e.g., attributes) of adequate maintenance records and the level of detail needed were perhaps ambiguous and confusing. In other words, some maintenance staff or contractors might not fully understand the agency's expectations for collecting quality maintenance data. If these distinctions undergo a course correction, important attributes like "Actual Total Cost" and "Description" may not be left empty or incorrectly assigned in the future.

A potential solution for steadily improving data completeness is through proper training. During each employee training session for the maintenance staff responsible for data entry, the maintenance supervisors should reiterate the importance of the stormwater maintenance database by going over the rationale and description behind each column in the work order entity. The supervisors should use examples to walk through the work order input process and remind the staff of the importance of data entry. Another way to improve data completeness would be to set up quality control measures: maintenance records with values missing in one or more fields should be automatically flagged by the system; supervisors should review the data logged periodically and follow up with the staff members failing to follow best practices.

*Bulk BMP Work Orders*

Aside from the challenge associated with data completeness, the stormwater work order database also suffered from problems caused by the bulk BMP work orders. These "overloaded" work orders only made up roughly 9% of the BMP work orders identified from the database, but they accounted for over 68% of the total number of BMP maintenance tasks conducted over the two-year period. A many-to-many relationship exists between the work orders and the BMPs due to the bulk work orders, which introduces a few challenges.

One challenge is that bulk BMP work orders typically fail to keep track of the list of BMP facilities maintained. Indexed by the work order IDs, the "SWM ID" column from the work order entity was designed to be a single-valued attribute that only accepts one SWM ID number. To log a bulk maintenance order, the staff has to either enter only one of the BMP's ID numbers or leave the "SWM ID" field completely blank because of the single-value constraint. For instance, a bulk work order from Salem district was generated without any "SWM ID" information, and in its "Description" field, the employee typed, "8 BMP Herbicide spraying." Even though the comment clearly indicated the total number of BMPs serviced and the maintenance activity performed, this record cannot be traced back to each individual BMP maintained, limiting the ability to track O&M costs by specific BMP types. Some staff members elected to store the SWM IDs of all relevant BMPs as a list separated by commas under the "Description" column of the bulk work order, thereby violating the first normal form (1NF) of the relational database. For one, 1NF requires each attribute to contain values of a single type. The attribute "Description," for instance, should contain comments on the maintenance activities only, no SWM IDs or BMP types. Additionally, each value stored under a column should be a single value, not an array or list of values (Conger 2011). These practices point to the need for better data entry tools. For example, the system should disaggregate the data from bulk work orders before entering it into the database.

Another issue with bulk BMP work orders is that there is no way to know the contribution of each BMP task against the total cost of maintenance. This hinders the ability to know the specific O&M cost per BMP. As mentioned before, VDOT wants to use the stormwater maintenance tracking database to remain in compliance with MS4 permit regulations and to determine the life cycle maintenance costs of various types of stormwater BMPs to guide them in future BMP selections. If the costs of maintenance activities from bulk work orders cannot be broken down to the facility level, it would be nearly impossible to determine which type(s) of BMP is low-maintenance and, therefore, more cost-effective. For example, the "Description" field of a bulk work order from the Northern Virginia district read "Semi-Annual Maintenance to 202 SWM BMPs during this period," and the "Actual Total Cost" field reported a value of "129387.8". One could argue that those 202 BMPs might be comprised of different types of stormwater BMPs, and consequently, the maintenance work conducted on-site could vary based on factors like BMP type and field conditions. Therefore, it would not be reasonable to divide the total cost of $129,387.8 up equally across 202 BMPs; as a result, the unit facility-wide costs of conducting a certain maintenance activity over multiple BMP types still remain unknown.

*Controlled Vocabulary*

The last major challenge identified through this analysis is the lack of a controlled vocabulary in the database. Since BMP maintenance work within each VDOT district is delegated to area headquarters staff or contractors (VDOT 2021), they often use slightly different words or terms to describe the same maintenance activities conducted on-site. For example, in the "Description" column of the annual inspection work orders, different staff members wrote the following different phrases: "Annual BMP Inspection", "Annual Assessment", and "Inspecting of storm ponds" to name a few. This made the database cleaning process more difficult because the generation of comprehensive lists of strings to categorize the work orders was extremely varied.

Another issue that arises from the lack of controlled vocabulary is the various combinations of routine maintenance activities logged in the "Description" field. As briefly mentioned in the Method section, how the maintenance work is handled can vary by VDOT district or area headquarter. Some districts preferred grouping mowing, spraying, and litter pick-up together, while other districts chose to couple trimming and spraying; some finished routine maintenance and inspection at the same time, while others conducted annual inspections separately. It would be much simpler to approximate the average cost of individual maintenance activities if all area headquarters within the same VDOT district (if not all nine districts) could come to an agreement on how the BMP maintenance is assigned and which pre-defined set of terms should be used when creating maintenance records in HMMS.

## Proposed Extensions to the Current Database Design

To help address the preceding challenges from the current database, a new database design is proposed and shown in Fig. 4. This design, while inspired by the VDOT HMMS database, is general and applicable to other agencies interested in better tracking BMP O&M costs. The most obvious difference between the existing and new database design is the addition of a third entity named "BMP Maintenance Task." Although many-to-many relationships are legitimate relationships in logical terms, no database can implement them without increasing data redundancy that eventually leads to data anomalies (Conger 2011). A many-to-many relationship in any relational database management system (RDBMS), therefore, must be resolved into two one-to-many relationships through the creation of a linking entity (Conger 2011). In this case, the newly added "BMP Maintenance Task" entity plays such a role that links the "Work Order" entity to the "BMP" entity. A stormwater work order can include zero-to-many BMP maintenance tasks and a stormwater BMP can be maintained zero-to-many times under different maintenance tasks.

Currently, all maintenance work orders related to stormwater are given the activity code of "72207 Storm Water Basin/BMP Maint." under the "Activity Description" column. However, these work orders were largely mislabeled since this study found that only 53% of the original 4,020 work orders were maintenance of BMP facilities. Hence, it is recommended that a pre-defined activity code of "72208 Non-BMP Maintenance" be added to the "Activity Description" attribute in the new design so that staff members can use this column to separate out BMP work orders from non-BMP ones. Non-BMP maintenance work will only be kept in the Work Order entity, whereas BMP maintenance will be recorded in both the Work Order and the Maintenance Task entities.

To re-create the bulk BMP work order from Fig. 2. in the database properly, the staff would need to create a new row in the "Work Order" entity, and then select "72207 BMP Maintenance" for the Activity Description column. Next, staff should provide a brief description of what the work order is intended for, such as "2018 NOVA District Annual BMP Inspection Package 1". Afterwards, quickly indicate whether the work order will be contracted out or not, followed by entering the number of tasks included and the number of BMP involved. It is important to recall that one BMT must relate to one BMP facility. Both the "Task Quantity" and the "BMP Involved Quantity" fields should therefore be given a value of "71". The next step is to create a maintenance task record for each inspection (each with a unique Maintenance Task ID). Next, select an appropriate maintenance category or group and an adequate type for the task. As shown in Fig. 4, the BMP maintenance tasks are categorized into the same three groups as discussed in the Method section: Routine, Non-routine, and Major Maintenance. For a BMT from the routine maintenance group, it can be labeled as "Inspection," "Mowing," or "Non-Mowing Ground Management." In the case of the example bulk work order, the apparent choices for the Group and Type columns are "0000-Routine

Maintenance" and "R1-Inspection," respectively. It is worth noting that in the proposed database design, the "Cost" column was moved from the "Work Order" entity to the "Maintenance Task" entity, in which case the latter should be able to keep track of the cost per facility at the maintenance task level. Lastly, the person responsible for entering the data should carefully enter the ID number for the work order and the SWM ID of the BMP facility; both columns are used as foreign keys so that a specific maintenance task can be traced back to an individual work order and a single BMP. A total of 71 records need to be created in the maintenance task entity for this specific bulk BMP work order. To simplify the data entry process for the maintenance staff, a software program can be adapted to batch generate maintenance task records within the database management system, in which case only the values for Cost and SWM ID fields need to be manually adjusted. A simplified version of the work order example and the maintenance task example (in the proposed database design) discussed above is shown in Fig. 5 and 6.

## CONCLUSION

This research highlights the role that proper database design plays in enabling the tracking of stormwater BMP maintenance. This work also describes challenges associated with BMP maintenance tracking, presents preliminary cost estimates associated with routine, non-routine, and major maintenance activities based on available data, and provides an extension to the current database design for improved stormwater BMP maintenance tracking.

Incomplete maintenance reporting, lack of controlled vocabulary, lack of standardized reporting entries, and bulk reporting can lead to lower accuracy of the maintenance data being collected. However, proper training, quality control assessments, and automatic flags associated with incomplete data can help mitigate incomplete reporting. The use of a set of pre-defined terms for each maintenance activity would facilitate querying and analysis of the data being collected, which increases the usefulness of the data being collected in terms of being able to evaluate trends associated with maintenance activities and cost. Additionally, controlled vocabularies are proposed for the "Activity Description", "Group", and "Type" columns to ensure each work order or each maintenance task can be clearly labeled and classified. The existence of bulk work orders forced a many-to-many relationship to form between the Work Order entity and the BMP entity and, as a result, facility-wide maintenance costs were unable to be quantified. The practice of bulk work order reporting should be avoided as there is no way to know the contribution of each BMP task against the total cost of maintenance. This hinders the ability to know the specific O&M cost per BMP.

BMP maintenance data is helpful for identifying the type, frequency, and cost of maintenance activities being performed. Analyzing available maintenance data from VDOT's tracking system, we find that preventative maintenance actions appeared to lower the need for non-routine or major repairs within the Virginia districts. Routine and non-routine maintenance costs were, on average, \$375 per task and \$812 per task, respectively. Both average costs have large standard deviations, which suggests that the costs of maintenance tasks are highly variable. One possible explanation for this is that some tasks include multiple maintenance services instead of a single activity. Out of the eight general practice types, the Basin routine maintenance task was found to cost the most, at nearly \$400, whereas that of the proprietary BMPs appeared to cost the least (less than \$100). It is likely that some of those manufactured devices, unlike the basins, were installed in the past three to five years, and therefore, they required very little maintenance attention. Averaging \$1,100, non-routine maintenance tasks from Infiltration practices were the most expensive among all other practice types.

After a few years of these solutions for stormwater BMP maintenance and database design being in place, valuable insight into the efficacy of specific BMPs can be determined. For example, estimates for BMP inspection frequencies can be determined for respective BMPs. Furthermore, an assessment can take place to determine the level of effort needed to maintain certain BMPs. These types of analyses could help approximate the life-cycle cost of BMPs to generate a reasonable maintenance budget, which would inform future decision-making on the types of BMPs that should be used for specific site conditions. Future research should focus on increasing the accuracy of the cost analysis for the maintenance of stormwater BMPs. Considering the goal is to increase the efficiency of BMP maintenance across all municipalities, it is recommended to normalize the results of the study so that they are more useful to other agencies. For example, the number of tasks could be normalized by the number of BMPs within a district, the cost of living in the district, or some other metric. Furthermore, it would be interesting to see if one could determine how maintenance tasks are influenced by socio-economic factors and spatial analysis considering BMP costs are highly dependent on the location.

## DATA AVAILABILITY STATEMENT

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request. The following data, models, or code are available:

- VDOT stormwater work order data created from October 2018 to September 2020
- VDOT stormwater BMP inventory data as of December 2020
- String-searching algorithm Python script

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## List of Tables

**TABLE 1.** Specific BMP types subsumed under eight VDOT-recognized general BMP types

| VDOT General BMP Type | Specific BMP Type (Virginia Stormwater BMP Clearinghouse Practice) |
|---|---|
| Basins | Constructed Wetlands (Practice 13), Wet Ponds (Practice 14), Extended Detention (ED) Ponds (Practice 15) |
| Filtration | Sheet Flow to Vegetated Filter Strip/Conserved Open Space (Practice 2), Filtering Practices (Practice 12) |
| Infiltration | Permeable Pavement (Practice 7), Infiltration Practices (Practice 8), Bioretention (Practice 9) |
| Conveyance | Grass Channels (Practice 3), Dry Swales (Practice 10), Wet Swales (Practice 11) |
| Miscellaneous | Level Spreaders, Check Dams, Riprap Berms |
| UMF | MTD/proprietary BMP: Filtering Devices (Practice 17) |
| UMH | MTD/proprietary BMP: Hydrodynamic Devices (Practice 16) |
| OU | E.g., Underground Pipe Detention Systems, Underground Vault Detention Systems, Underground Sand Filters |

Note: UMF = Underground Manufactured Filtering, UMH = Underground Manufactured Hydrodynamic, and OU = Other Underground Practices

**TABLE 2.** Lists of strings used for identifying maintenance activities of different BMP maintenance types

| BMP Maintenance Type | Maintenance Activity(s) | Must-Have String(s) | List of Strings to Include | List of Strings to Exclude |
|---|---|---|---|---|
| Routine | I | N/a | inspection, assessment, inspecting | re-, issues, prep, maintenance, GIS |
| | M | N/a | mow, 2nd cycle bmp | trim, spray, trash, clean, brush |
| | T | N/a | trim, cut, brush, weed, hand mowing | spray, mow, removal |
| | S | N/a | spray, herbicide | mow, trim, trash |
| | C | N/a | trash, clean | mow, routine, inspect, spray, repair, fix, grease, drop, sediment, catch basin, D/I |
| | M & T | mowing and brush cutting | N/a | N/a |
| | M & C | mow | trash, clean | weed, spray, trim, contractors |
| | M, T, & C | mow | trim, hand, weed | |
| | M, S, & C | cut grass | N/a | N/a |
| | M, T, S, & C | mow, spray, trash | trim, hand, weed | N/a |
| | T & S | sprayed and trimmed | N/a | N/a |
| | URM | N/a | routine maintenance, annual maintenance, maintenance, sb maint, prep for inspection | mow, annual inspection, corrective, issue |
| | URM & I | inspection | routine maintenance, annual maintenance, maintenance, sb maint, maintenace | issue, re- |
| | I & GM | GIS | N/a | N/a |
| Non-routine | SDSTR | N/a | sediment removal, debris removal, brush removal, tree work, riser cleared, Mooretown road, plant, leaf clog, vacuum, cleaning drop inlet, orfice, Ranchcrest Dr | catch basin |
| | ESR | N/a | repair, erosion, fixing, issue, replace, straw, stone, fence, beaver dam, rip rap, hydroseed | Top, DI, Murray Ln, corrective, Corrective, Corrections, Function, function, original, BMP Repaired, BMP 05, BMP 15, BMP 71, stock, washout |
| | Re-I | re- | N/a | N/a |
| Major | RRR | N/a | corrective, correction, function, BMP repaired, BMP 05, BMP 15, BMP 71, modification | drop inlet, top, northgate, pointe, mow, maintenance |

Note: For specific maintenance task(s), I = Inspection, M = Mowing, T = Trimming, S = Spraying, C = Clean-up, URM = Unidentified Routine Maintenance, GM = GIS Mapping, SDSTR = Sediment, Debris, Shrub, or Tree Removal, ESR = Erosion or Structural Repair, Re-I = Re-inspection, and RRR = Restoration, Rehabilitation, and Rebuild

**TABLE 3.** Number of BMP work orders, bulk BMP work orders, and BMP maintenance tasks by BMP maintenance type

| BMP Maintenance Type | BMP Work Order Count | Bulk BMP Work Order Count | BMP Maintenance Task Count |
|---|---|---|---|
| Routine | 1,217 | 113 | 4,947 |
| Non-routine | 158 | 1 | 182 |
| Major | 22 | 0 | 22 |
| Unknown | 739 | 72 | 993 |
| Sum | 2,136 | 186 | 6,144 |

**TABLE 4.** Number of BMP maintenance tasks performed by VDOT districts

| VDOT District | Routine | Non-routine | Major | Unknown | BMP Count |
|---|---|---|---|---|---|
| Bristol | 78 | 1 | 0 | 10 | 223 |
| Salem | 593 | 12 | 0 | 639 | 240 |
| Lynchburg | 107 | 10 | 14 | 15 | 145 |
| Richmond | 165 | 5 | 0 | 182 | 433 |
| Hampton Roads | 1 | 5 | 0 | 65 | 348 |
| Fredericksburg | 341 | 35 | 0 | 19 | 217 |
| Culpeper | 316 | 85 | 0 | 52 | 119 |
| Staunton | 116 | 26 | 0 | 6 | 206 |
| Northern Virginia | 3,230 | 3 | 8 | 5 | 712 |
| Sum | 4,947 | 182 | 22 | 993 | 2,643 |

**TABLE 5.** Number of BMP maintenance tasks occurred on different types of stormwater BMPs

| General BMP Type | Routine | Non-routine | Major | Unknown | BMP Count |
|---|---|---|---|---|---|
| Basin | 2,647 | 143 | 22 | 584 | 1,849 |
| Conveyance | 250 | 8 | 0 | 51 | 160 |
| Filtration | 6 | 0 | 0 | 4 | 46 |
| Infiltration | 179 | 10 | 0 | 39 | 135 |
| Miscellaneous | 160 | 5 | 0 | 105 | 157 |
| UMF | 224 | 10 | 0 | 5 | 169 |
| UMH | 94 | 2 | 0 | 0 | 55 |
| OU | 8 | 3 | 0 | 1 | 36 |
| Unspecified | 1,353 | 1 | 0 | 204 | 36 |
| Sum | 4,921 | 182 | 22 | 993 | 2,643 |

Note: UMF = Underground Manufactured Filtering, UMH = Underground Manufactured Hydrodynamic, and OU = Other Underground Practices

**TABLE 6.** Cost per maintenance task by BMP maintenance type

| BMP Maintenance Type | Average Cost | Median Cost | Std Dev | Work Orders Without Cost Info |
|---|---|---|---|---|
| Routine | $374.72 | $225.00 | $626.12 | 10% |
| Non-routine | $812.39 | $523.57 | $1,271.75 | 23% |
| Major | $62,576.57 | $36,120.00 | $89,518.29 | 14% |
| Unknown | $377.31 | $425.00 | $168.37 | 30% |

**TABLE 7.** Cost of BMP routine maintenance task by VDOT district

| VDOT District | Average Cost | Median Cost | Std Dev | BMP Maintenance Task Count | Work Orders Without Cost |
|---|---|---|---|---|---|
| Bristol | $212.57 | $105.00 | $215.54 | 69 | 12% |
| Salem | $385.12 | $350.00 | $193.14 | 411 | 6% |
| Lynchburg | $1,506.17 | $810.00 | $1,464.60 | 106 | 1% |
| Richmond | $299.13 | $247.16 | $314.40 | 37 | 51% |
| Hampton Roads | $1,209.35 | $1,209.35 | N/a | 1 | 0% |
| Fredericksburg | $58.98 | $47.98 | $194.46 | 338 | 1% |
| Culpeper | $470.11 | $414.68 | $359.99 | 38 | 50% |
| Staunton | $293.25 | $200.00 | $218.17 | 116 | 0% |
| Northern Virginia | $678.50 | $447.24 | $775.70 | 1,395 | 43% |

Note: The values shown in the BMP Maintenance Task Count column only represent the numbers of tasks used for calculations

**TABLE 8.** Cost of BMP non-routine maintenance task by VDOT district

| VDOT District | Average Cost | Median Cost | Std Dev | BMP Maintenance Task Count | Work Orders Without Cost |
|---|---|---|---|---|---|
| Bristol | | | N/a | | |
| Salem | $1,672.36 | $615.00 | $3,526.75 | 10 | 17% |
| Lynchburg | $1,311.51 | $952.69 | $1,629.93 | 9 | 10% |
| Richmond | $1,024.69 | $778.24 | $732.81 | 4 | 20% |
| Hampton Roads | $962.97 | $944.31 | $309.69 | 5 | 0% |
| Fredericksburg | $774.54 | $418.63 | $952.48 | 35 | 0% |
| Culpeper | $684.86 | $545.59 | $535.16 | 56 | 48% |
| Staunton | $430.65 | $200.00 | $493.49 | 26 | 0% |
| Northern Virginia | $1,450.00 | $1,450.00 | N/a | 1 | 67% |

Note: The values shown in the BMP Maintenance Task Count column only represent the numbers of tasks used for calculations

**TABLE 9.** Cost of BMP routine maintenance task by general BMP type

| General BMP Type | Average Cost | Median Cost | Std Dev | BMP Maintenance Task Count | Work Orders Without Cost |
|---|---|---|---|---|---|
| Basin | $399.95 | $225.00 | $680.48 | 916 | 8% |
| Conveyance | $357.37 | $200.00 | $338.56 | 38 | 17% |
| Filtration | $200.00 | $200.00 | N/a | 1 | 50% |
| Infiltration | $225.42 | $200.00 | $132.22 | 66 | 15% |
| Miscellaneous | $113.92 | $62.50 | $118.54 | 69 | 7% |
| UMF | $95.14 | $62.20 | $87.49 | 12 | 61% |
| UMH | $82.71 | $74.39 | $40.09 | 5 | 29% |
| OU | $96.63 | $89.70 | $29.76 | 6 | 0% |
| Unspecified | $534.40 | $425.00 | $426.26 | 1,398 | 19% |

Note: UMF = Underground Manufactured Filtering, UMH = Underground Manufactured Hydrodynamic, and OU = Other Underground Practices; the values shown in the BMP Maintenance Task Count column only represent the numbers of tasks used for calculations

**TABLE 10.** Cost of BMP non-routine maintenance task by general BMP type

| General BMP Type | Average Cost | Median Cost | Std Dev | BMP Maintenance Task Count | Work Orders Without Cost Info |
|---|---|---|---|---|---|
| Basin | $911.33 | $528.45 | $1,573.68 | 98 | 38% |
| Conveyance | $462.69 | $320.04 | $242.81 | 7 | 13% |
| Filtration | | | N/a | | |
| Infiltration | $1,123.26 | $1,273.50 | $576.47 | 10 | 0% |
| Miscellaneous | $554.40 | $399.49 | $433.50 | 5 | 0% |
| UMF | $313.30 | $144.05 | $463.88 | 8 | 20% |
| UMH | $192.07 | $192.07 | $0.00 | 2 | 0% |
| OU | $192.07 | $192.07 | N/a | 1 | 67% |
| Unspecified | $756.51 | $561.03 | $481.09 | 15 | 0% |

Note: UMF = Underground Manufactured Filtering, UMH = Underground Manufactured Hydrodynamic, and OU = Other Underground Practices; the values shown in the BMP Maintenance Task Count column only represent the numbers of tasks used for calculations

**TABLE 11.** Estimated total annual costs of BMP routine and non-routine maintenance tasks by general BMP type

| General BMP Type | Routine Maintenance | | | Non-routine Maintenance | | | Total Annual Cost |
|---|---|---|---|---|---|---|---|
| | Average Cost Per Task | Average Task Count Per BMP Per Year | Annual Cost | Average Cost Per Task | Average Task Count Per BMP Per Year | Annual Cost | |
| Basin | $399.95 | 0.93 | $373.06 | $911.33 | 0.79 | $720.24 | $1,093.31 |
| Conveyance | $357.37 | 0.95 | $339.50 | $462.69 | 0.5 | $231.35 | $570.84 |
| Filtration | $200.00 | 0.50 | $100.00 | | N/a | | $100.00 |
| Infiltration | $225.42 | 0.94 | $212.54 | $1,123.26 | 0.5 | $561.63 | $774.17 |
| Miscellaneous | $113.92 | 0.69 | $78.60 | $554.40 | 0.5 | $277.20 | $355.80 |
| UMF | $95.14 | 0.60 | $57.08 | $313.30 | 0.5 | $156.65 | $213.73 |
| UMH | $82.71 | 0.50 | $41.36 | $192.07 | 0.5 | $96.04 | $137.39 |
| OU | $96.63 | 0.50 | $48.32 | $192.07 | 0.5 | $96.04 | $144.35 |

Note: UMF = Underground Manufactured Filtering, UMH = Underground Manufactured Hydrodynamic, and OU = Other Underground Practices; the Average Task Count Per BMP Per Year represents the average maintenance frequency over the two-year study period