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Long-Term Performance and Life-Cycle Costs of Stormwater Best Management Practices

Performance à Long Terme et Analyse du Cycle de vie des Ouvrages Alternatifs de Gestion des Eaux Pluviales

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RÉSUMÉ

Ce projet de recherche appliquée évalue les performances à long terme des ouvrages spécifiques de traitement des eaux pluviales dans un environnement autoroutier, notamment dans leurs besoins en matière d'entretien, leurs durées de vie utile et leurs coûts de cycle de vie. La réalisation d'essais qualitatifs sur prototype n'est pas envisageable pour les ministères d'Etats de transport au vu de la profusion d'ouvrages spécifiques existants et émergents pour le traitement des eaux pluviales. Les ministères de transport des Etats Américains ont besoin de s'appuyer sur des niveaux de performance, des coûts and des besoins en matière d'entretien reconnus et validés afin d'établir des stratégies de planification et développer des conceptions de projets précis. Cette étude se fonde sur le vaste réservoir d'information existant dans ces domaines et présente les résultats sous forme d'un outil convivial pour faciliter la mise en oeuvre pratique des conclusions.

L'outil fonctionne comme un tableur, ce qui permet au praticien d'évaluer divers ouvrages spécifiques de traitement des eaux pluviales durant la phase de planification ou lors de la phase de conception d'un projet précis, afin d'en optimiser la sélection. En évaluant simultanément la performance et le coût global du cycle de vie des ouvrages de traitement, une solution optimisée pour la gestion des eaux pluviales peut être développée pour les projets d'amélioration des immobilisations.

ABSTRACT

This applied research project assesses the long-term performance of BMPs, maintenance requirements, performance longevity and total life cycle costs for treatment BMPs in the highway environment. It is impractical for departments of transportation (DOTs) to conduct prototype scale tests on the variety of BMPs that are available and emerging. DOTs need verified performance, cost and maintenance information to develop planning level strategies as well as project specific designs. This study draws on the vast body of information that is available in these areas to date, and provides it in a user-friendly tool format to facilitate application of the study results.

The tool is a spreadsheet based program that allows the DOT practitioner to assess various BMPs at a planning or design level to optimize BMP selection for a project. By assessing both the performance and whole-life cost of treatment measures, an optimized stormwater solution can be developed for capital improvement projects.

KEYWORDS

Best management practices, BMP effectiveness, Stormwater treatment, Sustainable drainage systems

1 BACKGROUND

This paper describes a National Academies of Sciences applied National Cooperative Highway Research Program (NCHRP) research project assessing the long-term performance of BMPs, maintenance requirements, performance longevity and total life cycle costs. The research is currently in draft form, but expected to be published shortly after the Novatech 2013 conference.

It is impractical for departments of transportation (DOTs) to conduct prototype scale tests on the wide variety of BMPs that are available and emerging. DOTs need verified performance, cost and maintenance information to develop planning level strategies as well as project specific designs. This study draws on the vast body of information that is available and provides it in a user-friendly tool format to facilitate application by the practitioner.

The study includes a comprehensive literature review to serve as a basis for the development of the research report and user tool. The literature survey was supplemented by a DOT survey that obtained information on cost, performance, operation and maintenance (O&M) for BMPs from DOTs in all 50 of the US States. The research team also obtained relevant information from the US Federal Highway Administration and the USEPA.

The study investigates the long-term performance of BMPs using data from the International BMP Database, the California Department of Transportation BMP Retrofit Pilot Program, and other long-term assessment studies obtained from the literature review. BMP performance information is combined with continuous simulation hydrologic modeling for various climates and soil conditions across the US to provide a comparison of unit load reductions associated with different BMP types commonly installed to treat highway runoff. The data has also been used to develop capital, O&M and life cycle costs for the specified BMPs. A Maintenance Indicator Document was prepared based on DOT experience nationally and includes BMP inspection protocols.

Whole Life Cost Models were developed in a spreadsheet format by BMP. The information is provided in a highly user-friendly interface that facilitates customization of cost data and provides the following information:

- Long-term performance vs. life cycle cost data by BMP type
- O&M costs, equipment and expected BMP service life
- Inspection procedures and recommended schedules
- Maintenance Indicator Document specific to each BMP
- BMP selection based on site constraints and incorporating long-term performance/whole life cost data

The purpose of the tool is to provide an efficient method for the practitioner to implement the study findings. The tool allows the practitioner to rapidly assess a variety of scenarios at all phases of project development to optimize the project environmental performance and minimize the life cycle cost.

2 DISCUSSION OF RESEARCH PROGRAM

The research program culminated in the development of a spreadsheet based tool for use by the practitioner. The remainder of this paper provides the background in the development of the tool, The final research report and tool will be available in an NCHRP report to be published in 2014.

2.1 Maintenance and Operation of BMPs

Long-Term Maintenance and Inspection Review and Guidance was developed through a review of thirty-nine prototype installations in Southern California. These locations were originally constructed in 1998 for a research investigation (Taylor, 2004) and remain in operation today. The study sites were extensively documented during each phase of the original project from siting, through design, construction, instrumentation, performance assessment (sampling), inspection, operation and maintenance. Inspection and maintenance protocols were developed and the maintenance and operation of each site (along with the performance of each site) was documented for a minimum 3-year period.

For the current study, the maintenance records for each site were obtained and the information supplemented with field visits to determine if the inspection and maintenance protocols established under the Program have been successful in ensuring operation and performance at the design level. The study sites provided an unprecedented opportunity to further calibrate the initially established inspection, maintenance and operation protocols after an additional twelve years of operation.

The frequency of both inspection and maintenance depends on how much and how often it rains. Climate is one of the foundations upon which stormwater management systems are designed and constructed. The characteristics of storms, such as rainfall intensity, depth, inter-event time, and percentage of annual precipitation as snow or rain, are also important factors in determining inspection frequency. The recommended time frames for inspection and maintenance vary depending on local climate and rainfall conditions. The more rainfall events and the greater the pollutant loading, the more work a stormwater management facility must do. Increased use or loading is directly related to the need for maintenance. Inspections may be needed more frequently in areas having a greater number of storms and greater storm magnitudes.

Detailed maintenance checklists for each type of BMP were developed as a part of the study. The maintenance function can be divided into two categories: aesthetic and functional. These two categories can overlap. Functional maintenance is important for performance and safety reasons, while aesthetic maintenance is important for public acceptance of stormwater facilities but not necessary for performance.

A *Maintenance Indicator Document* was prepared which includes a BMP specific guide for BMP field maintenance. The maintenance intervals were developed from experience in southern California. The frequency of required maintenance was translated to other regions in the country by normalizing the data using the total average annual volume of runoff treated. A linear relationship between inspection and maintenance frequency and runoff volume treated by the BMP was verified using data gathered for maintenance and inspection of BMPs from DOTs around the country. The maintenance activities were also adapted to other regions to account for cold climate conditions as well as habitat and species issues.

2.2 Long-term Performance of BMPs

The long-term performance of the selected BMPs was developed using data from the WERF project, *Monitoring of BMPs/SUDS to Determine Performance and Whole-Life Costs* (Lampe, et.al., 2005), BMP Retrofit Pilot Program (Caltrans 2004), the International BMP Database (ASCE, 2011), and other long-term assessment study data collected as a part of the literature review. Regression analyses were performed on selected data with paired influent and effluent composite samples. This allowed the prediction of effluent quality from each BMP based on any influent concentration of interest and selection of a BMP based on a comparison between the different technologies for specific constituents of interest. The regression equations were developed by BMP and for the following constituents:

- Total zinc
- Total lead
- Total copper
- Total nitrogen
- Total phosphorus
- Nitrate
- Total Kjeldahl Nitrogen (TKN)
- Dissolved phosphorus
- Total suspended solids (TSS)
- Bacteria

It is clear from a review of the data that for some BMPs and constituents, the relationship between influent and effluent concentrations appear to be linear, while for other BMPs and/or pollutant types the relationship appears to be more asymptotically monotonic (i.e., effluent concentrations approach an approximately constant value as influent concentrations increase). Therefore, before assuming any particular functional form of the relationship, a non-parametric regression techniques was used to

identify the nature of the influent and effluent relationship. An appropriate parametric equation was selected to estimate effluent concentration based on influent concentration.

Load reduction is an important component of the operation of most non-proprietary BMPs. Load reduction results from planned and incidental infiltration from the BMP. Performance studies often focus on concentration reductions or achievable effluent concentrations without considering the overall load reduced by a BMP. Thus, the importance of volume reduction when assessing the performance of BMPs is often overlooked or not directly quantified. For some BMPs, such as dry extended detention basins, volume reduction may be as or more important than the concentration reductions achieved when considering the overall impacts to receiving water bodies. The International BMP Database includes a few studies with reliable volumetric data that can be used to estimate influent and effluent loads for individual storms. Continuous simulation hydrologic modeling provides a mechanism for evaluating the infiltration performance of various BMP types and design configurations. Unit load modeling was used to achieve a more complete picture of relative BMP performance in this study. A summary of the steps that the project team used to estimate load reductions is:

1. Definition of scope of unit load reduction modeling evaluation
 - a) Evaluation will be limited to eight BMP types, including: a) swales, b) filter strips, c) dry detention basins, d) bioretention, e) wet ponds, f) sand filters and g) permeable friction course overlay.
 - b) Evaluation based on data from 30 climate regions distributed across the country.
 - c) Evaluation of influencing characteristics was restricted to variations in climatic region and variations in soil types based on the four hydrologic soil groups (A, B, C, and D).
2. BMP sizing – unit BMP sizes was selected based on the size required to capture approximately 80% of runoff volume for the various BMPs and climate regions being evaluated.
3. Continuous simulations were executed to determine long term performance of the BMPs with respect to volume reductions.
4. Using the results of the continuous simulation modeling, the influent and effluent regression relationships were updated to account for load reductions achieved through volume reductions in the various BMPs. Load reductions were quantified in terms of mass of pollutant removed per highway acre per BMP type.

The result of this modeling is general BMP performance estimates in terms of unit load reductions by region that explicitly account for volume losses in addition to concentration reductions.

The unit load reduction model estimates were incorporated into the spreadsheet tool to allow the user to assess the potential performance of various BMP technologies. Expected influent concentrations were developed for the constituents listed for various categories of highways (e.g., annual average daily traffic or AADT) for selected regions throughout the country as default values for use in the tool in the absence of user specified data.

Dissolved metals were not included in the analysis because they are not universally measured, the use of 'clean' techniques is important in sample collection for consistent results, and they are generally not regulated in favor of total metals. The dissolved fraction is important from a toxicity perspective, but partitioning is variable in the environment, and total metals are most often used as the standard assessment measure.

2.3 Capital and Operation and Maintenance Cost

The capital and operation and maintenance cost models in the WERF (2010) spreadsheet tools were refined to reflect new highway and retrofit highway construction. Whole life cost models (WLC) for a variety of BMPs were first developed as part of the WERF funded Project *Monitoring of BMPs/SUDS to Determine Performance and Whole-Life Costs*. The BMPs included in the original research included wet ponds, swales, porous pavement, and extended detention basins. These models were updated based on an examination of actual construction costs, maintenance activities, and resources required as documented by this study.

New WLC models were developed for innovative BMPs that are appropriate for implementation in the highway environment. New BMP cost models included vegetated filter strips (typical vegetated highway shoulder), media filter drain (i.e., the WsDOT Ecology Embankment), the permeable friction course, and bioretention areas.

Default values were developed for all model parameters (unit costs for construction items, labor rates, maintenance equipment, etc.) and guidance is provided on how these default values should be modified to account for regional differences in cost structure. One of the largest single variables driving cost is the cost for land, especially in urban areas.

A comparison of WLC cost was made between categories of BMPs suitable for use in particular situations (e.g., linear systems for roadways, end of pipe facilities, etc.) to allow DOTs to identify the most cost effective system.

2.4 The Performance of Non-Structural BMPs

Non-structural BMPs play an emerging role in compliance with a DOTs stormwater program, total maximum daily load requirements, and other water quality regulations. The research team used available data and information to evaluate a select number of control measures (BMPs and facilitation/feedback activities). Control measures were evaluated on three criteria: 1) pollution avoidance or pollutant removal effectiveness and BMP efficiency (e.g., potential to reduce pollutant loads and/or change behavior/knowledge in target populations); 2) cost of implementation; and 3) social/institutional impacts of implementation. This evaluation was intended to facilitate sustainable stormwater management decision-making using a “triple-bottom line” analysis, and where possible, quantify the benefit of non-structural BMP installation to allow the DOT stormwater managers to prioritize their implementation relative to other structural measures identified in this study as well as among the other non-structural controls. The measures that were included in the analysis are:

- Municipal separate storm sewer system (MS4) system cleaning
- Sweeping
- Irrigation runoff reduction practices
- Fertilizer/pesticide usage, and integrated pest management (IPM)
- Trash pickup programs
- Elimination of groundwater inflow to the MS4
- Slope and channel stabilization
- Education/outreach
- Enforcement
- Inspection and illicit connection/illegal discharge (ICID)
- Training (for DOT employees)

The overall objective of the non-structural BMP analysis was to provide the practitioner, in conjunction with the treatment BMP information, with a comprehensive set of cost-effective and high-performing tools compatible with the highway environment.

Non-structural BMPs are typically based on pollution avoidance rather than pollutant removal. The non-structural BMP portion of the research was developed as a stand-alone module that the practitioner can access to improve performance estimates of a comprehensive stormwater program – treatment and source control BMPs.

The practitioner may use the non-structural assessments to estimate a higher percentile of performance (say instead of median effluent quality for a BMP, the 75 percentile for example) for a sub-watershed with treatment BMPs. Additional value comes from identifying the key variables that impact the effectiveness of the non-structural BMPs, so that DOTs can optimize their implementation in their stormwater program.

3 SUMMARY

DOT stormwater program managers are faced with increasing National Pollutant Discharge Elimination System (NPDES) regulations, TMDL compliance obligations, contaminated sediment issues; endangered species act requirements, and limited resources to address these issues. Stormwater quality measures must be effective in mitigating the pollutants of concern, but should also have the lowest whole life cost, and have maintenance and inspection requirements that are

compatible with the highway environment. The results of this study provide two products for DOTs: a final guidance document and the companion tool for implementation to assist them in stormwater program compliance.

The final report describes the development of the study, data used, analysis methods, and conclusions. The Guidance Document provides overall guidance and, along with the companion tool, facilitates implementation of the study findings by DOT program managers. The tool allows for a comprehensive comparison between different treatment controls and non-structural controls, assisting the program manager to optimize performance while minimizing whole life cost.

The final guidance document describes the available BMP technologies, summarize the available data on their performance and O&M, and provide this data in an accessible format that divides the recommendations by important external variables, such as region, annual average daily traffic (AADT), and soil type. Most importantly, the report facilitates comparisons of BMP technologies at both the structural and non-structural level to allow the DOT stormwater program manager to develop a strategic program approach for TMDL and NPDES compliance, as well as select appropriate technologies on a project-by-project basis. Finally, the guidance document presents data compilation protocols and analysis methods to facilitate refinement of future study findings.

The spreadsheet tool provides simple access to the WLC, performance, inspection, maintenance and operation requirements. A significant benefit of the tool is the capacity to assess various compliance scenarios on a "what-if" basis to optimize BMP selection for both performance and WLC. Staff inspection and maintenance requirements are easily accessible. The tool provides options to output results by national region, as well as factors for cost escalation per the Engineering News Record (ENR) index in the future. The ENR index allows simple adjustment for inflation (or deflation) from year to year through an annually published index value.

This research is timely and helps solve several issues that DOTs now face with the selection of BMPs. First, development and enforcement of total maximum daily loads (TMDL) will require that existing facilities be retrofit to help achieve load reductions required under a TMDL implementation plan (Hon et al., 2003). Stormwater permits require implementation of stormwater BMPs on new projects or on projects with substantial modifications in many states. For new projects, there is the opportunity to consider BMPs in the design phase and to purchase additional right-of-way if necessary for example. This is not the case for TMDLs where any changes must be compatible with the function of the existing drainage system. Consequently, DOTs will increasingly be faced with the need to evaluate and select BMPs for conditions where right-of-way space for additional stormwater management facilities is limited, maintenance access is restricted, but performance must be known to document compliance.

TMDLs also differ substantially from requirements in most general stormwater permits. For example, TMDL requirements are normally constituent specific, as compared to permit language requiring a reduction in the discharge of pollutants in general. This project helps to identify which strategies are effective against specific pollutants and thereby facilitate selection of the appropriate water quality management or retrofit strategy. Secondly, the TMDLs generally have specific numeric targets for stormwater discharges. One objective of this research is to quantify the expected performance of various non-proprietary devices, so DOTs will be able to make an informed decision about whether the pollutant removal of a particular measure will achieve the regulatory objectives.

The implementation of non-structural programs/activities is also key in achieving a cost-effective stormwater program. This study develops performance estimates, where technically feasible, for non-structural BMPs used by DOTs to assist the stormwater program manager in quantifying the benefit of the entire BMP program. This will ensure the most efficient expenditure of resources as well as greatly reduce the risk of non-compliance with permit or TMDL requirements.

Finally, the rapidly changing regulatory landscape is also a key consideration in the development and utility of the results of this study. Increasingly, multiple objectives such as runoff volume control, hydromodification control, and green infrastructure are being required. The EPA's draft rulemaking for post-construction stormwater and pending legislation, support these approaches. Thus, the acceptable types of BMPs appear to be evolving to those that provide infiltration, volume capture and use, flow-duration control, and biofiltration.

Changing regulatory requirements mean that DOTs are increasingly faced with the need to modify existing drainage infrastructure to improve stormwater discharge quality. Stormwater management has progressed over the last 30 years from sediment and erosion control to hydromodification based

BMP strategies to address impairments. TMDL implementation will be a primary issue facing DOTs in the next 20 years. Emerging BMPs, such as permeable friction course and various forms of biofiltration will be important tools for the DOT practitioner. This timely research provides DOTs with a systematic method to optimize various strategies, and a selection tool that will confirm compliance and document the WLC.

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