Identification of Research Needs Related to Highway Runoff Management

DETAILS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 521

Identification of Research Needs Related to Highway Runoff Management

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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FOREWORD

By Christopher J. Hedges
Staff Officer
Transportation Research Board

This report presents an analysis of research needs in the area of highway water runoff management and control. Research directors and water-quality professionals from state departments of transportation (DOTs) participated in a survey to identify pressing needs related to the impacts and control of stormwater runoff. The survey results were supplemented with an extensive literature review and analysis by the research team. This report will be of great value in formulating high-priority research efforts at the national, state, and local levels.

The effect of polluted runoff on water quality is an important concern for federal, state, and local agencies with a stake in the planning, design, construction, and maintenance of transportation facilities. The National Pollutant Discharge Elimination System (NPDES) regulations (40 CFR 122 & 123) require the management of sources and impacts of contamination from runoff on municipal stormwater systems. In addition, highway runoff management techniques must be consistent with the objectives of nonpoint source control programs under Section 319 of the Clean Water Act and state coastal nonpoint pollution control plans developed under Section 6217 of the Coastal Zone Act Reauthorization Amendments. Therefore, water-quality information and data are needed to manage runoff and comply with the NPDES and other regulations.

At its meeting in March 1998, the AASHTO Standing Committee on Research (SCOR) met to review and select projects for the FY1999 NCHRP program. SCOR noted that there were 10 different problem statements the dealt with the impacts and management of highway runoff. SCOR directed NCHRP to convene a panel of experts to investigate the existing state of practice; identify research issues, gaps and needs; undertake research on high-priority topics; and recommend projects for future funding.

The first effort initiated by the panel was Project 25-20, which produced a report entitled "Management of Runoff from Surface Transportation Facilities: Synthesis and Research Plan," from GKY and Associates, Inc., published in March 2001 as *NCHRP Web Document 37*. The report was accompanied by the "Water Quality Knowledge Database," on CD-ROM.

Based in part on the recommendations of the GKY study, the panel then initiated Project 25-20(01) "Evaluation of Best Management Practices for Highway Runoff Control." This project was contracted to Oregon State University and is scheduled for completion in the spring of 2004.

Under NCHRP Project 25-20(02), "Identification of Research Needs Related to Highway Runoff Management," a research team led by Marie Venner and Eric Strecker undertook this follow-up effort to supplement and update the GKY effort with a review of the most current research findings. The report summarizes the significant stormwater management practices and research efforts, and it identifies the most pressing gaps and needs in the current state of knowledge in over 30 subject areas. The team developed full research project statements for the topics considered to be of highest priority.

This report will be of great interest in pursuing research to improve the ability of state DOTs and other road agencies to implement an effective stormwater runoff management program.

CONTENTS

IDENTIFICATION OF RESEARCH NEEDS RELATED TO HIGHWAY RUNOFF MANAGEMENT

SUMMARY

The purpose of research project NCHRP 25-20(02) is to identify and describe research projects that address priority needs in the area of highway runoff management and control. This project was designed to conduct a broader search of the available data and studies than was accomplished by NCHRP Project 25-20 and to identify state departments' of transportation (DOTs) research activities and priority research areas for improving the quality of stormwater runoff. This report provides an updated and thorough list of research needs that can be used in the decision-making and prioritization processes regarding funding of future research.

State DOT research directors and water quality professionals were contacted to locate existing research and research-in-progress and to list what they believed were the most important remaining needs related to research on water quality control and stormwater impacts on receiving waters. DOT water quality professionals—including engineers, National Pollutant Discharge Elimination System (NPDES) specialists, and other program managers—from all 50 states participated. The DOTs expressed the strongest needs and interests in the area of cost and performance of stormwater control facilities or best management practices (BMPs). The DOTs' top interests paralleled gaps in the literature in most cases; where such gaps were not identified in the literature but where DOT interest was high, mechanisms for information sharing are needed. A combined literature review, DOT preferences, and research team recommendations are itemized in Table 4-1 of this report. The research needs identified through the DOT survey, literature review findings, and the opinions of the stormwater experts involved in this investigation were prioritized by rank on a scale from 1 to 5.

RESEARCH GAPS AND NEEDS

The following paragraphs summarize the conclusions of the investigation. A brief discussion of the research gaps and needs identified in the literature is presented, followed by the literature review and itemized research statements identified by DOTs as research needs. Some research statements span multiple research categories and likely would be combined into single projects.

BMP Maintenance and Longevity

A compilation of the results of current studies on BMP operations and maintenance is needed, potentially in the form of a nationally applicable manual on BMP operations and maintenance, with guidance on estimating maintenance frequencies based on influent characteristics and site conditions. The costs of BMP maintenance are not factored in during the initial planning and BMP selection phases of construction projects. Agencies often lack the tools to make good estimates of the staff-hours needed to adequately maintain BMPs. Guidance on estimating life-cycle costs of BMPs appears to be needed. Finally, there is a need for further development of methods to increase the longevity and minimize maintenance requirements of infiltration BMPs, such as the use of presettling basins or polyacrylamides to maintain infiltration rates.

With regard to sedimentation, research is needed to evaluate sediment toxicity as a function of maintenance frequency and methods for disposing or reusing BMP maintenance-generated wastes. See section 3.2.11 for a discussion on BMP maintenance and longevity.

Itemized Research Needs

1. Development of contract administration of BMP requirements and contractual methods to improve BMP implementation,
2. Compilation of BMP maintenance and lifetime effectiveness information,
3. Cost–benefit analysis of BMP maintenance practices,
4. Guidance for estimating life-cycle costs of BMPs that account for maintenance required for continually functioning and efficient BMPs,
5. Development of nationally applicable BMP operations and maintenance guidance (maintenance frequencies, logistics and personnel requirements, estimates based on influent characteristics and site conditions),
6. Development of methods for increasing longevity and minimizing maintenance requirements of infiltration BMPs,
7. Evaluation of sediment toxicity as a function of maintenance frequency,
8. Evaluation of issues and methods of disposing or reusing BMP maintenance-generated wastes, and
9. Evaluation of designs and maintenance of BMPs to reduce conflicts with endangered and threatened species.

Information Sharing and Technology Exchange

A compilation of major syntheses extracted from stormwater runoff research is needed to support, encourage, and facilitate a more efficient and comprehensive exchange of information among stormwater professionals. This report, and that of the National Highway Runoff Data and Methodology Synthesis (NDAMS), presents a good starting point for such a compilation. The International Stormwater BMP Database primarily contains BMP design and monitoring data but makes no direct links to published literature. A research project linking an extensive bibliographic database, such as a refined and value-added NDAMS database, to a water quality and BMP performance database, such as the International Stormwater BMP Database, would create a useful tool for stormwater practitioners. See section 3.1.1 in this report for a synthesis of recent major highway runoff research.

Itemized Research Needs

1. Compilation of major syntheses extracted from stormwater runoff research and linkage into a master bibliographic database;
2. Development of a stormwater runoff research database and a BMP performance and design database specific to highways using the International Stormwater BMP Database as a model;
3. Development of an information-sharing system that links the two databases listed in item 2 into an online, user-friendly database for data entry and retrieval; and
4. Identification of and guidance on practical and accepted monitoring methods for highway runoff.

Watershed Planning

Although much literature supporting watershed management exists, there is still a need for the development and evaluation of techniques to integrate transportation-related runoff analysis with overall watershed management. Stream channels respond to changes in flow volume and sediment loading, which subsequently produce recognizable patterns and forms. Watershed change is known to have a corresponding effect on channels leading to bank erosion and head cutting. Although these processes are well understood and descriptions of channel morphology are well developed, effective predictive models of channel geomorphic response are lacking. Correspondingly, research to support development of regulatory structure more appropriate to the episodic nature of runoff also is needed, along with identification of indices and indicators specific to transportation-related runoff. See section 3.3.1 for a discussion on watershed planning.

Itemized Research Needs

1. Development and evaluation of techniques to integrate transportation-related runoff analysis into overall watershed management;
2. Development of standard methods, models, and data for establishing critical needs within a watershed to prioritize areas for retrofit and BMP implementation;
3. Development of geomorphologic models for estimating watershed development impacts on receiving streams;
4. Quantification or development, or both, of indices and indicators of the contribution of state highway infrastructure relative to total impervious surface area in a watershed;
5. Evaluation of the ability of watershed or regionally based enhancements of wet weather storage capacity to improve baseline (high and low flow) hydrology and ecological productivity downstream;
6. Characterization of the availability and prioritization of sites on a watershed basis for constructed wetlands and wet ponds; and
7. Demonstration of the costs and benefits of alternative, off-site, and watershed-based stormwater mitigation.

Economic Analysis and Assessment

The review of literature pertinent to the economic analyses and assessment of BMPs revealed cost estimation information for nearly all proprietary BMPs and most of the common nonproprietary structural BMPs. For a number of BMP types, cost regression equations have been developed that are primarily based on imperviousness, land use, and flow rates and volumes; however, life-cycle costs, opportunity costs, and externalities often are neglected in cost estimation. There is a need to develop BMP cost estimation tools that account for land value, site constraints, construction, operations, and maintenance, as well as receiving waters protection, aesthetics, and infrastructure savings on conventional drainage structures. Quantification of benefits from receiving waters protection requires the use of existing water quality, habitat, and bioassessment monitoring data for both the runoff and receiving waters.

Costs associated with public education, catch basin maintenance, and roadside vegetation control activities would aid in the optimization and adequate allocation of stormwater management funds. Cost evaluations and comparisons of BMP treatment trains, distributed BMPs, and large centralized regional BMP systems also are needed. See section 3.2.14 for a discussion on economic analysis and assessment of BMPs.

Itemized Research Needs

1. Guidance on quantifying BMP life-cycle costs and benefits associated with receiving waters protection;
2. Evaluation of potential cost reductions of stormwater treatment through alternative siting within the watershed;
3. Evaluation of the BMP benefits and constraints in highly urbanized corridors;
4. Cost comparisons of BMP treatment trains, distributed BMPs, and regional BMP systems;
5. Development of BMP cost-estimation tools that account for land value, site constraints, construction, operations, and maintenance, as well as receiving waters protection, aesthetics, and infrastructure savings on conventional drainage structures; and
6. Cost estimates for nonstructural BMPs.

General BMP Evaluation and Selection

There are many different ways to evaluate BMPs. The most common methods monitor the effluent and influent water quality with the primary goal of estimating BMP efficiency. Several methods exist for monitoring, analyzing, and reporting BMP efficiency. The most common methods include the efficiency ratio, summation of loads, regression of loads, mean concentration, efficiency of individual storm loads, reference watersheds, and before-and-after studies. More recent methods include effluent probability, flow-dependent removal efficiency, minimum influent concentration, and the pollutant flux ratio. Of all these methods, the most promising for the consideration of standard BMP efficiency are the effluent probability method, which is recommended in *Urban Stormwater BMP Performance Monitoring: A Guidance Manual for Meeting the National Stormwater BMP Database Requirements* (GeoSyntec Consultants, 2002), and the minimum influent concentration removal efficiency methods, referred to in the *Stormwater Best Management Practice Demonstration Tier II Protocol for Interstate Reciprocity* (2001). The former provides greater detail on the actual performance of a BMP; the latter provides an easier way to understand the transferable measure of BMP efficiency. However, neither method can be used to estimate adequately the efficiency of BMPs without well-defined inlets and outlets, such as infiltration-type facilities or source controls. Reference watersheds and before-and-after studies are used often in these situations.

Because there are so many methods available for evaluating and reporting the efficiency of BMPs, consensus and guidance clearly are needed. Selection of BMPs often is based on performance claims and reported efficiencies in relation to water quality goals, but many other factors are involved, including budgetary and site constraints, which include available land, climate, soil and vegetation conditions, topography, surrounding land use, and local regulatory issues. All of these factors make it difficult to select and design BMPs. As stated in the GKY Synthesis and Research Plan, "[p]ractitioners need quick and ready access to BMP information and a means of quickly applying applicable portions of it to site-specific situations—an expert system." This current effort agrees that such an "expert system" is needed to aid in the selection and design of highway stormwater BMPs. See section 3.2.1 for a discussion on general BMP evaluation.

Itemized Research Needs

1. Development of standard performance measure(s) for BMP efficiency,
2. Development of an expert system for BMP selection and design, and
3. Assessment of and design guidance for ultra-urban BMPs.

Low-Impact Development and Distributed BMPs

Pilot projects conducted by several researchers have demonstrated the potential of low-impact development (LID) to meet regulatory requirements, but substantial work needs to be conducted on developing LID design strategies, performance standards, and specifications. LID's decentralized approach to stormwater management technology has tremendous potential to supplement, or in some situations completely replace, conventional centralized stormwater BMP approaches. However, LID's applicability, efficacy, and long-term economic sustainability for transportation systems have yet to be determined or documented. A long-term research need is to document the type of hydrologic losses that via LID can be achieved regionally and under various climatic, soil, slope, and vegetation conditions. See section 3.2.9 for a discussion on LID.

Itemized Research Needs

1. Development of LID design strategies, performance standards, and specifications;
2. Documentation of LID's applicability, efficacy, and long-term economic sustainability for transportation systems;
3. Evaluation of the type of hydrologic losses that can be achieved under various climatic, soil, slope, and vegetation conditions;
4. LID modeling and design guidance for accurately sizing end-of-pipe control systems; and
5. Development of methods and technologies to promote the reuse of stormwater.

Design Variables Affecting BMP Performance

Primary design variables affecting BMP performance are those that control flow. These include outlet structures, baffles, berms, and vegetation density, in addition to the total volume a system is able to capture. Design features specific to individual types of BMPs, such as specific surface area for detention facilities and flow length for swales, also are significant factors to consider when evaluating and comparing BMP performance. These design variables are related directly to physical treatment mechanisms of sedimentation and filtration. Variables related to the biochemical and geochemical treatment mechanisms, such as vegetation and soil type, also may be important design factors; however, no studies were found that compared BMP performance according to these variables, indicating a potential research gap. Before sufficient field data are available to make assessments of design variables that influence treatment, pilot-scale experiments can be conducted to ascertain some of the needed design and performance information. See section 3.2.7 for a discussion of design variables affecting BMP performance.

Itemized Research Needs

1. Evaluation of design variables that are related to biochemical and geochemical treatment mechanisms, and
2. Execution of pilot-scale experiments that evaluate the relation of various design variables on BMP performance.

BMP Modeling

With regard to BMP modeling, the unit processes of sedimentation and infiltration appear to be well covered in the literature. However, other BMP water quality treatment unit processes such as sorption processes (absorption and adsorption), biodegradation and uptake, photolysis, and volatilization still need further study before reliable BMP performance models can be developed. Information on the modeling of BMP treatment trains appears to be lacking as well. A better understanding of BMP longevity and the decrease in the treatment efficiency as a function of time are required so that the optimization models that are used to select cost-effective BMP systems can provide better estimates of the lifetime costs and benefits of BMPs. How sources of pollutants are represented in models also merits further exploration. Many models still use a "build-up–wash-off" approach as the only way the pollutants get into stormwater, which can lead to faulty results if the BMP acts directly on that function. The development of a review of modeling approaches and guidance on their selection and application would be a useful resource for stormwater practitioners. See section 3.2.10 for a discussion of BMP modeling.

Itemized Research Needs

1. Evaluation of modeling approaches and guidance on model selection and application;
2. Use of pilot experiments to collect data needed for parameter estimation and model calibration;
3. Development of unit treatment models that incorporate sorption, biodegradation and uptake, photolysis, and volatilization;
4. Development of models for simulation of BMP treatment trains;
5. Development of BMP treatment models that account for treatment efficiency losses over time; and
6. Development or evaluation of models that can be used for modeling pollution plumes in BMPs.

Hydraulic Assessment

Based on the review of literature with regard to the hydraulic assessment of stormwater control facilities in relation to BMP performance, the most pressing gaps appear in the evaluation of the characteristics and effects of short-circuiting and bypass or overflow (e.g., ponds or wetlands discharging over the low-flow outlet or bioswales when depths and velocities for good treatment are exceeded). The influence of hydraulic residence time on BMP performance has been well studied, and it has been confirmed that detention time correlates positively with pollutant removal (at least for particulate-bound pollutants). However, no studies were found that investigated the nature of the correlation (linearly, asymptotically, etc.). Also, hydraulic residence is calculated usually by dividing the permanent pool volume by the average outflow discharge rate of a BMP. The true hydraulic residence time depends on the flow path through the system, which requires some means of estimating the velocity field of the system such as the use of tracers, ultra-sensitive velocity meters, or two- and three-dimensional hydrodynamic models. See section 3.2.3 for a discussion on hydraulic assessment.

Itemized Research Needs

1. Evaluation of the characteristics and effects of short-circuiting, bypass, and overflow;
2. Investigation of the nature of the correlation between detention time and pollutant removal;
3. Development of methods or models for estimating the true hydraulic residence in stormwater ponds; and
4. Development of methods to optimize detention basin design to maximize treatment.

Methods to Improve Pollutant Removal in Existing Stormwater Systems

One promising method to improve pollutant removal in existing stormwater systems is detailed design guidance that includes overall feasibility cost–benefit comparisons between retrofit alternatives and potential impacts to flood protection. Another need is to sponsor research to evaluate if other less-conservative flood control methods—such as the use of more-refined continuous simulation approaches to assess flood detention needs—could be employed safely.

With regard to coagulants, the reviewed literature (as well as the plethora of literature available in the area of wastewater management) suggests that further research in this area is unlikely to be a high priority. However, in selected locations, coagulant use may be necessary to achieve water quality goals, thus more detailed guidance on design for highway situations may be valuable. Potential impacts to receiving waters from coagulant use may warrant further research, particularly for stormwater treatment products (either new products or ones not used widely—such as chitosan). Recommendations for soil amendments to use in BMPs to more passively improve performance also are areas for potential research. See section 3.2.5 for a discussion on methods to improve pollutant removal in existing stormwater systems.

Itemized Research Needs

1. Cost–benefit analysis of alternative flood control retrofits with consideration of overall feasibility and potential impacts to flood control;
2. Risk assessment of alternative, less-conservative flood control methods through the use of continuous runoff simulation modeling;
3. Development of detailed design guidance for flood control retrofits;
4. Evaluation of the effectiveness of BMP retrofits;
5. Development of recommendations for soil amendments for use in BMPs to passively improve performance;
6. Development of methods for improving or maintaining hydraulic conductivity of infiltration-based stormwater control facilities;
7. Evaluation of the effectiveness of combining sedimentation, filtration, and chemical addition for stormwater BMP construction projects;
8. Evaluation of the potential impacts of coagulants to receiving waters;
9. Detailed guidance for areas that require coagulant use to meet water quality objectives; and
10. Development of new technologies or improvements on existing designs to increase the removal of high-priority pollutants.

Sedimentation and Turbidity Impacts

With regard to sedimentation and turbidity impacts to fish in general and salmonids in particular, some of the significant research needs identified by Bash et al. (2001) include (1) developing new exposure metrics that account for sublethal effects (as opposed to direct mortality); (2) examining the effect of frequent short-term pulses of suspended sediment; (3) conducting additional research on correlations between particle size, shape, and composition of sediments to fish sensitivity; (4) studying relationships between seasonal timing and effect of sediment load; and (5) determining whether knowledge of survival responses to turbid flows can be used to develop mixing zones, work windows, treatment systems, and buffers that will allow fish to perform their necessary life functions during project construction and operation. See section 3.5.3 for a discussion of sedimentation and turbidity impacts.

Itemized Research Needs

1. Development of new exposure metrics that account for sublethal effects (as opposed to direct mortality);
2. Examination of the effects of frequent short-term pulses of suspended sediment;
3. Additional research on correlations between particle size, shape, and composition of sediments to fish sensitivity;
4. Evaluation of the relationships between seasonal timing and the effect of sediment load;
5. Evaluation of the applicability of the knowledge of fish survival responses to turbid flows to the development of mixing zones, work windows, treatment systems, and buffers that will allow fish to perform their necessary life functions during project construction and operation;
6. Identification of practical means of controlling turbidity; and
7. Development of hydromodification measures (estimated downstream hydrological changes) and measures for assessing potential downstream channel and bank instability.

Erosion and Sediment Control

With regard to temporary vegetation controls, sufficient research appears to be available on the erosion control effectiveness of compost and mulch, erosion control mats and blankets, and cellular confinement technologies. Adequate guidance exists as well (see Appendix B for a list of selected guidance manuals). Erosion control effectiveness for removing fine particulates does not seem to be covered adequately in the literature. However, the use of polyacrylamides or other flocculants in conjunction with temporary vegetation controls holds promise for controlling erosion of fine particulates.

More research may be needed on ways to increase germination and survival rates of native vegetation. With regard to bank protection, research is needed to investigate the feasibility and performance of vegetated riprap and alternative bank stabilization designs that minimize impacts to riparian habitat. NCHRP 24-19, expected in 2004, will help to fill this gap. See section 3.2.6 for a discussion of erosion and sediment control.

Itemized Research Needs

1. Evaluation of the effectiveness of erosion controls at removing fine particulates;
2. Evaluation of the effectiveness of using polyacrylamides or other flocculants in conjunction with other sedimentation and erosion control practices;
3. Development of techniques to increase germination, soil coverage, and survival rates of native vegetation;
4. Evaluation and comparison of the different types of vegetation for riprap planting;
5. Research on the necessary top elevation for conventional riprap as a function of velocity, turbulence, and flow duration;
6. Comparison of terraced versus sloping riprap in terms of hydraulic performance and planted vegetation success;
7. Evaluation of alternative bank stabilization techniques that have a lesser effect on riparian and aquatic habitat than riprap;
8. More detailed inspection of riprap where vegetation is growing now or has grown previously to better understand its impacts on bank stability;
9. Guidance for seed mixes and effective establishment and maintenance of erosion control vegetation for short-term first growth and long-term establishment;
10. Evaluation of potential water quality impacts of soil stabilizers used in erosion control;
11. Development of standard, approved postconstruction erosion control inspection and enforcement programs;
12. Evaluation of slope and soil conditions necessary for vegetation establishment;
13. Evaluation of new and innovative erosion control technologies;
14. Evaluation of erosion control methods for arid regions;
15. Evaluation of the performance of nonvegetative permanent soil stabilizers for reducing erosion and potential water quality impacts; and
16 Development and evaluation of temporary nonvegetative soil stabilization techniques.

General Constituent Characterization

Many state DOTs have studied highway runoff, so there are several studies available that generally characterize highway runoff quality. The constituents sampled and the concentrations detected do not appear to vary significantly among the studies; therefore, in general, characterization of highway runoff does not represent a primary research need. However, there are gaps in this research for some chemical constituents, including trace elements—such as polycyclic aromatic hydrocarbons (PAH); benzene, toluene, ethylbenzene, and total xylene (BTEX); methyl tert-butyl ether (MTBE); and platinum group metals—not normally included in characterization studies. See section 3.4.1 for a discussion on general constituent characterization.

Itemized Research Needs

1. Characterization of chemical constituents not generally monitored but believed to be frequently present in highway runoff, and
2. Evaluation of methods for monitoring and analyzing oil and grease and total petroleum hydrocarbons.

Atmospheric Deposition

Based on the review of literature, more studies that relate transportation systems to atmospheric deposition of pollutants are needed to quantify the contribution of atmospheric deposition to pollutant concentrations found in highway runoff and to gain a better understanding of the pollutant sources. Standard methods for evaluating the contribution of atmospheric deposition to highway runoff should be developed. The contribution of organic and inorganic pollutants from atmospheric deposition likely differs between urban and nonurban areas. See section 3.4.3 for a discussion on atmospheric deposition.

Itemized Research Needs

1. Studies that directly relate highways and transportation systems to atmospheric deposition,
2. Development of methods to evaluate the contribution of atmospheric deposition to highway runoff pollution, and
3. Evaluation of the fractions of pollutants contributed by atmospheric deposition for different land uses and classes of contaminants.

First Flush Characterization

There is seemingly a need for the adoption of a standardized method for defining and identifying first flush phenomena. Some parameters appear to exhibit a first flush, while others do not. Therefore, a comprehensive list of highway runoff pollutants that tend to exhibit a first flush may be useful for evaluating receiving water impacts and the feasibility of treating only the first flush of a storm. The current research effort did not find any studies that investigated specifically how the first flush effect was related to hydrological and watershed characteristics, indicating a potential research gap with regard to first flush characterization and assessment. See section 3.4.6 for a discussion on first flush characterization.

Itemized Research Needs

1. Adoption of a standardized method for defining and identifying first flush phenomena,

2. Development of a list of highway runoff pollutants that tend to exhibit a first flush,
3. Evaluation of road surface runoff toxicity from different phases of a runoff event,
4. Correlation of toxicity with respect to pollutographs and hydrographs,
5. Evaluation of the effects of watershed characteristics on first flush phenomena, and
6. Evaluation of BMPs designed to capture the first flush.

Impacts of Highway Construction and Vegetation Maintenance

To evaluate erosion control practices, suspended sediment is the primary (and often the only) parameter monitored during highway construction runoff characterization studies. It is unclear in the literature whether total suspended solids (TSS) or suspended-sediment concentrations are being reported; these two terms often are used interchangeably but may yield vastly different results. There appears to be a need to evaluate the differences and consequences of using TSS for sediment load calculations and a need to make stormwater practitioners aware of this potential issue.

Sediment particle-size distribution is an important parameter that is not monitored frequently. Particle-size distribution plays an important role in the transport and aquatic biota impacts of mobilized sediment, metals, nutrients, and trace organics. Since monitoring for particle size and other parameters may increase significantly the costs of a construction project, it would be beneficial to have an initial screening method for assessing the quality of site soils on a grain-size basis to determine if sediment and erosion controls are necessary to prevent impacts to receiving waters.

Additional work also may be needed in the area of roadside vegetation management. The potential for herbicides to migrate from roadsides to receiving waters is strongly dependent on the type of chemical applied (i.e., depends primarily on solubility and hydrophobicity). Numerous herbicides—only a small number of which have been studied for their mobility and potential toxicity to aquatic biota—are in use by DOTs throughout the country. More herbicide runoff characterization studies during storm conditions are needed as are toxicity studies of the concentrations found. Also, an analysis of the adsorption of herbicides to various grain sizes would aid in determining the potential for migration. When more information is available on the potential impacts of herbicides, a detailed cost–benefit comparison of using herbicides (as opposed to other vegetation control methods, such as manual clearing), should be considered. See section 3.4.8 for a discussion on the impacts of highway construction and vegetation maintenance.

Itemized Research Needs

1. Standardization of suspended-sediment measurement and reporting methods,
2. Development of screening methods for assessing the quality of site soils on a grain-size basis so as to determine the level of monitoring as well as sediment and erosion controls necessary to prevent impacts to receiving waters,
3. Characterization of herbicide runoff and assessment of toxicity,
4. Guidance on maintenance facility BMP design,
5. Development of guidance for fertilizer utilization for seeding and turf establishment near sensitive water bodies (nutrient runoff prevention), and
6. Equipment testing methods and performance assessment of mechanical and mechanical/vacuum sweepers.

Stream Crossings

Receiving waters are most vulnerable to highway runoff at stream crossings. Stormwater runoff or by runoff generated during maintenance activities such as bridge deck cleaning may cause direct impacts. Other bridge maintenance activities such as painting, surface treatments, substructure repair, joint repair, drainage structures repair, and pavement repair or repaving also may impact receiving waters depending on storm event timing, duration, and intensity. With regard to highway runoff, potential impacts to receiving waters at stream crossings have been assessed by only a limited number of researchers. NCHRP Project 25-13 is the most extensive assessment to date on this topic. See section 3.5.2 for a discussion on stream crossings.

Itemized Research Needs

1. Examination of the water quality effects of maintenance practices through field studies,
2. Development of a bridge deck runoff quality constituents database,
3. Examination of the potential risks associated with hazardous material spills,
4. Evaluation of how bridge design and average daily traffic affects runoff quality,
5. Assessment of potential receiving water temperature changes and mitigation, and
6. Development and evaluation of BMPs and standards for abating receiving water temperature impacts.

Unit Treatment Processes

Because NCHRP Project 25-20(01) was initiated to begin filling highway stormwater performance evaluation and assessment research gaps identified by earlier investigators and because the final report will include the identification of additional research gaps and needs with regard to unit process evaluations, it is premature to include such an identification here. Based on the opinion of the 25-20(01) project team, the most likely gap will be treatability data and information that can be used to characterize the fundamental removal processes (unit processes) in action within a given BMP, as well as the simple lack of monitoring data of several different BMP types. See section 3.2.8 for a discussion on unit processes.

Itemized Research Needs

1. Characterize and evaluate the fundamental treatment processes within different BMP types;
2. Conduct pilot-scale experiments for the collection of data on unit treatment processes for various BMP types;
3. Compile and assess available unit treatment processes data;
4. Research to obtain within-storm data on BMP effectiveness to assess short-term pollutant issues and collect unit treatment processes information;
5. Evaluate metals fractionation under anaerobic and anoxic conditions;
6. Develop the ability to measure accurately and analyze unit treatment processes;
7. Evaluate BMP design and performance with respect to particle-size distribution in stormwater runoff and associated metals; and
8. Evaluate the physical, chemical, and biological treatment processes of BMPs.

Toxicity and Bioassessment

The top two research needs identified by GKY and Associates in the original NCHRP 25-20 report were (1) to identify and develop regional aquatic biological indicators for assessing impacts of highway runoff and (2) to conduct research methods for assessing the toxicity of highway runoff. This review supports this claim; bioassessment methods for assessing impacts of highway runoff on receiving water systems are inadequate, particularly for the time-scales typical of stormwater-runoff events. Also, a wide variety of assessment methods are currently in use by the few highway water quality researchers conducting toxicity and bioassessment studies. As a result, it is difficult to compare quantitatively the existing data or to make any general assessment of the impacts of highway runoff on receiving water biota. In addition, more within-storm toxicity testing needs to be conducted to ascertain which parts of storm events are most toxic. Another research gap is comparison of runoff toxicity from different drainage systems (e.g., vegetated versus piped conveyance).

Itemized Research Needs

1. Development of standardized bioassessment methods for assessing impacts of highway runoff on receiving water systems;
2. Evaluation of the parts of storm events most toxic to receiving waters;
3. Assessment of BMP performance in terms of toxicity reduction or other biological impact indicators;
4. Guidance on BMP selection based on toxicity;
5. Evaluation of chemical, physical, and toxicity impacts to aquatic biota of stormwater discharges; and
6. Evaluation of viral pathogen indicators and development of treatment options.

Fate and Transport of Highway Runoff Constituents

More detailed studies of sediment transport mechanics in relation to blockage of full and partly full conduits in various cross-sections may be needed. Comprehensive studies on the effects of soils, topography, land use, and various storm hydrographs on sediment yield appear to be limited in number. In addition, the behavior of sediment at inlets, junctions, and transitions in the drainage system may require further study. Good predictive models that consider runoff–storm relationships, particularly storm scour and redeposition, are unavailable.

Research on the speciation of pollutants has focused primarily on the dissolved and particulate fractions of the common metals found in highway runoff, cadmium, copper, lead, and zinc. However, there appears to be a need for better characterization of the bioavailability of dissolved metal complexes, as well as trace organics, in highway runoff.

Sorption plays an important role in the speciation and bioavailability of pollutants; however, the factors controlling sorption—such as cation exchange capacity and specific surface area—are poorly understood. There is a general need for more research on the sorption of pollutant to sediment in highway runoff. It would be beneficial to highway agencies to have information on the sorption capacity of roadside soils for the purposes of prioritizing retrofits and installations of treatment control practices. See section 3.4.5 for a discussion on fate and transport of highway runoff constituents.

Itemized Research Needs

1. Identification of sediment sources and evaluation of transport rates and residence time of sediment in highway runoff, treatment facilities, and receiving waters;
2. Evaluation of sediment transport mechanics and blockage at inlets, junctions, and transitions in full and partly full conduits;
3. Comprehensive studies on the effects of soils, topography, land use, and various storm hydrographs on sediment yield;
4. Evaluation of nutrient leaching and the sorption and desorption processes of roadside soils;
5. Development of predictive models that consider runoff–storm relationships, particularly storm scour and redeposition; and
6. Characterization of the bioavailable fraction of dissolved metals and trace organics in highway runoff.

Market-Driven Approaches: BMP Asset Management and Pollutant Trading

Because market-driven, watershed-based stormwater management approaches are relatively new, further research into the practicality of such approaches is needed, particularly for the application to highway runoff management. A current study funded by the Water Environment Research Foundation, when completed, should provide information and guidance on how a market-driven, watershed management system could be applied to the highway environment. See section 3.3.2 for a discussion on market-driven approaches.

Itemized Research Needs

1. Research into the practicality of pollutant trading as a viable approach to highway runoff management, and
2. Enhancement of maintenance management systems to facilitate asset management of BMPs.

Gross Pollutant Removal and Drain Inlet Studies

The effectiveness of gross pollutant source controls—such as street sweeping, public education, and catch basin cleaning, particularly with regard to the overall effects of catch basin bypass—have not been demonstrated clearly. Most researchers quantify gross pollutants by either weight or volume. Some segregate according to material type, such as plastic and metals. For the purposes of data transfer, development of standard methods for quantifying gross pollutants is needed. A uniform definition of gross solids (and its components) needs to be identified for purposes of standardizing the reporting of data. An ASCE/EWRI committee is working on this issue, but protocols developed for highway situations may be appropriate to help standardize BMP performance.

The effects of gross solids on receiving waters are not well documented in the literature. These effects need to be ascertained for the purposes of assessing future total maximum daily load (TMDL) requirements potentially faced by highway runoff managers. Modeling and estimation techniques for gross solids need to be developed especially in relation to TMDLs. Leaching and sorption capacity of pollutants captured in catch basins represents another potential research gap. See section 3.2.2 for a discussion on gross pollutant removal and drain inlet studies.

Itemized Research Needs

1. Evaluation of the effectiveness and limitations of source controls at reducing gross solids in highway runoff (e.g., public education, catch basin cleaning, and street sweeping);
2. Development of a standard method for measuring and reporting gross solids;
3. Development of modeling and estimation techniques for gross solids;
4. Evaluation of the impacts of gross solids in highway runoff;
5. Evaluation of leaching or sorption capacity, or both, of pollutants captured in catch basins; and
6. Guidance on gross solids removal device design and performance.

Pollutant Retention

Some studies investigated the potential for leaching or resuspension of previously captured pollutants. They indicate resuspension of sediments in catch basin sumps and oil/grit separators may be significant. Resuspension also may occur in bioretention areas before the complete establishment of vegetation. Once captured, heavy metals do not appear to go easily into the dissolved phase, but nutrients do, particularly if there is a change in the oxidation-reduction potential. The pH of the stormwater affects the solubility of captured metals. With regard to pollution retention, it appears that the primary research needs and gaps are in identifying the conditions—such as pH, oxidation-reduction potential, hardness, and organic content—that affect desorption or dissolution, or both, of captured pollutants in stormwater treatment systems. See section 3.2.4 for a discussion on pollutant retention.

Itemized Research Needs

1. Investigation of the potential for leaching or resuspension of previously captured pollutants;
2. Investigation of how changes in pH, oxidation-reduction potential, hardness, and organic content may affect desorption or dissolution, or both, of captured pollutants;
3. Assessment of the long-term ability of BMPs to keep pollutants sequestered; and
4. Bioavailability of pollutants in the sediments of wet ponds and wetlands used for highway stormwater treatment.

Water Quality Runoff Modeling

As with BMP modeling, there is a general need for accurate and representative data for parameter estimation and model calibration and for stochastic models and model development. There also is a need for data collection efforts that focus more on new constituents that may be required by models of the future. Additionally, hybrid models that take advantage of both stochastic and deterministic methods need to be developed. Adaptation of agricultural models for herbicide and pesticide modeling for highway runoff management could provide insights into the transport of pesticides and herbicides. Finally, existing models need to be extended and enhanced to simulate a wider range of contaminants in highway runoff. See section 3.4.7 for a discussion on water quality runoff modeling.

Itemized Research Needs

1. Forward-looking data collection efforts that focus more on the new parameters that may be required by models of the future,
2. Development of hybrid models that take advantage of both stochastic and deterministic methods,
3. Adaptation of agricultural models for herbicide and pesticide transport,
4. Extension and enhancement of existing models to simulate a wider range of contaminants, and
5. Evaluation of the validity of build-up and wash-off as a method of estimating pollutant loads.

Cold Weather Studies and Deicing Agent Impacts

Based on the literature review, a clear need exists for more monitoring and characterization of snowmelt runoff from highways. The reviewed studies indicate that snowmelt runoff—especially during the first major snowmelt runoff events of the year—often has highly elevated pollutant concentrations. Some guidance is available from the Center for Watershed Protection (http://www.cwp.org/cold-climates.htm), but more guidance is needed. Models that can be used to predict the occurrence of a snowmelt runoff event could be helpful to determine when monitoring should take place. The performance and feasibility of stormwater BMPs during cold weather also need to be evaluated, along with the management of removed urban highway snow.

With regard to the receiving water impacts associated with deicing agents, a database containing an evaluation of the human health and receiving water impacts along with toxicity test results for all existing deicing agents is needed to aid in the selection of deicing agents. Other potential research needs include the evaluation of the persistence and implications of various deicing agents in roadside soils, the evaluation of the factors that influence or compound receiving water impacts, and the development of strategies to minimize those impacts. Recommendations suggested by Fischel (2001) include the development and implementation of deicing strategies for reducing the amount of chemicals required and the development of decision support systems based on weather conditions to optimize deicing operations. Finally, there is also a need for guidance and methods for applying the minimum amount of deicing chemicals necessary to maintain safe road conditions. See section 3.4.10 for a discussion on cold-weather studies and deicing agent impacts.

Itemized Research Needs

1. Guidance on monitoring roadside snow as well as snowmelt runoff;
2. Development of modeling methods for estimating snowmelt runoff events;
3. Evaluation of the performance and feasibility, as well as maintenance issues, of stormwater BMPs during cold weather;
4. Assessment of deicing agent and traction materials impacts on receiving waters;
5. Guidance on the management and storage of snow removed from urban highways to minimize impacts of snow storage area runoff;
6. Development of deicing agent selection criteria based on cost, effectiveness, and potential environmental impact; and
7. Guidance and methods for applying the minimum amount of deicing chemicals and traction sand necessary to maintain safe road conditions.

Modeling of Water Quality Impacts to Receiving Waters

The category of water quality modeling shares research gaps identified under the BMP Modeling and Water Quality Modeling section of this report. These research gaps include the availability of data for accurate and representative parameter estimation, the ability to measure accurately and analyze unit processes, and model calibration, as well as the need for an expert model evaluation and selection system. Other potential knowledge gaps pertinent to water quality modeling include guidance on modeling temperature change impacts from pavement runoff, further development and enhancement of stochastic water quality models, evaluation of the limitations imposed by snow on water quality modeling methodologies, and the development of solutions for more accurate simulation of the effects of snow in water quality models. See section 3.5.5 for a discussion on modeling of water quality impacts to receiving waters.

Itemized Research Needs

1. Research and data collection to support model parameter estimation,
2. Guidance on water quality model selection,
3. Development of stochastic water quality models, and
4. Development of models that predict pollutant bioavailability and toxicity.

BMP Vector Control

The potential for vectors, particularly mosquitoes, to inhabit and breed in stormwater control facilities is of increasing concern to stormwater management practitioners. The evident scarcity of studies and literature pertaining to the incidence of vectors in stormwater BMPs makes this whole category a research need. Research needs include the development and evaluation of maintenance and design practices that deter vectors. Poor water quality has been linked to the mosquito proliferation. Mosquito larvae thrive in stagnant and nutrient-rich waters, as nutrients provide food for the bacteria and algae on which mosquito larvae feed. A better knowledge of the relationship between mosquitoes and water quality and flow rate may aid in assessing opportunities for vector control in highway BMPs. See section 3.2.15 for a discussion on BMP vector control.

Itemized Research Needs

1. Evaluation of public health impacts of various stormwater management alternatives, and
2. Evaluation of maintenance and design methods for controlling mosquitoes and other vectors in highway BMPs.

Runoff Characterization with Independent Variable Correlation

With regard to suspended sediment and particle-size distribution, better characterization of constituents associated with different-sized particles in highway runoff, particularly heavy metals, nutrients, and hydrocarbons is needed. Average daily traffic does not appear to be a consistently good predictor of pollutant concentrations and loads. Vehicles during a storm may be a better predictor for some metals and nutrients, as well as TSS, chemical oxygen demand, biochemical oxygen demand, and oil and grease. There was only one study found that investigated the effects of antecedent dry period traffic count; this may be indicative of another possible research gap. In general, traffic volume studies need to be evaluated according to their statistical significance.

Runoff volume, rainfall volume, intensity, and duration are hydrological factors that have been shown by a few researchers to affect runoff constituent levels. Total storm volume affects loads of some water quality parameters—such as TSS and oil and grease—but does not appear to significantly affect concentrations. Correlations between intensity and duration with constituent levels are sparse in the literature reviewed, indicating this may be another research gap.

Land use appears to affect average stormwater runoff concentrations, yet no studies have been found that show statistically significant differences in concentrations based on land use type alone. Characterization of runoff quality according to the various highway classifications, especially urban versus rural, on-ramps and off-ramps, and percent impervious area appears to be an area needing further research.

Staff at the Center for Watershed Protection, together with Dr. Robert Pitt, are compiling and summarizing the available national data on urban runoff water quality and conducting data explorations to ascertain potential explaining factors. See section 3.4.2 for a discussion on runoff characterization with independent variable correlation.

Itemized Research Needs

1. Better characterization of constituents associated with different-sized particles in highway runoff, particularly heavy metals, nutrients, and hydrocarbons;
2. Evaluation of statistically valid traffic volume-related studies;
3. Development of correlations between storm event intensity and duration with constituent levels;
4. Identification of statistically significant differences in concentrations in relation land use type alone;
5. Runoff quality characterization according to the various highway classifications (e.g., urban, rural, on-ramps, off-ramps, and total impervious area); and
6. Establishment of traffic thresholds beneath which certain pollutants in highway runoff can be considered negligible or irreducible.

Wetland Impacts

Based on the review of literature, the potential highway runoff impacts on natural and mitigated wetlands appear to be well documented. The tendency for many highway runoff pollutants to accumulate in wetland sediments and vegetation raises some concern with regard to long-term impacts on wetland biota. There are various sediment toxicity methods available for assessing impacts to both freshwater and estuarine benthic organisms. Indicators may be needed for assessing impacts to wetlands from highway runoff; this may require a detailed analysis of currently available data on wetlands receiving runoff from highway facilities. See section 3.5.9 for a discussion on wetland impacts.

Itemized Research Needs

1. Compilation and analysis of available water quality, sediment quality, and bioassessment data for wetlands receiving runoff from highway facilities, and
2. Development of bioindicators for assessing impacts to wetlands from highway runoff.

Public Perception and Aesthetics

A limited amount of research has focused on the use of aesthetics and public perception as a BMP evaluation measure. Public opinion surveys that attempt to assess BMPs with respect to public perception may aid in selecting and improving the aesthetics of BMPs and may provide insight on how to improve the public's opinion of stormwater management. Furthermore, research that quantifies the impacts of various types of BMPs on property values may aid in the development of tools for evaluating the actual costs of BMPs. Such tools also could be used in public education and outreach programs. Finally, methods and guidance are needed for maximizing the net benefit of BMPs by increasing their multi-use functionality, such as making treatment wetlands safe and accessible to the public for bird watching or using porous pavements in pullout areas and rest stops. See section 3.2.13 for a discussion on public perception.

Itemized Research Needs

1. Development of public opinion surveys to assess the public's perception of stormwater management, in general, and BMPs in particular;
2. Guidance on how to improve public perception of various types of BMPs; and
3. Quantification of BMP impacts to property values and evaluation of methods to improve aesthetics and multi-use functionality.

Impacts of Highway Construction and Repair Materials

A literature review on highway construction and maintenance materials as a source of runoff contaminants reveals a limited number of studies on the subject (NCHRP Project 25-09 is the most comprehensive to date) and a significant amount of research in progress. Currently, potential gaps include the availability of materials properties data; sorption and desorption processes in roadside soils; a better understanding of the speciation, bioavailability, and toxicity of metals in highway construction material leachate; the effects and influence of temperature on the leaching of pollutants from construction materials; and a better understanding of the capabilities of existing BMPs to mitigate impacts from highway construction material contamination. See section 3.4.4 for a discussion on the impacts of highway construction and repair materials.

Itemized Research Needs

1. Compilation of properties data for highway construction and repairs materials;
2. Evaluation of the speciation, bioavailability, and toxicity of metals in highway construction material leachate;
3. Evaluation of the effects and influence of temperature on the leaching of pollutants from construction materials; and
4. Evaluation of the capabilities of existing BMPs to mitigate impacts from highway construction materials contamination.

Groundwater Quality Analysis and Impacts

Based on the research review, information is needed on the potential impacts to groundwater caused by infiltration of stormwater runoff. The methods used to assess impacts are difficult to implement and the results are difficult to assess. State DOTs need a procedure to estimate the potential extent and magnitude of groundwater quality degradation from transportation BMPs, particularly those that rely on infiltration as their primary treatment mechanism. Guidance would include procedures for identifying and evaluating current and potential uses of groundwater and water quality requirements that could be affected by transportation BMPs. See section 3.5.8 for a discussion on groundwater quality analysis and impacts.

Itemized Research Needs

1. Development of a standardized procedure for monitoring and assessing soil and groundwater impacts caused by infiltration facilities;
2. Evaluation of the pollutant retention capacities of different soil types and geological conditions;
3. Evaluation of the potential groundwater impacts of soluble highway runoff pollutants such as herbicides, nutrients, deicing agents, petroleum hydrocarbons (e.g., BTEX), and gasoline oxygenates;
4. Determination of the sources of MTBE in groundwater;
5. Development of infiltration guidance to prevent groundwater contamination; and
6. Development of approaches addressing groundwater pollutants introduced to surface waters from dewatering operations.

Water Quality Impacts of Combined Sewer Overflows

Combined sewer overflow (CSO) systems are widely variable, and water quality impacts depend on a host of site-specific parameters. Assessment of impacts is based primarily on computer simulations. There are needs for better monitoring of CSO effluent quality in relation to meteorological factors, identification of the prevailing conditions or factors for increasing or decreasing CSO impacts, and methods for mitigating impacts (structural and nonstructural). However, CSOs are being phased out slowly through retrofits and new construction, so CSO research needs are considered a low priority for highway runoff control and management. See section 3.5.6 for a discussion on the water quality impacts of CSOs.

Itemized Research Needs

1. Hydraulic assessment of highway runoff contributions to CSO impacts to receiving waters,
2. Better monitoring of CSO effluent quality in relation to meteorological factors,
3. Evaluation of the prevailing conditions or factors that increase or decrease CSO impacts, and
4. Development and evaluation of practices (structural and nonstructural) to mitigate CSO impacts.

DETAILED PROJECT STATEMENTS

The research statements identified in this document are a subset of the numerous research gaps that exist in the area of highway runoff management. The combination of a detailed survey, a literature review, and the opinions of stormwater experts has resulted in identifying the most pressing research gaps in the area of highway runoff management. The individual research gaps identified in Table 4-1 were combined to form the various projects described below with tasks that will address the identified objectives.

BMP Maintenance, Costs, and Longevity

There is little information available that has been based on actual field data regarding the amount and frequency of the BMPs maintenance needed to maintain the pollutant removal effectiveness and the related costs. The purpose of this research would be to develop better information on the types and frequencies of BMP maintenance needed and on the cost-effectiveness of such maintenance. Guidance on how to factor BMP maintenance costs into life-cycle costs for BMP selection also would be developed. In addition, this project would investigate the state of the practice in how costs of BMP maintenance are being tracked in maintenance management systems, as well as how such information could be compiled and shared nationally on a more continuous basis. See sections 3.2.11 and 3.2.14 for discussions about BMP maintenance, costs, and longevity. The research gaps addressed under this research statement are listed under the BMP Maintenance and Longevity and the Economic Analysis and Assessment of BMPs sections of Table 4-1.

Research Objectives

Specific research topics addressed by this proposed project include the following:

- Develop BMP maintenance versus performance information, including how to maintain infiltration BMPs to extend the effective life of these facilities and how maintenance (pollutant removal) can reduce potential build-up of pollutants to hazardous levels;
- Identify the state of the practice in how BMPs cost information is being tracked within maintenance management systems as well as how such information could be compiled and shared nationally on a more continuous basis;
- Identify how maintenance costs should be incorporated into life-cycle costing for BMP selection for highways (for overall evaluation of cost-effectiveness);
- Develop nationally applicable BMP operations, inspection, and maintenance guidance (maintenance frequencies, logistics and personnel requirements, and estimates based on influent characteristics and site conditions), including suggestions on contractual methods to improve BMP implementation, removal, and disposal of BMP captured pollutants, and environmentally sensitive BMP maintenance (to reduce effects on endangered and threatened species, wetlands, and pond treatment systems); and
- Identify whether maintenance data could be overlaid with other geographic information system information to determine cost factors across various landscapes. Determine cost factors across landscapes using pilots in several locations selected to tease out patterns in cost differences in rural, suburban, and urban landscapes and different climatological zones.

Tasks

1. *Search Literature and Gray Literature*: Reassess available research on BMP maintenance from highways and other urban areas for information on BMP maintenance versus performance and for the other research questions above. Critically

assess what information still needs to be collected via field studies. Recommend two BMP types for an example study that could be performed to assess maintenance needs; include a biofiltration-type BMP (e.g., wetland, pond, bioswales) and a more structural-type BMP (e.g., underground vault or filtration type BMP).

2. *Survey DOTs to Identify the State of the Practice in How BMP Cost Information is Tracked*: Survey DOTs to identify the state of the practice in how BMP cost information is tracked in construction budget reporting and within maintenance management systems and to determine how such information could be compiled and shared nationally on a more continuous basis.
3. *Develop a Field Evaluation Plan for BMP Maintenance Testing*: Develop a field testing plan for a 6-year study of maintenance versus performance for the initial two BMP types. The purpose of this task is to test an initial set of BMPs, so that testing on other BMP types could be recommended and completed based on what is learned from the program. For each type of BMP, 6 facilities should be tested (i.e., a total of 12 for two BMP types). The testing should include a minimum of six storms per year in which storm flow-weighted composite samples and selected grab samples for a suggested suite of parameters (minimum of TSS, dissolved and total heavy metals, nutrients, and oil and grease) are collected during a storm. The test plan should suggest how to alter maintenance strategies so that the performance of the BMP can be evaluated (e.g., alternating maintenance levels for 3 years for each site or comparison sites).
4. *Conduct Field Evaluation*: Under this task the above study plan will be implemented. Produce interim reports at 2 and 4 years and a final report at 6 years. The final report should recommend additional testing of BMP types and improvements to the testing plan and strategies.
5. *Develop Recommended Draft National Guidance*: Based on the literature review and the results of the field evaluation, prepare guidance on BMP operations and maintenance that addresses the above research questions. The Draft National Guidance would be updated as additional BMPs are tested.

Estimated Project Budget: $800,000 to $1,200,000; 36 months to complete.

Highway Runoff Information Sharing and Technology Exchange Systems

Although there are still many research needs regarding highway runoff, a great deal of information exists on highway runoff characterization impacts to receiving systems, construction and post-construction water quality control technologies, and nonstructural practices. Many states have made significant investments in new technology evaluations and highway runoff studies. Nevertheless, this information has not been readily available to practitioners in forms that are useful for assisting in highway runoff planning and design efforts. DOTs need ways to better access the fragmented and scattered information that already exists. The purpose of this project would be to establish an Internet site that would be developed in conjunction with other NCHRP best practice information collection efforts, such as NCHRP 25-25(04), and water quality BMP evaluation projects, such as NCHRP 25-20(01). The Internet site could speed and expand availability of relevant transportation runoff water quality programs and practices so that the findings of research efforts could be used.

Electronic exchange through the Internet, list servers, or electronic subscriptions or newsletters has been noted as the preferred method for information exchange by DOTs; there is a need for a central repository of this information. Practitioners manually review many paper products and develop their own information networks. Beyond AASHTO's Environmental Technical Assistance Program, no formal system keeps practitioners aware of new information. Timeliness of getting new information is a function of data availability, and practitioners are frustrated with the difficulty of finding relevant information. The purpose of this project is to recommend an information exchange mechanism for sharing and disseminating information that supports more effective water quality management at DOTs. See section 3.1 and Chapter 3 of the GKY report (*NCHRP Web Document 37*) for a summary of major runoff management information sources. The research gaps addressed under this research statement are listed under the Information Sharing and Technology Exchange Systems section of Table 4-1.

Research Objectives

The Internet-based resource would extend highway runoff characterization, impacts, and best practice collection and technology transfer by including

- The community's best bibliography of titles and authors, with as many annotations and cross-references as possible;
- An extensive online library of as many complete sources as possible (or links to sites where such information is available) to shorten the acquisition time for information on subjects covered;
- An area for postings and roundtable discussions of research updates and progress reports on work of interest to the community [The discussion forum would facilitate professional exchange of information publicly (through the forum) and individually (off line)]; and
- A strategy for publicizing the site's existence and incorporating access to it into appropriate online resources.

Tasks

1. *Develop a Conceptual NCHRP Highway Runoff Information Sharing Plan*: Develop a formal list of information needs based on the NCHRP 25-20, 25-25(04), and 25-20(01) research efforts. Review existing literature, on line and published, for supplementary information. Develop a recommended plan for implementation, to include
   - Development of a bibliographic database for compilation of major syntheses addressing stormwater runoff research and guidance;
   - Development of a stormwater runoff and BMP performance and design database specific to highways or identification of suitable databases with relevant links (e.g., the National Stormwater BMP Database);
   - Development of an information sharing system for highway runoff research documents and monitoring data;
   - Development of an online chat area for discussion of highway runoff issues;
   - Development of links to other best practices information collection efforts and online resources; and
   - Development of links to guidance available on line for highway runoff related issues, including monitoring procedures, impact analyses, and BMP design.
2. *Finalize Implementation Plan*: Finalize the implementation plan based on meetings with the project committee and on discussions with NCHRP staff.

3. *Implement Information Sharing Program*: Implement the information sharing program, including instructions for continued operation of information sharing tools by an appropriate entity.

Estimated Project Budget: $200,000 to $300,000, 18 months for implementation. $40,000 to $50,000 per year to maintain information sharing tools (not included in this project).

Watershed-Based Highway Runoff Mitigation Approaches and Guidance

There is a high potential to increase the cost-effectiveness of highway stormwater management through greater DOT participation in watershed planning and information collection and sharing efforts. Such participation has the potential to result in alternative BMP siting within a watershed and increased cost-effectiveness of stormwater controls. Transportation project delivery often is impeded by regulatory requirements for the mitigation of water quality, hydrology, and habitat impacts within or adjacent to the transportation system right-of-way (in-ROW mitigation) or by DOT reluctance to use something other than onsite BMPs. Onsite BMPs are problematic in some cases and may be less effective than desired because of site-specific constraints such as a lack of available land, presence of protected natural resources, unstable slopes, shallow water tables, excessive costs of construction or maintenance, or marginal environmental benefits of the technology employed. Additionally, the limits inherent in in-ROW mitigation can impede the ability to address a community or watershed's most critical water quality needs. On the other hand, opportunities may exist in areas with substantial ROW to boost treatment of runoff from adjacent areas, again enhancing the public sector's ability to address water quality issues on a watershed basis.

Many states and local municipalities currently support projects that are assessing surface water quality, groundwater quality, floodplain impacts, wetland protection, and streambank–shoreline erosion at the watershed–ecosystem level. Transportation systems potentially could use the flexibility that watershed-based mitigation provides to reduce project costs, maximize environmental benefits, and address multiple ecological needs and functions. The more piecemeal approach typically employed today can result in less cost-effective mitigation strategies and inequitably burdened mitigation costs.

New approaches and flexibility for mitigation are needed if transportation systems are to improve project delivery and to maximize the benefits of environmental investments. The purpose of this project would be to develop a guidance document, with case studies, of how transportation agencies could participate in watershed efforts to mitigate highway runoff impacts. See section 3.3 for a discussion on watershed-based approaches. The research gaps addressed under this research statement are listed under the Watershed Planning section of Table 4-1.

Research Objectives

- Evaluate pilot watershed-based transportation approaches undertaken in Washington State, North Carolina, and other model states.
- Identify protocols that have been developed for establishing critical needs and local priorities (including methods developed under the North Carolina Ecosystem Enhancement Program, Center for Watershed Protection, and EPA) and for identifying opportunities for mitigation banking, retrofits, offsite mitigation development, pollutant abatement trading, and watershed-based BMP design and place-

ment. Identify gaps and needs for a protocol that could be used by transportation agencies on a national basis.

- Develop a model by which to consider the relative costs and benefits of watershed-based mitigation versus site-specific mitigation from a cumulative effects perspective, linked to loss of function from impacted sites. Assess quantitatively and qualitatively the monetary and ecological benefits of watershed-based mitigation.
- Develop guidance on watershed-based approaches for transportation agencies with case studies.

Tasks

1. *Conduct a Review of Watershed-Based Approaches*: Conduct a critical review of watershed-based approaches and protocols that have been implemented and assess their potential for application to transportation agencies. The results of this review should include overall synopses of potential approaches and particular case studies of potential models. The review should include water quality and hydromodification (hydrology changes) in addition to a review of pollutant trading, as applied to surface waters. The review also would include an evaluation of existing regulatory policies and impediments to implementation. Gaps and needs for a protocol that could be used by transportation agencies on a national basis would be identified.
2. *Develop Potential Protocols*: Based on Task 1, develop potential protocols that could be used by transportation agencies for addressing impacts of highway runoff via a watershed-based approach. Models for considering the relative benefits and costs of watershed approaches versus onsite approaches should be included in the protocol. The product of this task would be a report on the suggested protocol that the project committee could discuss.
3. *Develop Watershed-Based Highway Runoff Mitigation Guidance*: Based on project committee feedback, develop a guidance document on how watershed-based approaches can be applied to mitigation of highway runoff. Include guidance on how “over-mitigation” of highway runoff or adjacent land uses, or both, might provide value to a transportation agency.

Estimated Project Budget: $200,000 to $250,000, 18–24 months to complete.

Economic Analysis and Assessment of BMPs

The costs for selecting, designing, and installing (and maintaining—an emphasis of RS-1) BMPs are not well understood and in many cases are not tracked. Costs also often can be misleading. For example, frequently land-intensive BMPs are placed in areas that would have been landscaped in any case, and therefore no additional land costs are procured with BMP implementation; yet, these land costs are sometimes included in assessing BMP costs. In order to improve the information available on BMP costs, a more uniform set of protocols is needed for recording and tracking such information. In addition, guidance is needed on how to use available and improved cost information, so that BMPs can be compared and selected on a cost-effectiveness basis. See section 3.2.14 for a discussion on the economic analysis and assessment of BMPs. The research gaps addressed under this research statement are listed under the Economic Analysis and Assessment of BMPs section of Table 4-1.

Research Objectives

- Development of highway runoff BMP cost determination protocols that account for land value (if land had to be purchased or eliminated from another use), construction, operations, and maintenance, as well as receiving waters protection, aesthetics, and potential infrastructure savings on conventional drainage structures;
- Guidance on quantifying and comparing BMP lifecycle costs and benefits associated with receiving waters protection;
- Cost comparisons of BMP treatment trains, distributed BMPs, and regional BMP systems; and
- Cost estimates for nonstructural BMPs.

Tasks

1. *Conduct a Review of BMP Costs and Benefits*: A literature review and survey of available state DOT BMP cost and benefits data and methodology should be conducted. Available data on BMP costs should be summarized in a concise report.
2. *Develop BMP Cost and Benefit Protocols*: A protocol by BMP type (e.g., National BMP Database Classifications or other suitable BMP classification scheme) will be developed for recording BMP cost information and the benefits to receiving waters. The protocol will include costs for BMP design and construction; BMP maintenance; land costs, including whether they were additive or not; avoided costs (such as reduced piping or other conveyance structures); and estimates of the monetary benefits of receiving waters protection from pollutants and hydrological impacts (such as avoided fines and required restoration). The protocol also will include a tool for assessing the lifecycle costs and benefits of highway runoff BMPs.
3. *Compile and Summarize Available Data on BMP Costs and Benefits*: Data from the sources in Task 1 will be compiled and placed into the protocols where appropriate. Establish identification of different qualities of data. Subsequently summarize by BMP type the cost and benefit data. Assess the value of available costing data.
4. *Develop Guidance on BMP Costs and Benefits*: Develop a guidance manual on how to track costs and benefits of highway runoff BMPs based on the previously listed data. The guidance will be by BMP type and activity, based on the protocols developed above. In addition, the guidance will include the information available on costs and benefits of BMPs by BMP type as established in Task 3. Once it is implemented, cost and benefit information could be exchanged in the Information Sharing System described in RS-2.

Estimated Project Budget: $200,000 to $275,000; 24 months to complete.

BMP Evaluation and Design Expert System—Construction Sites

The selection and design of construction site BMPs is very dependent on site specifics. To productively use existing BMP effectiveness studies, practitioners must determine the aspects applicable to a specific site under consideration and how that information applies to the site. Such a system could be developed as an automated interface and database, which users could access on desktop systems or via the Internet. Better guidance on the selection and design of construction site BMPs would be helpful in improving the cost-effectiveness of construction site BMPs. See section 3.2.6 for discussions on erosion and sediment control. The research gaps addressed under this research statement are listed under the General BMP Evaluation and Selection section of Table 4-1 of this report and Chapter 6 of the GKY report (*NCHRP Web Document 37*).

Research Objectives

- Development of guidance on highway construction site factors versus construction site BMP selection and design, and
- Development of an expert system for use in construction site BMP selection and design based on developed guidance.

Tasks

1. *Conduct a Review of Existing Highway Construction Guidance Documents*: Conduct a critical literature review on available construction site BMP selection and design; make recommendations on how the available guidance documents can be used to develop a national-level guidance document.
2. *Develop a National-Level BMP Selection and Guidance Document for Highway Construction Projects*: Develop a national-level guidance document targeted toward transportation agencies. The guidance document should include how specific site factors, receiving water sensitivity, and other factors should be used in selecting and designing construction site BMPs.
3. *Develop an Expert System*: Incorporate the guidance document into an expert system that can be used to guide construction site BMP selection and design. The expert system will be able to be customized by individual agencies to meet their respective needs.

Estimated Project Budget: $250,000 to $300,000; 24 months to complete.

Evaluation and Design Expert System—Post-Construction

The selection and design of post-construction site BMPs is very dependent on site specifics. State DOTs have indicated that having better guidance on the selection and design of post-construction site BMPs would be helpful for improving the cost-effectiveness of BMPs. To effectively use existing BMP effectiveness studies, practitioners currently must determine which portions are applicable to a specific BMP under consideration and how that information applies to a particular site. Practitioners could benefit from accessible BMP information and a means of quickly applying applicable portions of it to site-specific situations—hence, an expert system. Such a system could be developed as an automated interface and database, which users could access on desktop systems or via the Internet. A critical component of this work is the development of a recommended set of protocols for assessing BMP performance for highway BMPs. The use of percent removals of pollutants has been found to be very problematic. See section 3.2.1 for a discussion on general BMP evaluation. The research gaps addressed under this research statement are listed under the General BMP Evaluation and Selection section of Table 4-1 in this report and Chapter 6 of the GKY report (*NCHRP Web Document 37*).

Research Objectives

- Development of a recommended set of protocols for characterizing the performance of BMPs. The National BMP Database team has suggested that post-construction

BMPs should be characterized by (1) how much runoff is prevented, (2) how much of the runoff that occurs is treated by the BMP, and (3) what are the effluent quality characteristics of the runoff that is treated. There are many other suggested performance measures that should be considered in the development of a set of highway BMP performance protocols.

- Development of overall guidance on the selection and design of highway runoff BMPs.
- The term "ultra-urban" has been used to describe areas of the country where space for stormwater BMP implementation in urban areas is limited. The goal of ultra-urban technology is to provide cost-effective, low-maintenance solutions to stormwater management problems in the ultra-urban environment. A number of ultra-urban BMPs were identified in a national study by FHWA on ultra-urban BMPs, the purpose of which was to provide a planning-level review of the applicability and use of new and more traditional BMPs in ultra-urban settings. A specific research objective of this work is to develop guidance on the selection and design of such measures.
  - Collect existing research on ultra-urban BMPs and identify pilots or demonstrations that are still needed. Demonstrate and evaluate a number of case studies for practicality, so that initial comprehensive design guidance may be undertaken.
  - Evaluate likely ultra-urban BMP designs in ultra-urban settings for operational effectiveness as a function of maintenance requirements.
  - Identify regional and site-specific issues and guidance.
  - Incorporate results into the design guidance manual.
- Development of an expert system for use in post-construction site BMP selection and design based upon developed guidance.

Tasks

1. *Conduct a Review of Existing Highway Post-Construction BMP Selection and Design Guidance Documents*: Develop a critical literature review on available post-construction BMP selection and design, including recommendations on how the available guidance can be used to develop a national-level guidance document.
2. *Develop a Set of Proposed BMP Effectiveness Protocols*: Develop a recommended set of protocols for assessing the performance of highway runoff BMPs, so that the performance of various BMPs could be compared to one another and contrasted with receiving water goals and standards.
3. *Develop a Research Report on Ultra-Urban BMPs*:
   - Collect existing research on ultra-urban BMPs and identify pilots or demonstrations that still are needed. A number of case studies need to be demonstrated and evaluated for practicality so that initial comprehensive design guidance can be undertaken.
   - Evaluate likely ultra-urban BMP designs in ultra-urban settings for operational effectiveness as a function of maintenance requirements.
   - Identify regional and site-specific issues and guidance.
4. *Develop a National-Level BMP Selection and Guidance Document for Highway Post-Construction BMPs*: Develop national-level guidance targeted to transportation agencies. Include how specific site factors, receiving water sensitivity, and other factors should be used in selecting and designing post-construction BMPs and include in-depth exploration of ultra-urban BMPs.

5. *Develop an Expert System*: Incorporate the guidance document into an expert system that can be used to guide post-construction BMP selection and design. The expert system would be able to be customized by individual agencies.

Estimated Project Budget: $450,000 to $550,000; 30 months to complete.

Low Impact Development/Distributed BMPs

LID/Distributed BMPs are gaining increasing attention in the stormwater management field and among selected DOTs; however, their functioning in various geographic conditions and environments is not well known, particularly as applied to highway environments. LID design guidance is being prepared under NCHRP 25-26. In the course of this work, additional research needs regarding LID/Distributed BMPs will be identified. It is likely that these will include

- Documentation of LID's applicability, efficacy, and long-term economic sustainability for transportation systems;
- Evaluation of the type of hydrologic losses that can be achieved under various climatic, soil, slope, and vegetation conditions; and
- Development of methods and technologies to promote the reuse of stormwater.

This area of research was ranked as a relatively high priority by state DOTs and was included here for that reason; it should be modified based on the results of the ongoing 25-26 project. See section 3.2.9 for a discussion on LID. The research gaps addressed under this research statement are listed under the Low Impact Development/Distributed BMPs section of Table 4-1.

Research Objectives

- Conduct a review of LID/Distributed BMPs that are in the ground and operating.
- Conduct an assessment of the types of hydrological losses that can be achieved under different scenarios of climates, soils, slopes, and vegetative conditions and an assessment of how the losses will reduce or eliminate downstream impacts of increased runoff from highway environments.
- Determine feasibility of and conditions for re-use of captured stormwater.

Tasks

1. *Perform a Survey and Review of In-the-Ground Applications of LID/Distributed BMPs*: Critically review constructed LID-type projects to assess potential benefits and costs. Interview state DOTs to ascertain what monitoring (water quantity and quality, as well as visual, maintenance, and problem) has been completed. Develop a report of case studies and include recommendations for future designs.
2. *Conduct a Hydrological Loss Assessment*: Unless Task 1 includes some detailed hydrological monitoring that can be used to ascertain losses from LID-type BMPs, base the hydrological assessment primarily on the use of existing continuous simulation models (such as SWMM) to ascertain on regional and national levels what types of runoff hydrological losses can be achieved and how these reductions in runoff affect potential downstream channel erosion levels. Include

in the the assessment an evaluation of the site conditions (such as climatic, soil, slopes, and downstream water body sensitivity) and LID types and level of implementation necessary to fully or partially mitigate downstream erosional impacts.
3. *Develop Potential Water Re-Use Methods and Technologies*: Review potential highway runoff water re-use applications. Develop potential conceptual water re-use scenarios and evaluate them for potential costs and benefits. Perform long-term simulation modeling to ascertain the storage size that may be required; evaluate the potential for draining the storage to ascertain the costs and benefits.

Estimated Project Budget: $150,000 to $250,000; 18 months to complete.

BMP Design Variables

The effect of BMP design variables on BMP performance is not well understood. To date, major efforts such as the National Stormwater BMP Database have been able to confirm only a few of the major design variables that can be shown statistically to affect BMP performance. The BMP design guidance developed to date has been based primarily on "good engineering judgment" and on some limited modeling studies. This research project would develop an approach for conducting more rigorous evaluation of BMP design versus performance on one or two selected BMP types and would make recommendations for future evaluations. Research Project 25-20(01) is developing a unit processes evaluation of BMP performance that should indicate some of the important design variables for BMP performance. This research is intended to build on that effort by conducting more in-depth evaluations of the design parameters that appear to affect BMP performance but are not well understood. See section 3.2.7 for a discussion on BMP design variables. The research gaps addressed under this research statement are listed under the Design Variables Affecting BMP Performance section of Table 4-1.

Research Objectives

- Evaluation of design variables that are related to biochemical and geochemical treatment mechanisms in BMPs, and
- Implementation of pilot-scale experiments that evaluate the relation of various design variables to BMP performance.

Tasks

1. *Review the Findings of NCHRP 25-20(1) and Select Design Variables*: Select one or two BMP types and design variables, based on the findings of NCHRP 25-20(1), to further evaluate design versus performance. Prepare a study plan to conduct a laboratory or field program (preferable), or both, to explore these design variables.
2. *Conduct BMP Design Variables Evaluation*: Conduct a laboratory or field program evaluation, or both, of BMP design parameters. Report on findings in terms of recommendations for improving designs. Develop recommendations regarding future testing and evaluation efforts.

Estimated Project Budget: $250,000 to $400,000; 24–36 months to complete.

BMP Modeling Tools

BMP modeling tools are important to transportation agencies, particularly when highway runoff is draining into sensitive receiving waters. Increased understanding of BMP performance, the factors and designs that affect performance, and how BMPs ultimately affect receiving water quality has increased the need to identify and to improve BMP modeling capabilities. Several NCHRP projects, as well as other projects, have resulted in increased understanding of BMP performance. The purpose of this project is to develop guidance on BMP performance modeling. See section 3.2.10 for a discussion on BMP modeling. The research gaps addressed under this research statement are listed under the BMP Modeling section of Table 4-1.

Research Objectives

- Evaluation of state-of-the-art BMP modeling approaches and development of guidance for model selection, needed model improvements, and application;
- Development of unit treatment models that incorporate sorption, biodegradation and uptake, photolysis, and volatilization;
- Development of simulation models for BMP treatment trains;
- Implementation of pilot experiments to collect data needed for parameter estimation and model calibration; and
- Development or evaluation of models that can be used for simulating pollution deposition within BMPs to assess potential impacts to wildlife.

Tasks

1. *Review the Findings of NCHRP 25-20(1) and BMP Modeling Research*: Evaluate the results of the NCHRP 25-20(01) project to develop unit process descriptions of BMP performance and other relevant BMP modeling papers and to compile a listing or description of potential needs for BMP modeling improvements. Identify model approaches that may apply faulty logic (such as attributing all pollutant generation to model "build-up–wash-off" functions that then result in faulty street sweeping effectiveness estimates).
2. *Review Available BMP Models and Approaches*: Review the available models that typically are employed to model BMP performance and suggest a detailed list of needed improvements to such models, in order to address the stated research objectives.
3. *Select One Publicly Available Model and Develop Model Improvements*: Select a public domain model, such as SWMM, that typically is used for BMP modeling and implement recommended improvements.
4. *Develop a Pilot Experiment Plan*: Develop a pilot experiment plan to collect the data needed for the adapted model's parameter estimation and calibration. Develop a case study and guidance on the model's application.

Estimated Project Budget: $200,000 to $275,000; 18–24 months to complete.

Stormwater Detention Hydraulic Performance and Retrofit Options

The hydraulics of stormwater detention systems (ponds and vaults), including wet ponds and dry extended detention systems and the various combinations of these two (including stormwater wetlands) are thought to greatly influence water quality. The purpose of this proposed research project is to evaluate how the performance of ponds and other types of detention-based BMPs can be optimized using the careful consideration and design of hydraulic characteristics of flows routed to and within these types of BMPs.

Existing transportation infrastructure includes drainage management facilities such as detention ponds and storm sewers, which must be used, enhanced, and potentially extended to respond in a cost-effective manner to the increasing requirements of NPDES, TMDL, and the Endangered Species Act. Practitioners need practical guidance for capturing water quality benefits from BMP infrastructure already in place. Currently, there are no coordinated programs to address how existing infrastructure can be modified to benefit water quality. Existing infrastructure removes water from the roadway, and many hydraulic facilities can be retrofitted to provide water quality benefits; examples include catch basin–inlet modifications, detention pond retrofit to embankments and outlet works, riser structures added to culvert–embankment systems, and the fostering of pipe storage in storm drains. The overall potential of retrofit depends on the incidence of existing drainage systems available and on the receptivity to retrofits. See section 3.2.3 for a discussion on hydraulic assessment of BMPs. The research gaps addressed under this research statement are listed under the Hydraulic Assessment of BMPs and the Methods to Improve Pollutant Removal in Existing Stormwater Systems sections of Table 4-1.

Research Objectives

- Evaluation of the characteristics and effects of short-circuiting, bypass, and overflow;
- Evaluation of the nature of correlation between hydraulic residence time and performance;
- Development of methods or models for estimating the true hydraulic residence in stormwater ponds;
- Development of methods to optimize detention basin design to maximize treatment; and
- Assessment of retrofit options for flood-control basins and systems that maximize water quality while maintaining adequate flood-control protection.

Tasks

1. *Review the findings of NCHRP 25-20(1) and BMP Modeling Research*: Evaluate the results of 25-20(01) to develop unit processes descriptions of BMP performance and other relevant BMP modeling papers and to prepare a review of the potential characteristics that can be used to optimize performance of detention systems. Based on this review, develop a detailed study plan for modeling and field analyses to assess the hydraulic characteristics that lead to improved stormwater detention BMP design.
2. *Develop and Apply Models for Residence Times*: Develop or adapt available models to evaluate the effects of short-circuiting and the relationship between residence time and performance. Apply models that evaluate the effects of by-pass and overflow on overall performance on a regional basis. This evaluation will examine the effects of larger detention sizes versus performance and will include an assessment of the trade-offs between longer residence times and increased by-pass or overflow, or both. The results of the task will create a report on how

short-circuiting can be minimized in ponds via optimization of pond design and on sizing and drain times versus overall water quality performance. Based on the modeling work, develop a relationship between pond design factors and hydraulic residence times for use in design work.

3. *Evaluate How Existing Flood-Control Systems May Be Altered to Improve Water Quality*: The purpose of this task is to develop an approach that evaluates systematically existing flood-control facilities for the feasibility of retrofits to improve water quality. Identify elements of typical existing hydraulic facilities that may be modified or enhanced to provide water quality benefits. Review operation and design principles that can enable feasible and cost-effective modifications—hard design, extension of the treatment train, and management change. Find and evaluate existing retrofits of detention facilities reported in the literature and report on their cost-effectiveness. Develop water quality retrofit conceptual designs to enhance water quality elements for as many drainage element types as possible—detention systems are the primary focus, but also include storm sewers, roadside channels, trenches, and drainage swales. An assessment of the potential to reduce flood protection, based on long-term simulations of flooding versus design, should be made to determine if some systems may be overdesigned and, therefore, whether some detention volume may be available for water quality improvement.
4. *Develop a Guidance Manual*: Develop a practical guidance manual for transportation practitioners to select, design, and implement water quality retrofits for existing highway drainage systems.

Estimated Project Budget: $225,000 to $275,000; 18 months to complete.

Assessment of the Effects of Hydromodification, Sedimentation, and Turbidity

Changes in runoff volumes due to increased impervious surface from development have been receiving increasing attention for effects on downstream erosion, sedimentation, and turbidity. Sedimentation and turbidity from the highway runoff can be an issue, particularly in areas where sanding is employed. Highway construction sites can be a source of sediments and particulates during the construction phase. The purpose of this project is to assess the potential for highway sites to contribute to these problems and to examine how they can impact receiving systems. The project also would evaluate and produce recommended methods for reducing sources of turbidity and sediments and would attempt to describe where vegetated swales may treat or reduce adequately runoff from highways. See section 3.5.3 for a discussion on sedimentation and turbidity. The research gaps addressed under this research statement are listed under the Sedimentation and Turbidity Impacts section of Table 4-1.

Research Objectives

- Examination of the effects of frequent short-term pulses of suspended sediment;
- Identification of additional research needs on the correlation between particle size, shape, and composition of sediments to fish sensitivity;
- Evaluation of the relationships between seasonal timing and the effect of sediment load;
- Evaluation of how the knowledge of fish survival responses to turbid water flows can be applied to the development of mixing zones, work windows, treatment systems,

and buffers that will allow fish to perform their necessary life functions during project construction and operation;

- Identification of practical means of controlling turbidity; and
- Development of hydromodification measures (estimated downstream hydrological changes) from highway runoff and, subsequently, development of measures for assessing potential downstream channel and bank instability.

Tasks

1. *Prepare a Review of How Sedimentation, Turbidity, and Hydromodification Can Affect Receiving Waters*: Conduct a literature review on the potential impacts of sedimentation, turbidity, and hydromodification on receiving waters, with an emphasis on highway runoff. Include a characterization and evaluation of particle sizes, shapes, and composition from construction sites as well as from completed highways for different drainage system configurations. Make recommendations for data gathering on needed information.
2. *Conduct a Hydromodification Assessment*: Using long-term simulation models, perform an assessment of the conditions under which highway runoff (e.g., highway area as compared to watershed area of receiving waters, soils, drainage system types, BMP effects, climate, etc.) might either cause or contribute significantly to downstream erosion and sedimentation issues. Estimate where a highway contribution might be negligible as compared to other watershed sources of runoff and where vegetated swales may treat or reduce adequately runoff from highways. Prepare guidance on how to conduct more local assessments.
3. *Develop Guidance on Minimizing Impacts on Receiving Systems from Turbidity and Sedimentation*: Make recommendations on the relationships between seasonal timing and effect of sediment load for various geographic regions targeted to important species. Include recommendations on the development of mixing zones, work windows, treatment systems, and buffers that will allow fish to perform their necessary life functions during project construction and operation. Identify practical means of controlling turbidity to reduce impacts.

Estimated Project Budget: \$125,000 to \$175,000; 18 months to complete.

Methods to Improve Performance of BMPs

The need for potential enhancements to existing BMPs as well as potential additions to the design of new BMPs has been identified as a research need. For example, although BMPs have been shown to be able to achieve certain levels of phosphorus in their effluent, sometimes there is a need to achieve lower levels. This research project is designed to explore potential enhancements to BMPs to improve their performance through such methods as passive chemical additions, real-time chemical additions, and improving and maintaining the ability to infiltrate while protecting groundwater and other enhancements. See section 3.2.5 for a discussion on methods to improve pollutant removal in BMPs. The research gaps addressed under this research statement are listed under the Methods to Improve Pollutant Removal in Existing Stormwater Systems section of Table 4-1.

Research Objectives

- Development of soil amendment recommendations for use in BMPs to passively improve performance;

- Development of methods for improving or maintaining hydraulic conductivity of infiltration-based stormwater control facilities;
- Evaluation of the effectiveness of sedimentation, filtration, and chemical addition combinations for stormwater BMP construction projects;
- Evaluation of the potential impacts of coagulants on receiving waters;
- Detailed guidance for areas that require coagulant use to meet water quality objectives; and
- Development of new technologies and improvements on existing designs to increase the removal of high-priority pollutants.

Tasks

1. *Review the Findings of NCHRP 25-20(1) and BMP Modeling Research*: Evaluate the results of NCHRP 25-20(1) to develop unit process descriptions of BMP performance and other relevant BMP-modeling papers and review other literature on BMP enhancement options. Prepare a review of the potential enhancements that could be developed for BMPs, including passive and active chemical addition, infiltration capabilities maintenance and enhancement, reductions in human pathogens, and other enhancements to improve the removal of additional targeted pollutants. Potential factors that should be evaluated for enhancing infiltration capabilities may include soil amendments, transitional underground storage areas, check dams, and French drains.
2. *Prepare a Recommendations Report*: Based on the review in Task 1, prepare a highway BMP enhancements recommendations report that describes potential enhancements and how they might be applied to BMPs for highway runoff treatment. The enhancements should focus specifically on improvements to targeted pollutant types.
3. *Develop a Testing Plan for BMP Enhancements*: Develop a testing plan to conduct field evaluations of highway BMP enhancements based on the recommendations report and Task 1. The testing plan should recommend at least two passive and two active chemical addition technologies, along with other higher potential BMP enhancements.

Estimated Project Budget: $125,000 to $150,000; 12 months to complete.

Assessment of Potential Impacts on Biota Using BMPs That Incorporate Habitat

Concern has been expressed increasingly with regard to BMPs that include significant habitat components (primarily stormwater wetlands) and whether such BMPs expose wildlife to captured pollutants. Because there is little data to evaluate whether this is in fact a problem, many turn to examples of wetlands (e.g., Kesterson Marsh in the Central Valley of California, an agricultural marsh) where the problems have been created from other pollution sources to draw conclusions. Consequently, potential impacts may be far overstated. In addition, some regulatory agencies have mandated that mitigation wetlands not be used for water quality enhancement. Such restrictions may result in suboptimal use of water resources as well as cost and environmental effectiveness inefficiencies, since the option of using larger wetlands to satisfy both requirements of habitat replacement and water quality enhancement would not be available, therefore, resulting in the employment of potentially less effective BMPs. Finally, good design guidance is needed for minimizing potential negative impact to biota when BMPs that incorporate habitat areas are used. See section 3.5.4 for a discussion on the potential toxicity of highway runoff and section 3.5.9 for a discussion on wetland impacts. The research gaps addressed under this research statement are listed under the Toxicity and Bioassessment and the Wetland Impacts sections of Table 4-1.

Research Objectives

- Critical assessment of available information on the potential for highway runoff BMPs to cause problems for biota and on what habitat values can be achieved safely with such systems, and
- Development and implementation of a monitoring plan to assess the potential impacts on biota and the value of habitat created by highway runoff stormwater treatment wetlands.

Tasks

1. *Conduct a Review of Literature on Impacts on Biota from Use of Highway Runoff BMPs and Constructed Wetlands in Particular*: Conduct a literature review on impacts on biota from the use of constructed wetlands and other BMPs as appropriate. Assess the availability of information on highway runoff BMPs and constructed wetlands. Evaluate the available information on the value of wetlands created by highway runoff as well as those designed specifically to treat highway runoff. Develop a detailed study plan to assess two wetland systems for the potential impacts and habitat benefits provided.
2. *Conduct a Biological Impacts and Values Study*: Conduct a study on the two wetlands selected that assesses the risk to the biota using these BMPs as habitat and foraging areas. Include sampling and reporting on water column, sediment, plant tissue, and invertebrate tissue pollutant testing in areas near inlets and outlets and in the middle of systems. Perform an ecological risk assessment on the potential for such systems to impact wildlife and under what conditions and circumstances. Assess the biological values provided at these two systems by a comparison with natural wetlands as well as with unintentionally created wetlands with hydrology from past highway or urban runoff development. Prepare a report that documents the results of the study.
3. *Develop Guidance*: Based on the above tasks, develop guidance on how to design highway runoff BMPs that protect biota and on how to maximize the habitat value.

Estimated Project Budget: $300,000 to $350,000; 24 months to complete.

Evaluation of BMP Design and Performance with Respect to Particle-Size Distribution in Stormwater Runoff and Associated Metals

Practitioners need effective ways to confine heavy metal toxins to rights-of-way and to prevent contamination of offsite waters. Suspended solids may be used as indicators of overall water quality if correlations can be developed with other parameters. Monitoring costs can be reduced if the number of individual analyses can be reduced by correlating water quality to suspended solids concentrations. Improving the accuracy of measurements and representativeness of samples will increase the confidence in loading calculations and correlations.

Most of the contaminants found along highways are associated with particles of a wide range of sizes (<0.1 m to >2 mm), but regulatory requirements and biological effects typically center on the dissolved constituents. Particle-associated contaminants are critical to environmental protection and regulatory compliance because

- Contaminants can move between particle bound and dissolved states (e.g., during a runoff event or during settling in a detention basin),
- Particle-associated contaminants <0.45 mm are counted operationally as dissolved but could be removed by efficient coagulation and filtration processes in ways that dissolved contaminants cannot, and
- Future regulations may target directly sediment quality.

DOTs are faced with the technical challenge of developing or modifying existing BMP designs, so that they also can effectively capture dissolved-phase heavy metals. Most BMPs aim to treat runoff by removing particles and their associated contaminant load, but currently there is little understanding of which particles are retained by particular BMPs and what conditions favor particle retention. At least a portion of the variability of BMP performance may be attributed to poor understanding of particle dynamics. This project will address inconsistencies in the performance evaluation of stormwater runoff BMPs through less costly and more effective particle monitoring compared with current wet flow monitoring techniques. In addition to the proper evaluation of BMPs, the proposed project has the potential to eliminate most pollutant chemical (dissolved and particulate) analyses by replacing them with particle concentration-based correlations, saving DOTs significant analytical costs. See section 3.4.2.1 for a discussion on suspended solids and particle-size distribution. The research gaps addressed under this research statement are listed under the Unit Treatment Processes and the Runoff Characterization with Independent Variable Correlation sections of Table 4-1.

Research Objectives

- Identification and evaluation of accurate and applicable methods for monitoring particle-size distribution of suspended sediment concentrations;
- Correlation of heavy metals concentrations to suspended sediment in highway runoff;
- Evaluation of BMPs performance, according to suspended sediment removal and changes in particle-size distribution;
- Recommendation of improvements for existing stormwater BMPs to improve sediment capture and retention; and
- Recommendation of future research projects for evaluating the potential to treat metals concentrations not associated with sediment.

Tasks

1. *Develop, Test, and Refine Particle Measurement and Collection Methods*: Include hydrographic measurement of particles (first flush, peak, and end-stage of storm events), testing and development of online particle-size analysis systems, comparison of particle sizing methodologies, and study of the impacts of storage and detention time on particle coagulation and removal,
2. *Test the Efficiency and Variability of Particle Removal in Selected BMPs in the Field*: Determine the particle-size distribution of runoff entering and exiting existing BMPs (or those under development) to characterize removal efficiencies and

to determine conditions that degrade removal. The dynamics of the particle wash-off process during storm events also would be examined as degradation in BMP performance may be related to fine particle breakthrough that will be detected by this study.

3. *Test Measures to Improve Particle Retention and BMP Performance*: Based on the results of the first two tasks, propose and test corrective actions to improve BMP performance. A critical result of the year-three activities would be to develop correlations between particle concentrations and dissolved contaminant concentrations, which may be useful in replacing chemical analyses by particle-size measurements in most (or possibly all) applications.
4. *Identify Modifications to Basic Treatment Systems to Improve Their Dissolved Metals Removal Capability*: Undertake a thorough literature review of available treatment technologies that could be applied to highway runoff for reducing metals levels not associated with particulates. Options to be examined should include, but not be limited to, carbonate/hydroxide/sulfide precipitation, stone/gravel biofilters, compost or humic filters, and engineered fabric filters. This task would result in a list of recommended research projects that focus on dissolved metals removal.

Estimated Project Budget: $250,000 to $350,000; 36 months to complete.

Implications and Impacts of TMDLs on DOTs and Guidance in Responding

The Federal Clean Water Act requires that TMDLs for pollutants of concern are established for Section 303(d)-listed impaired water bodies. Once TMDLs are established, waste load allocations (WLAs), or maximum allowable pollutant loads, from each identified source are set by the state regulatory agency responsible for issuing NPDES permits. State DOTs are increasingly being subject to the regulatory requirements of NPDES permits, including WLAs, for stormwater discharged from their facilities. The issue of TMDLs is a concern to DOTs because meeting WLAs and numeric effluent limits may increase significantly the cost of stormwater management. Some DOTs are ill-prepared to make the paradigm shift that the implementation of TMDLs requires. In order to comply with newly established NPDES regulatory requirements, DOT stormwater practitioners need to be able to accurately identify pollutant sources, estimate loads, and know of methods to reduce those loads if necessary. DOTs also must be aware fully of the legal and economic implications of TMDL development, implementation, and enforcement. There appears to be a need to provide guidance specific to DOTs on the effect that TMDLs will have on DOT stormwater management activities. To this end, the following research objectives and associated tasks have been developed for consideration. See section 1.1.1 for an additional discussion of TMDLs. The research gaps addressed under this research statement are listed under the NCHRP Panel Recommended Research Needs section of Table 4-1.

Research Objectives

- Identification and evaluation of the impact of TMDLs on DOTs;
- Development of guidance on new and improved BMP technologies for runoff management in the context of TMDLs;
- Provision of guidance on runoff and BMP monitoring to facilitate compliance with TMDLs;
- Development of recommendations on the types of effluent limits most appropriate and feasible for DOTs in complying with TMDLs; and

- Identifications and evaluation of suitable tools for runoff and BMP modeling for prediction of pollutant loads and BMP performance in relation to TMDLs.

Tasks

1. *Literature and Practitioner Survey to Determine the State of the Practice and to Identify Available Sources of Information*: Distribute survey forms to and conduct phone interviews with practitioners to document the needs and challenges facing practitioners with regard to TMDL compliance. The literature review will provide insights into technologies and management strategies as well as ongoing research on TMDLs.
2. *Evaluate the Use of BMPs and New Management Strategies as a Means of Meeting TMDLs*: Evaluate BMPs in the context of TMDL compliance. The result of this phase will be a short list of BMPs and target pollutants typically regulated by DOT NPDES permits and strategies for compliance.
3. *Synthesize Guidance for Runoff and BMP Monitoring Necessary for Demonstrating Compliance with TMDL*: Evaluate monitoring methods and provide standardized monitoring recommendations that can be used to demonstrate TMDL compliance.
4. *Develop Guidance for Pollutant-Load Modeling and Estimation Techniques for TMDLs*: Examine pollutant-load modeling and estimation techniques and provide analytical methods to be used as planning tools. Examine and test alternative methods of demonstrating compliance with TMDLs. Emphasize production of reliable, reproducible, and defensible modeling results.
5. *Develop Guidance or Tools, or Both, for Cost Analysis of TMDL Implementation*: Examine methodologies for estimating the costs that may be incurred through TMDL implementation and compliance. Results of the DOT stormwater practitioner survey likely would be a major component in this research.
6. *Develop a Synthesis of Guidance Methods for TMDL Determination and Implementation*: Combine the results of the first four tasks into a guidance document that can be used by practitioners for TMDL and WLA determination in addition to stormwater runoff and BMP modeling and monitoring.

Estimated Project Budget: $120,000 to $150,000; 10–12 months to complete.

CHAPTER 1

INTRODUCTION

1.1. REGULATORY ENVIRONMENT FOR STATE DEPARTMENTS OF TRANSPORTATION

Runoff water quality from highways and developed land is an environmental concern for federal, state, and local agencies involved in the planning, design, construction, and maintenance of transportation facilities. As conveyances of urban stormwater runoff, state department of transportation (DOT) facilities carry suspended metals, sediments, algae-promoting nutrients (nitrogen and phosphorus), floatable trash, used motor oil, raw sewage, pesticides, and other toxic contaminants into streams, rivers, lakes, and estuaries across the United States (64 CFR 68,722,4,7, Dec. 8, 1999). In 1985, 75% of the states surveyed cited urban stormwater runoff as a major cause of waterbody impairment, and 40% reported construction site runoff as a major cause of impairment (64 CFR 68,726).

Congress enacted the Clean Water Act (CWA) in 1948 to "restore and maintain the chemical, physical, and biological integrity of the Nation's waters" [33 USC § 1251(a)] (originally codified as the Federal Water Pollution Control Act, 62 Stat 1155). The CWA prohibits the discharge of pollutants from a "point source" (any discernible, confined, and discrete conveyance) into the waters of the United States without a permit issued under the terms of the National Pollutant Discharge Elimination System (NPDES) [33 USC § 1311(a), § 1342]. An NPDES permit requires dischargers to comply with technology-based pollution limitations (generally according to the "best available technology [BAT] economically achievable") [33 USC § 1311(b)(2)(A)].

Storm sewers are established point sources subject to NPDES permitting requirements [*Natural Res. Def. Council v. Costle*, 568 F.2d 1369, 1379 (DC Cir 1977)]. In 1987, to better regulate pollution conveyed by stormwater runoff, Congress enacted CWA § 402(p), 33 USC § 1342(p), *Municipal and Industrial Stormwater Discharges*. Sections 402(p)(2) and 402(p)(3) mandate NPDES permits for stormwater discharges "associated with industrial activity," discharges from large and medium-sized municipal storm sewer systems, and other activities, including construction sites. In CWA § 402(p), Congress also directed a second stage of stormwater regulation by ordering the Environmental Protection Agency (EPA) to identify and address sources of pollution not covered by the Phase I Rule and to establish procedures and methods to control them as "necessary to mitigate impacts on water quality" [33 USC § 1342(p)(5)].

For municipal-type stormwater systems, the technology-based requirements in the federal stormwater regulations call for the implementation of controls [procedures and best management practices (BMPs)] to reduce the discharge of pollutants to the maximum extent practicable (MEP). In September 2003, the Ninth Circuit Court of Appeals amended an

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The National Environmental Policy Act and the Clean Water Act of 1972, as amended. These acts hold federal decision makers accountable for activities having the potential to impact features of the natural environment—in particular, water quality (Bank et al., 1995).

The National Pollutant Discharge Elimination System. This program requires discharge permits for industrial and municipal (point source) effluents containing pollutants. Effluent regulations include characterization of stormwater runoff, possibly originating directly from highways and the construction and maintenance of the highway systems.

The Nonpoint Source Management Programs, Title 3, Section 319. This program also promotes the implementation of best management practices regarding highway runoff, as a potential nonpoint source pollutant of surface and ground water.

The Department of Transportation National Transportation Policy, the Federal Highway Administration Environmental Policy Statement, and the Intermodal Surface Transportation Efficiency Act. These policies and acts specify increased environmental responsibilities for policies and programs developed by federal and state transportation agencies.

The Coastal Zone Reauthorization Amendment. This amendment regulates highway runoff water quality and its environmental impacts in coastal areas.

Other legislation—such as **the Safe Drinking Water Act, the Endangered Species Act, the Resource Conservation and Recovery Act,** and **the National Wild and Scenic Rivers Act**—also contains provisions that may pertain to the water quality of highway runoff.

earlier decision concerning the Phase II program and reconfirmed that the CWA requires that municipal stormwater dischargers (including state transportation agencies) have to remove pollutants to the MEP. Attainment of water quality standards is not required but may be added at the discretion of the state. For construction projects that disturb areas of one acre or more, technology-based requirements include the use of BAT and best conventional pollutant control technology (BCT).

DOTs meet these obligations through the implementation of control programs and technologies—BMPs. As used in this document, the term BMP refers to operational activities or physical controls applied to stormwater and other runoff to reduce pollution. BMP refers to structural and nonstructural controls that have direct effects on the release, transport, or discharge of pollutants.

1.1.1. Total Maximum Daily Loads for Impaired Waters

The CWA, amendments, and associated regulations require that states assess the condition of surface waters within their jurisdictions to determine whether they are impaired. Where water quality is not adequate to sustain beneficial uses, surface waters must be listed as required by Section 303(d) of the CWA. For specific constituents, a total maximum daily load (TMDL) must be developed for each of the listed segments for the constituents that are contributing to the impairment of beneficial uses. The TMDL is the maximum pollutant load that can be assimilated by the waterbody without impairing the water's beneficial use.

The task of properly determining TMDLs for constituents is staggering; more than 20,000 such impaired waters have been identified nationally, comprising more than 300,000 miles of rivers and streams and more than 5 million acres of lakes. Once a TMDL is developed for a surface waterbody, a waste load allocation (WLA) must be developed. The WLA specifies how much of a given constituent can be contributed by each discharge and discharger, including highway agencies, to the waterbody. As TMDLs and WLAs are developed for the impaired segments, dischargers, including highway agencies, have to implement BMPs to reduce their contribution of a constituent from transportation land uses and associated facilities.

1.1.2. Other Laws and Regulations Imposing Water Quality Requirements on Departments of Transportation

In addition to NPDES and TMDL requirements, highway runoff management techniques must be consistent with the objectives of nonpoint source control programs under Section 319 of the CWA and state coastal nonpoint pollution control plans developed under Section 6217 of the Coastal Zone Act Reauthorization Amendments.

Other legislation such as the Safe Drinking Water Act, the Endangered Species Act (ESA), the Resource Conservation and Recovery Act, and the National Wild and Scenic Rivers Act also contain provisions that may pertain to the water quality of highway runoff. The water quality requirements for species listed as threatened or endangered under ESA have presented particular challenges for DOTs. Often state and EPA requirements for attaining water quality standards may not replicate necessarily what the National Oceanic and Atmospheric Administration's (NOAA's) National Marine Fisheries thinks is needed or what the U.S. Fish and Wildlife Service deems appropriate.

On a state-by-state basis, DOTs face a wide range of water quality control requirements with which they must comply. Many of these requirements are based on previous research, not conducted necessarily by those same DOTs. In some cases a DOT's requirements have been based on the requirements of other DOTs or on a limited amount of supporting data. These requirements then become the basis for the guidelines and manuals. Research results indicate that 60% of state DOTs have developed highway runoff manuals for designers. Many DOTs also have developed training for construction and maintenance staff. However, much research remains to be done in order to implement the most effective and efficient water quality programs and measures possible and to improve continuously runoff water quality.

1.2. SUMMARY OF GKY STUDY AND GAPS

In March 1998, the AASHTO Standing Committee on Research (SCOR) met to review and select projects for the FY1999 NCHRP program. SCOR noted that there were 10 different problem statements addressing the impacts and management of highway runoff. SCOR directed an NCHRP panel to convene a panel of experts to investigate the existing state of practice; identify research issues, gaps, and needs; undertake research on high-priority topics; and recommend projects for future funding.

The first effort initiated by the panel was Project 25-20. The resulting report (from GKY and Associates, Inc.), *Management of Runoff from Surface Transportation Facilities: Synthesis and Research Plan*, was published in March 2001. The GKY report was accompanied by the Water Quality Knowledge Database (CD-based), which includes 14 full-length documents from the existing literature. Also on the CD is a limited annotated bibliography of 127 items listed by author; however, the annotations generally consist of only an abstract, which briefly reviews what was studied but only occasionally includes research results. GKY listed 916 unannotated references on the CD.

GKY asked a variety of transportation practitioners each to specify three areas in which they thought research was needed. GKY then categorized those areas according to the "a priori ranking of panel issues" or "high-likelihood priority areas" given to them by the NCHRP 25-20 oversight panel. Subsequently, GKY produced a research needs statement for each of the 11 areas (approximately one per topic area identified in advance by the panel).

The following subsections summarize briefly the contents of each chapter in GKY's report.

1.2.1. GKY Report, Chapter 2 Summary: High-Likelihood Research Need Topic Areas

Chapter 2 summarizes and ranks topic areas of highway runoff research gaps and needs identified a priori by the NCHRP panel. The panel's high-ranking topic areas of interest included receiving waters assessment, BMPs, and information systems and technology exchange. Medium-ranked topic areas of interest included systems planning, constraints and regulations, and stormwater hydrology and hydraulics related to water quality. Low-ranking topic areas of interest included constituents and loadings and groundwater.

1.2.2. GKY Report, Chapter 3 Summary: Information Technology

Chapter 3 describes the following: how the information compiled on the CD is organized and how it can be searched, a listing of the 14 primary references included on the CD, sources of information, an evaluation of the compiled information, and identification of the gaps in the literature review. The evaluation of the compiled information is organized according to three primary topic categories related to highway runoff: loadings, intervention, and impacts.

Under the loadings category, highway runoff pollutant sources are identified, and several studies are referenced. Three primary subcategories are discussed briefly: the influence of average daily traffic on pollutant loadings, land use-based pollutant loads characterization, and the correlation of suspended sediment with nutrients and metals. Although the topic of highway runoff water quality characterization has been well studied, several more subtopics either were mentioned only briefly or were overlooked entirely in the GKY study. Those subtopics include, but are not limited to, first flush characterization, highway construction and maintenance, atmospheric deposition, cold weather studies, and fate and transport of highway pollutants.

Under the intervention category, stormwater BMPs are discussed according to BMP type: conventional structural BMPs, space-limited BMPs, and nonstructural BMPs and related considerations. General BMP design is discussed and a few design manuals are referenced; however, specific information on individual BMP types is not included. Furthermore, despite the breadth of the category of BMP performance, only one BMP performance study is included in the document. This is considered the product's largest shortcoming. Hundreds of studies evaluate BMP performance, but since there are so many different BMP types and configurations, this is an area of study that is still developing, particularly in relation to highway runoff and space-limited BMP designs.

The GKY report provides the most information under the "impacts to receiving waters category" (more than it provides in the loadings and intervention categories). The report presents an adequate discussion of the steps involved in assessing receiving water impacts: obtaining and reviewing existing data, the use of water quality and ecological impact models, conducting bioassessments, and toxicity testing. Although these are important areas of study, other topics related to receiving water impacts were not discussed adequately, including channel stability (e.g., sedimentation and scour), wetland mitigation, groundwater quality impacts, mixing zone dynamics, bioaccumulation and bioavailability, and in-stream BMPs.

1.2.3. GKY Report, Chapter 4 Summary: Practitioner Survey

Chapter 4 describes the results and conclusions of a survey of transportation practitioners. The GKY report indicated that the practitioners surveyed had little agreement on where research gaps and needs are, but the report provided a ranking of potential research topic areas in the following order of perceived priority: water quality receiving water impacts, deicing, data collection and information transfer, habitat assessment and ecological issues, bridge BMPs, BMP site constraints, nonstructural BMPs, and BMP effectiveness and performance. In addition, the report noted that practitioners expressed an overall need for information, with an emphasis on erosion and sediment control, to assist in the selection and design of appropriate BMPs. GKY judged the lack of information exchange as the most likely cause of the discrepancy in practitioners' opinions on research gaps and needs, as a number of DOTs made suggestions for improved information transfer such as an Internet-based bibliographic database.

1.2.4. GKY Report, Chapter 5 Summary: Analysis of Information

GKY ranks the following as the highest priority research topics: receiving water quality assessment, space-limited BMPs, information systems, constituents and loads, biological/ecological impacts, groundwater, habitat quality, BMP design, systems planning, BMP maintenance, and BMP selection.

1.2.5. GKY Report, Chapter 6 Summary: Research Program

Based on the ranked research topic areas identified in Chapter 5, Chapter 6 presented a 12-project, 5-year research program organized according to ranked problem statements. Each problem statement includes the research topic and needs, the project objectives, estimated budget and timeline, and the urgency and payoff potential of the project. The project titles and associated problem statements are listed in Table 1-1.

1.2.6. GKY Report, Overview and Conclusions

The GKY study identifies primary highway runoff management research topics in need of additional study. However, the context is broad and describes inadequately the research topics identified. For instance, the research topic of BMP effectiveness and performance is extensive and may involve several levels of investigation. Furthermore, the GKY study defines neither BMP effectiveness nor performance even though there are several different definitions currently in use (Strecker et al., 1999). The document focuses on ecological and biological impacts and provides some valuable references and identifies some important topic areas. With regard to the broader range of highway runoff management research and research needs, the GKY findings require expansion in the areas of receiving water impact assessment, highway runoff characterization, BMP evaluation, systems planning, and data collection and analysis. NCHRP 25-20(02) attempts to identify the gaps in the GKY study.

Based in part on the recommendations of the GKY study, the panel initiated Project 25-20(01): Evaluation of Best Management Practices for Highway Runoff Control. The project was contracted to Oregon State University and has been combined with a study on low-impact development; the final report is scheduled for completion in the winter of 2004. The research will evaluate the basic scientific and technical criteria that can be used for the quantitative assessment of wet-weather flow control alternatives (often referred to as BMPs) for highways and other highway-related facilities and will apply the results of the evaluation to facilitate effective implementation of these controls. To avoid duplication of project 25-20(01), the current project, 25-20(02) limits the category of evaluation of best management control practices to include only a summarization of related topics, gaps, and research needs found during the literature review. A detailed assessment of BMP unit processes and treatment performance in relation to BMP design will be provided in the NCHRP 25-20(01) report.

The GKY report includes an overview of potential funding sources. Identification of funding sources is not part of the scope of NCHRP 25-20(02), but related information on potential funding sources is included in the original report.

1.3. GOALS AND OBJECTIVES OF NCHRP 25-20(02)

NCHRP 25-20(02) will identify and describe research projects that will address priority needs in the area of highway runoff management and control. The assessments described in this document are based on DOT research priorities and a broader search of the available data, studies, and DOT research in progress than was available in the initial 25-20(01) research. Final research statements will be presented in the final report, subsequent to panel approval of the research team's assessment.

1.4. RESEARCH METHODOLOGY

This comprehensive highway runoff investigation includes a review of readily available highway runoff literature and state highway transportation agencies' unpublished literature, current research efforts, and research priorities that could be acquired through contact with all 50 states. A discussion follows on the methodology used for each portion of the research for this project.

1.4.1. Contact with Water Quality Professionals

Realizing that information on stormwater quality research and needs may occur in different and often multiple parts of a state transportation agency, researchers contacted state transportation agencies and divisions within these agencies to ascertain current practices, problems and issues, and research related to stormwater quality. Research directors identified on AASHTO's list of members for SCOR were contacted by phone and e-mail to locate existing research and research in progress. Lead stormwater professionals in each agency were asked about research in progress and research priorities.

The practitioner contact effort for 25-20(02) started with a long list of research needs areas, including questions raised in TRB Committee A2AO3, AASHTO's Natural Resources Subcommittee, and through the Standing Committee on the Environment's Environmental Technical Assistance Program. Questions also were identified by calling leading state DOTs regarding water quality issues (California, Maryland, and Washington State). The list of potential questions was reviewed by practitioners and researchers in the aforementioned states, by the NCHRP 25-20 Chair, and by the full team of consultants involved in this effort. The resulting suggested revisions and additional questions were incorporated into the list of priority research areas ranked by DOTs.

All 50 state DOTs were contacted successfully to provide their level of prioritization of the final list of 45 research areas. Each state DOT provided a low-medium-high ranking of research interest to attain a finer gradation of understanding of DOT research needs than indicated by the GKY study. In addition, to ensure that the full range of potential research

TABLE 1-1 Summary of potential research projects identified by GKY and Associates

No.	Project Title	Problem Statement
1	Identification and Development of Regional Aquatic Biological Indicators to Assess Impacts of Highway Runoff	Biological indicators can be used to assess receiving waters impacts of highway runoff and to evaluate the effectiveness of stormwater best management practices (BMPs). Practitioners need guidance on the appropriate use and interpretation of cost-effective methods of regional biological indicators.
2	Research Methods for Assessing the Toxicity of Highway Runoff	Several toxicity testing methods are available to assess the acute and chronic toxicity of water quality samples. However, results are highly variable depending on the method used, and each method has a limitation on its applicability. Highway practitioners need toxicity testing protocols to address specifically the runoff entering different receiving water ecosystems.
3	Water Quality Management Information System	Highway practitioners rely on published literature for addressing highway runoff management and control. Practitioners need a readily accessible, up-to-date information system for searching and reviewing existing studies and reports, as well as for adding new information as it becomes available.
4	Isolation of Pollutants in Transportation Runoff	Highway runoff has been recognized as a potential contributor to water resources impairment, but the specific water quality parameters causing impairment are not well known. Practitioners need access to statistically significant runoff quality data from highway facilities for the development of cost-effective monitoring programs.
5	Causal Analysis of Pollutants in Transportation Runoff	In order to manage effectively the quality of highway runoff at the source, practitioners need to understand the factors that influence the chemical characteristics of the highway runoff, such as average daily traffic, climate, rainfall chemistry, construction materials, and more.
6	Integration of Multidisciplinary Methods for Evaluation of Transportation Runoff Impacts to Aquatic Ecosystems	The goals of highway runoff quantity management and runoff quality management often conflict. Practitioners need methods and alternatives for dealing with both issues of highway runoff management.
7	Expert System for Transportation BMPs	Practitioners need readily available access to BMPs information and a means of quickly applying applicable portions of the information to site-specific situations.
8	Design Criteria for Bridge BMPs	NCHRP Project 25-13 is investigating the impacts of bridge runoff on receiving waters. When the project is complete, practitioners will need design guidance on BMPs for bridge runoff.
9	Heavy Metals Management Options	Heavy metals are known highway runoff pollutants that tend to migrate from the roadway to receiving streams. Practitioners need effective ways to confine heavy metals to the rights-of-way.
10	Demonstration of Ultra-Urban BMPs	Practitioners need access to case studies that evaluate the performance of ultra-urban BMPs, so that applicable and effective space-limited BMPs can be selected.
11	Hydraulics and Hydrology of BMP Retrofitting	Practitioners need practical guidance for retrofitting existing flood control and drainage structures to maximize water quality benefits.
12	Enhanced Expert System for Transportation BMPs	Building upon the system developed under No. 7, an enhanced expert system would include additional information and results made available since the system's initial deployment.

interests was covered, DOTs were asked to describe agency research interests in an open-ended manner for design, construction, maintenance, and receiving water assessment. This intensive interview and survey effort was designed to produce a current and accurate basis for identifying present gaps and research needs. The following DOT professionals participated in identifying and ranking research needs:

- Environmental, stormwater, and civil engineers;
- Research engineers;
- Senior hydraulics engineers and heads of hydraulic divisions;
- Chiefs of design;
- Directors of location and environment;
- Managers of roadside development sections;
- Agronomists, geologists, and landscape architects;
- Environmental program managers and other section chiefs;
- Wetlands unit supervisors;
- Bioengineering managers (for Section 401 and 404 concerns);
- Natural resources specialists and unit managers;
- Water quality and resources specialists; and
- Directors of university stormwater research centers who, on referral, worked closely with the DOTs.

The survey, included as Appendix A in this report, was conducted by phone and on line. All information was entered into an online system, so that results may be viewed easily (go to www.vennerconsulting.com/stormwater and click "View Results"). In an effort to minimize inconvenience to DOT participants and to rationalize the broad scope of information being collected, two state-initiated water-quality surveys were combined. Researchers pooled the existing data, voluntarily assisted the Virginia Transportation Research Center (VTRC) in completing the survey effort they had started, and focused on reaching all 50 state DOTs for participation in sections 2 through 8, which provide information most directly pertinent to NCHRP 25-20(02).

At the same time they were completing previously started surveys, researchers solicited information on the whole set of questions and presented the current state of knowledge about practice in each state for completion and updating as necessary or desired by the DOT. A large number of states contributed information, facilitating related research efforts at VTRC and providing a basis for further research and information sharing about water quality best practices. DOT research directors were contacted separately to report on the water quality research performed or funded by their state DOT and to provide electronic copies or online links if available. In many cases researchers were referred to the water quality practitioners who were the focus of the survey effort.

This wide level of involvement produced input about existing research programs and about state DOTs' research preferences. In conjunction with the literature review below, the input has provided a solid foundation for identified research needs.

1.4.2. Review of Literature and Current Research

Information on current practices, problems and issues, and research related to highway runoff management was reviewed to identify relevant work and where the work is occurring. Data sources included, but were not limited to, the following:

- 2001 GKY report (materials related to the survey effort were not available from GKY and Associates);
- ASCE/EPA BMP Database and other ASCE publications;
- FHWA studies and publications;
- EPA publications;
- Water Environment Research Foundation and American Water Works Research Foundation;
- Environmental research in progress online database at the Center for Transportation and the Environment;
- TRIS database at TRB;
- TRB A2A03 Hydrology, Hydraulics, and Water Quality Committee;
- University water research centers online publications; and
- Recent, current, and planned research by state DOTs (internally conducted research or research conducted in conjunction with universities and other contractors).

A database was created using the above sources to hold the available citations as well as to enable the categorization of the publications. Researchers identified and obtained more than 2,500 annotated bibliographies related to highway runoff management. More than 900 of the most relevant citations were categorized on the basis of various combinations of key word searches. The categorization scheme in the database was designed to reflect closely the major categories of this document. Table 1-2 shows a breakdown of the number of documents under each primary category.

In addition to the primary categories, each citation is categorized further with objective statements and by document type. The database was created with an initial set of objective statements that represented various areas of interest and possible knowledge gaps on the subject of highway runoff management. The ability to extend the initial set of the objects was built into the database enabling researchers to add objective statements as the need arose during the literature review process. The number of unique objective goals is more than 300 for the categorized documents. More than 400 of the categorized documents were assigned more than one objective. Researchers further grouped the research objectives under each primary category into groups such as general objectives, water quality objectives, hydrologic/hydraulic objectives, and in some cases, economic objectives and public perception objectives. In addition to categorizing object statements,

TABLE 1-2 Database document summary by primary categorization

Primary Category	Number of Documents
Evaluation of Stormwater Control Facilities and Programs	332
Watershed-Based Approaches	73
Highway Runoff Characterization and Assessment	232
Receiving Waters Impact Assessment	80
Design of Stormwater Control Facilities and Programs	108
Other	59
TOTAL	**884**

researchers reviewed the BMP types and pollutants studied and discussed in the documents and extracted study locations, study goals, and monitoring information where available. The BMP names were selected from a list of more than 100 practices, some of which may refer to similar BMPs. Currently, the database contains links to more than 300 full-text online documents. The database was used mainly as a tool to expedite the literature review process; however, with additional refinement, an online version of the database could become a valuable information exchange tool for DOTs, consultants, and researchers.

1.4.3. Delivery of Findings

The knowledge gleaned from the survey of state DOTs and the literature review was compiled to identify and prioritize research needs and gaps in highway runoff management and receiving waters impacts. For the most part, researchers found that the gaps and needs identified during the literature review agreed with the gaps and needs identified by the survey of state DOTs. However, a few research areas not identified during the literature search were identified by state DOTs and vice versa. This paired approach arguably offers a more comprehensive compilation of research needs than would have resulted if the review of literature were conducted first and the survey second, as the research team would have recommended in a more lengthy research period.

The findings of the DOT survey are presented primarily as tables of ranked and sorted research priorities and associated text. The findings of the literature review are presented in summary paragraphs identifying potential research gaps and needs for each subtopic area. The findings of both investigations are compiled and summarized in a final narrative and matrix of ranked and sorted research topic areas.

1.4.4. Ranking of Research Needs

The three separate rankings were used to prioritize (on a scale from 1 to 5) the research needs shown in Table 5-1. The DOT rankings are based on the results of the practitioner surveys, which include both the average score assigned to each topic area and the self-identified research gaps and needs. Subject areas that were assigned lower priorities by DOTs were assigned lower rankings. The literature review rankings are based on the availability of documents on the subject matter and the amount of research that has been done or is being done on the subject as well as on the recommended areas of additional research often included in the conclusion of reported research. Using a rating scale from 1 to 5, well-covered subject areas are assigned a lower ranking and less covered subject areas are assigned a higher ranking. The third ranking—the ranking from the researchers—is based on a combination of the literature review ranking, the DOT ranking, and professional judgment of the research gaps and needs encountered in the extensive work in the field of stormwater management. The third ranking also is based on a scale of 1 to 5, with 1 being assigned to lower priority research needs and 5 being assigned to higher priority research needs.

1.4.5. Document Organization

The document begins with an overview of the 45 research priority areas ranked by DOT water quality practitioners and an overview of further (often overlapping) research topics recommended by DOTs (in their own words, in various categories). This section is followed by the literature review, which attempts to summarize key studies and knowledge in each area, and in some cases, provides examples for use in developing the prioritized research needs. The literature review is not an exhaustive discussion of the details of all related highway runoff research work that has been completed.

Due to the nature of the primary research categories, an individual study may include components of multiple categories or subcategories, making these studies difficult to classify. Effort was made to cross-reference studies that span more than one category or subcategory for the maximum benefit to the reader and for a more complete assessment of research gaps and needs. Study classification is partially subjective and dependent upon the depth of information included in the reviewed literature, which in many cases is limited to only an abstract. Consequently, it is possible that the reader may not completely agree with the inclusion of some research topics within a chosen research category. Therefore, in addition to cross-referencing studies, effort also was made to describe the rationale for including some studies under a particular research category for those studies where classification was not obvious.

This report includes a table of the identified research needs with explanations on how the needs were ranked by the state DOTs as well as the researchers' assessment of the needs based on the literature. Researchers then gave an overall ranking to a research need and identified the top priorities. Research statements developed by the team are included in the Executive Summary.

Following this introductory section, the main section headings are DOT Research Preferences, Review of Published Literature and Potential Research Needs, and Summary of Identified Research Gaps and Needs. The review of published literature has been organized according to the primary research categories identified in Table 1-2.

CHAPTER 2

DEPARTMENT OF TRANSPORTATION RESEARCH PREFERENCES

All 50 state departments of transportation (DOTs) ranked 45 research priority areas identified by lead DOTs and the research team and added information regarding any further preferences with regard to research needs; see Table 2-1. All items on the ranked list had been identified as a high-priority research area by at least one DOT, and in many cases the phrasing for a particular problem statement originated with a DOT.

Each area was weighted in order to identify those with the highest positive and the lowest negative preferences. To develop an overall ranking of research preferences, including the priorities of all 50 state DOTs, and to produce sufficient separation of results (minimization of duplicate rankings or ties), researchers assigned the following weightings to reported rankings:

- A weight of 4 for high-priority research,
- A weight of 2 for medium-priority research, and
- A negative weight (-1) for low-priority research.

When multiple practitioners from a state DOT participated in suggesting rankings, researchers used the highest ranking assigned to each category, ensuring each research area the best opportunity at being ranked highly and to fully represent the states most avid research interests and priorities. In other words, if one of the state's leading stormwater practitioners thought it was a high-priority research area for that state, it was listed as high priority. The number of high-priority research areas a state could include was not limited.

It should be noted that even low-ranked research priority areas were still high-priority research areas for a small number of DOTs. In addition, the DOTs indicating interest in research topics had a wide geographic dispersal in all cases, without obvious geographic trends. While northern and mountainous states had interests in deicing agent selection criteria (as might be expected), even states with temperate climates such as Arizona and Hawaii expressed moderate interest. Interest in traction sand removal was the most limited to a particular region of the United States, in this case the northern states, though interest extended as far south as Virginia. States in both arid and moist climates placed a priority on mosquito control. Alaska, Hawaii, and Washington were interested in arid region erosion control as were states with much larger arid areas. Interest in small footprint BMPs was a high priority in relatively low-density states as well as high-density ones. Conversely, opportunities for roadside dispersal were of interest in the most densely populated states as well as the more rural ones. Nevertheless, state DOTs may still be interested in identifying fellow agencies with strong interests in seeing research performed in given areas. State DOTs that placed a high or medium priority on research topics in the survey are identified in Table A-2 in Appendix A. For readers' convenience, a summary table of rankings by combined preference for all research priorities is included as Table A-1.

2.1. TOP-RANKED AREAS OF NEEDED RESEARCH: STORMWATER CONTROL FACILITIES AND PROGRAMS

The survey yielded some interesting and perhaps surprising results given the panel and GKY's previous emphasis on research pertaining to receiving water impacts. DOTs expressed the strongest needs and interests in the area of stormwater control facility cost and performance.

Out of a total of 45 research areas, all 6 of the top-ranked priority areas addressed evaluation of stormwater control facilities and programs; see Table 2-2.

- DOTs ranked research on the operations and maintenance costs of BMPs as their highest interest area—only four states ranked it a low-priority research area. Research on operations and maintenance costs was ranked as a high priority by 75% of the DOTs. Evaluation of construction costs of BMPs was ranked 5th and the need for development of a methodology to quantify BMP benefits and costs was ranked 4th.
- Some of the other strongest interest areas of the DOTs relate to BMP effectiveness, including evaluation of BMP efficiencies, technical feasibility, and new erosion-control technology, which ranked 2nd, 3rd, and 6th. Among new technology evaluation, development of small footprint BMPs was a particular interest area and was ranked 9th.

Each of the research areas discussed above was ranked as a high or medium priority by at least 80% (40 out of 50) of the state DOTs.

TABLE 2-1 Research areas pertaining to evaluation of stormwater control facilities and programs ranked in priority by state DOTs

RANK	Research Areas Pertaining to Evaluation of Stormwater Control Facilities and Programs	Number of State DOTs Ranking Each Research Area			SCORE
		High Priority (3)	Mid-level Priority (2)	Low Priority (1)	
	WEIGHT	**4**	**2**	**-1**	
1	Operations and maintenance costs of BMPs	36	10	4	160
2	Construction BMPs efficiencies	37	8	5	159
3	Technical feasibility of BMPs	30	14	6	142
4	Methodology to quantify BMPs benefits and costs	27	17	6	136
5	Construction costs of BMPs	29	12	9	131
6	New erosion control technology evaluation	28	13	9	129
9	Development of small footprint BMPs	22	18	10	114
10	Performance of nonvegetative permanent soil stabilizers for reducing erosion and potential impacts of products on stormwater quality	23	15	11	111
11	Applicability and effectiveness of particular low impact design (LID) methods in linear corridors/for transportation	19	19	9	105
12	Temporary nonvegetative soil stabilization evaluation	23	13	14	104
15	Performance of BMPs retrofits/effectiveness (removing constituents of concerns, hydraulic performance, export of elements to receiving waters)	21	14	15	97
17	Vegetation establishment	20	15	15	95
18	BMPs benefits and constraints in highly urbanized corridors	17	19	12	94
19	Selection of treatment BMPs and documentation of process	18	18	14	94
20	Detention basin design optimization	16	20	14	90
21	Effectiveness of combination of sedimentation, filtration, and chemical addition for stormwater BMPs construction and retrofit projects	17	18	15	89
22	Guidance for seed mixes and effective establishment and maintenance of erosion control vegetation for short-term first growth and long-term establishment	20	13	17	89
29	Soil evaluation process for slope vegetation	13	20	17	75
30	Bypass detention basin design and effectiveness	13	19	17	73
31	LID modeling and design, so that end-of-pipe control systems can be sized accurately	13	18	16	72
34	Design and maintenance of BMPs to reduce mosquito and other vermin populations	15	12	23	61
36	Gross solid removal device design and performance	12	15	23	55
38	Practical and effective ways to improve dissolved metal removal in current systems	9	19	22	52
39	Traction and removal BMPs for snow areas	12	12	26	46
40	Toxicity controls	7	20	22	46
43	Physics and chemistry of BMPs design	5	15	29	21
44	Arid region erosion control	10	5	34	16
45	Viral pathogen indicators and treatment	4	10	34	2

A separately identified category, performance of BMP retrofits/effectiveness (removing constituents of concerns, hydraulic performance, and export of elements to receiving waters), was ranked 15th by state DOT water quality professionals and was still in the top one-third of research priority areas overall. Considerably more research has occurred in this field, though gaps remain. NCHRP 25-20(01), to be completed in January 2005, will involve collecting and evaluating information on BMP effectiveness and unit treatment process.

Other research areas ranked in the top one-half of identified research areas, in order of preference, included

- Performance of nonvegetative permanent soil stabilizers for reducing erosion and potential impacts of products on stormwater quality;
- Applicability and effectiveness of particular low impact development (LID) design methods in linear corridors and for transportation;
- Temporary nonvegetative soil stabilization evaluation;

TABLE 2-2 Alternative mitigation and stormwater management flexibility practices in use at state DOTs

Alternative Mitigation and Stormwater Management Flexibility	Number of States Using	Number of States Not Using
Onsite mitigation	40	10
Offsite (within sub-basin)	26	24
Offsite (within larger watershed)	17	33
Alternative mitigation	12	38
Stormwater banking	7	43
Cross-category trading	3	47

- Valid monitoring methods;
- Demonstration of the costs and benefits of alternative, offsite, or watershed-based stormwater mitigation;
- Best methods for improving stream ecology through water quality BMPs—alternatives to regulating runoff in urban areas;
- Vegetation establishment;
- BMP benefits and constraints in highly urbanized corridors;
- Selection of treatment BMPs and documentation of process;
- Detention basin design optimization;
- Effectiveness of combination of sedimentation, filtration, and chemical addition for stormwater BMP construction and retrofit projects;
- Guidance for seed mixes and effective establishment and maintenance of erosion control vegetation for short-term first growth and long-term establishment;
- Infiltration guidance to prevent groundwater contamination;
- Design and maintenance of BMPs to reduce conflicts with endangered and threatened species;
- Soil evaluation processes for slope vegetation;
- LID modeling and design so that end-of-pipe control systems can be sized accurately; and
- Compliance with numeric water-quality standards.

Ranked lower in overall priority but still of medium importance to many respondents were "methodologies to determine where flow control of runoff volumes and high-flow durations are appropriate to prevent stream bank erosion in ultra-urban areas."

2.2. WATERSHED APPROACHES

A watershed approach offers the opportunity to plan comprehensively and offer solutions that promote sustainable and economically productive watersheds. The approach often seeks to ensure the integration of transportation planning and project delivery into statewide watershed recovery efforts and the direction of mitigation dollars toward high-priority watershed recovery efforts in a basin.

Of the topics pertaining to a watershed approach, DOTs were interested mostly in a runoff characterization question: what was the contribution of highway runoff to watershed loadings. This was a high-priority research area for more than 50% of all DOTs, and a mid-level priority for another 25%. More than 80% of the DOTs also had a medium- or high-level interest in demonstrating the costs and benefits of alternative, offsite, and watershed-based stormwater mitigation. Methods for improving watershed stream ecology through alternative and perhaps offsite water quality BMPs were of interest to 72% of the DOTs. Also, 70% of the DOTs wanted to see methodologies developed to determine where flow control of runoff volumes and high-flow durations are appropriate to prevent stream bank erosion in ultra-urban areas.

Characterizing sites for offsite water quality treatment on a watershed basis is relatively uncommon. A minority of states indicated that they enjoyed some flexibility with mitigating for stormwater management off site where it would produce greater environmental benefit for the watershed.

Although identifying priority investments has the potential to improve environmental outcomes on a watershed basis, the DOTs had a lower interest in how they could improve ecological productivity elsewhere in the watershed, especially without discussion of how they might receive credit (such as modified expectations for onsite BMPs) in exchange for such work. Of watershed-related research questions, the DOTs ranked relatively low the ability of watershed or regionally-based enhancements of wet weather storage capacity to improve baseline (high and low flow) hydrology and ecological productivity downstream and water quality problems due to urbanization and heavy metal concentration in relation to or projected from Total Connected Impervious Area in the watershed. Still, two-thirds ranked the former as a mid- or high-level research priority and more than 60% considered the latter as such. Table 2-3 contains a complete list of watershed research priority areas and rankings.

2.3. RUNOFF CHARACTERIZATION

As illustrated in Table 2-4, the highest rankings among state DOT topic areas pertaining to highway runoff characterization suggest the DOTs' interest in research that characterizes their responsibilities and where they should devote the most attention:

- Contribution of highway runoff to watershed loadings (a high or mid-level priority to 82% the DOTs; ranked 7th), and
- Threshold traffic densities below which certain pollutants in highway runoff can be considered negligible or irreducible and can be dispersed on roadsides (a high or mid-level priority to 76% of DOTs; ranked 8th).

Both of these research questions were characterized as high priorities by more than 50% of the DOTs. To better answer such questions and to address requests of regulatory agencies with relation to the National Pollutant Discharge Elimination System (NPDES) permits and to the total maximum daily load (TMDL) allocations, 70% of the DOTs ranked identification of valid monitoring methods as a research priority.

Ranked lower, but still a priority area to more than 50% of the state DOTs were deicing agent selection criteria. The role of total suspended solids (TSS) and dissolved organic carbon (DOC) in controlling dissolved metal concentration was also an area of interest and ranked 28th. Regulatory pressures are more acute in some areas than in others; water quality problems due to urbanization and heavy metal concentration in relation to or projected from total connected impervious area in the watershed also was ranked relatively low (37th), but this rapid assessment technique is considered promising in areas looking for creative and cost-effective approaches to TMDL allocations and endangered species concerns. Only one-half of the state DOTs indicated that they conduct stormwater monitoring, perhaps explaining the lower-than-anticipated level of interest in runoff characterization or receiving waters impact assessment.

2.4. IMPACTS TO RECEIVING WATERS

Chemical, toxic, and physical impacts on aquatic biota of stormwater discharges—topics at the top of many university researchers' lists—received only middling interest from DOT

TABLE 2-3 Watershed research areas ranked in priority by state DOTs

RANK	Research Areas Pertaining to Watersheds	Number of State DOTs Ranking Each Research Area			SCORE
		High Priority (3)	Mid-level Priority (2)	Low Priority (1)	
	WEIGHT	4	2	-1	
8	Contribution of highway runoff to watershed loadings	26	12	11	117
14	Demonstrating the costs and benefits of alternative, offsite, and watershed-based stormwater mitigation	17	21	9	101
16	Best methods for improving stream ecology through water quality BMPs–alternatives to regulating runoff in urban areas	18	18	12	96
24	Methodologies to determine where flow control of runoff volumes and high flow durations are appropriate to prevent stream bank erosion in ultra-urban areas	14	21	12	86
26	Characterization on a watershed basis and the availability and prioritization of sites for constructed wetlands	14	19	14	80
32	The ability of watershed or regionally based enhancements of wet weather storage capacity to improve baseline (high and low flow) hydrology and ecological productivity downstream	13	18	18	70
37	Water quality problems due to urbanization and heavy metal concentration in relation to or projected from total connected impervious area in the watershed	8	21	20	54

TABLE 2-4 Research areas pertaining to highway runoff characterization ranked in priority by state DOTs

RANK	Research Areas Pertaining to Highway Runoff Characterization	Number of State DOTs Ranking Each Research Area			SCORE
		High Priority (3)	Mid-level Priority (2)	Low Priority (1)	
	WEIGHT	4	2	-1	
7	Threshold traffic densities below which certain pollutants in highway runoff can be considered negligible or irreducible and can be dispersed on roadsides	26	15	8	126
8	Contribution of highway runoff to watershed loadings	26	12	11	117
13	Valid monitoring methods	23	12	14	102
28	Role of total suspended solids and dissolved organic carbon in controlling dissolved metal concentration	14	15	11	75
35	Deicing agent selection criteria	14	13	23	59
37	Water quality problems due to urbanization and heavy metal concentration in relation to or projected from total connected impervious area in the watershed	8	21	20	54
42	Herbicide runoff characterization	5	17	27	27
45	Viral pathogen indicators and treatment	4	10	34	2

stormwater staff and engineers, in terms of potential for this research to boost performance in achieving water quality goals. Of the 49 responding states, 17 indicated this area was a low priority for them, dragging down the overall rankings. The Environmental Protection Agency's (EPA's) adoption of a biological criteria (biocriteria) approach seems to have had less effect on DOT stormwater quality improvement efforts than the standard NPDES program requirements and current or impending 303(d) listings of impaired waters, with associated regulation of potential loadings from highway runoff (U.S. EPA, 1992). Also, in discussion, some of the DOTs questioned the expense of the research and whether or how it ultimately was used.

DOTs' top-ranked research areas pertaining to impacts on receiving waters were ranked between 16th and 25th (none in the top one-third of identified priorities). As indicated in Table 2-5, the DOTs' top interest areas (supported as a mid- or high-level priority by 60–70% of the DOTs) were

- Best methods for improving stream ecology through water quality BMPs—alternatives to regulating runoff in urban areas,
- Infiltration guidance to prevent groundwater contamination,
- Methodologies to determine where flow control of runoff volumes and high-flow durations are appropriate to prevent stream bank erosion in ultra-urban areas, and
- Design and maintenance of BMPs to reduce conflicts with threatened and endangered species.

The DOTs did express an interest in research funding for critical types of receiving systems, namely those already subject to TMDLs or likely to be subject to TMDLs in the future.

Of the research priority areas, the following received the fewest high-priority rankings and the most low-priority rankings:

- Receiving water temperature changes,
- Herbicide runoff characterization,
- Physics and chemistry of BMP design, and
- Viral pathogen indicators.

These areas (like erosion control in arid environments, which also generally received a low ranking) are nevertheless important research areas for a few and are of high regional importance.

2.5. AREAS FOR FURTHER RESEARCH IDENTIFIED BY DEPARTMENTS OF TRANSPORTATION

Respondents from the DOTs were asked individually to identify important areas for further research that could lead to an increased ability of the DOTs to improve the quality of stormwater runoff. Their feedback follows in subsequent sections. It is important to note that each bullet represents feedback from a single individual; the DOTs typically did not detail further research needs in exactly the same areas. Con-

TABLE 2-5 Research areas pertaining to receiving water ranked in priority by state DOTs

RANK	Research Areas Pertaining to Receiving Waters	Number of State DOTs Ranking Each Research Area			SCORE
		High Priority (3)	Mid-level Priority (2)	Low Priority (1)	
	WEIGHT	4	2	-1	
16	Best methods for improving stream ecology through water quality BMPs—alternatives to regulating runoff in urban areas	18	18	12	96
23	Infiltration guidance to prevent groundwater contamination	18	15	16	86
24	Methodologies to determine where flow control of runoff volumes and high flow durations are appropriate to prevent stream bank erosion in ultra-urban areas	14	21	12	86
25	Design and maintenance of BMPs to reduce conflicts with threatened and endangered species	17	15	18	80
27	Chemical, toxicity, and physical impacts to aquatic biota of stormwater discharges	16	16	17	79
32	The ability of watershed or regionally based enhancements of wet weather storage capacity to improve baselines (high and low flow) hydrology and ecological productivity	13	18	18	70
33	Compliance with numeric water quality standards	14	15	21	65
35	Deicing agent selection criteria (considering effects on receiving waters and biota)	14	13	23	59
40	Toxicity controls	7	20	22	46
41	Receiving water temperature change reduction	5	19	25	33

solidated rankings for all 50 states on 45 topic areas were discussed previously. This section serves as a useful check to see if the wide body of DOTs raised research issues that were not incorporated initially.

The DOTs' individual respondents identified the following general areas pertaining to stormwater as important to increasing DOT ability to improve water quality:

- BMP performance studies specific to DOT operations and to individual states;
- Cost–benefit analyses of BMPs and retrofits;
- Determination of the water quality benefits of employing source control measures;
- Determination of the effectiveness of treatments and if and when they become feasible economically; and
- Effectiveness of BMPs, selection criteria, and construction and maintenance costs.

These areas, listed separately by state DOTs in the respondents' own words, do not differ significantly from the prelisted priority areas on which DOT rankings were requested, though the source control area was not listed as such in the initial ranked list. The remaining topics were high-priority research areas as indicated by DOTs in the ranked portion of the survey. Other recurring research needs were easy guides for the best stormwater control measures (by region) and a synthesis of nationwide best practices (structural and nonstructural).

Design or Efficiency of Stormwater Management Measures During Construction

Individual DOT respondents identified the following topics as important areas of needed research that could lead to an increase in their agency's ability to improve water quality through design or efficiency of stormwater management measures during construction:

- Effectiveness of BMPs to control pollutants in construction-related runoff;
- Identification of practical means of controlling turbidity;
- Quantification of the effectiveness of using mulches or erosion control mixes versus using a silt fence;
- Evaluation of productivity and cost-effectiveness of BMP installation;
- Performance data on erosion control BMPs;
- What to do with the information after you get the data; a decision tree for possible data—how much is enough?
- BMP selection guidance based on construction site conditions;
- An easy-to-use guide for measures that are best to use, by region;
- Protocols (approval processes and specifications) used by other DOTs for use of polymers for erosion and sediment control;
- The status of all state DOT stormwater management programs; and
- A synthesis of best practices.

Retrofitting Existing Stormwater Management Measures

DOT individual respondents also identified the following topics as the most important areas of needed research that could lead to an increase in their agency's ability to improve water quality in retrofitting and site selection for retrofitting:

- An easy-to-use guide for measures that are best to use, by region;
- A synthesis of best practices;
- Models or data, or both, that will help distribute limited funding for retrofits that will achieve the greatest overall environmental impacts;
- Research on improved flood control downstream of stormwater ponds;
- Retrofits in space-limited, ultra-urban areas;
- Requirements for below-ground storage of water; and
- Watershed assessment and prioritization techniques that incorporate roadway and water resource characteristics.

Maintenance of Stormwater Control Measures during Construction

DOT individual respondents identified the following topics as the most important areas of research that could lead to an increase in their agency's ability to improve water quality in the area of maintenance of stormwater control measures during construction:

- Evaluation of BMP installation cost-effectiveness (efficacy of vactron escavator was mentioned as a particular interest area);
- Determination of BMPs installation production rate;
- Tools to justify costs of action versus no action, for example, match hydraulic need versus time of concentration, and storage needs versus human safety;
- Selection of BMPs based on construction site conditions;
- A synthesis study on the contract administration of stormwater requirements in construction;
- Use of best available technology with a focus on the treatment train;
- Development of guidance for fertilizer utilization in seeding and turf establishment near sensitive water bodies (nutrient runoff prevention);
- An easy-to-use guide for measures that are best to use, by region;
- A synthesis of best practices and a compilation of applied knowledge;
- Effluent management strategies for concrete truck washing; and
- Sharing of ways to monitor impacts to environmental controls after runoff events.

Post-Construction Maintenance Aspects of Stormwater Management Measures

The most important research topics in the area of post-construction maintenance aspects of stormwater management measures that could increase the DOTs' ability to improve water quality were listed as

- An easy-to-use guide for measures that are best to use, by region;
- A synthesis of best practices;
- An estimation of the need for the additional maintenance personnel who are required to maintain properly the existing BMPs;
- Technology improvements, for example, the need for vactor trucks to be able to clean greater than 80% of sediment and debris from catch basins, structures, and manholes;
- Testing methodologies for maintenance of stormwater BMPs and specifications for effective use, for example, vacuum sweeper testing methodology and specifications to improve water quality;
- Mulches and erosion-control mixes;
- Data on maintenance requirements and frequency for BMPs based on location and land use type;
- Design for lifetime maintenance of the project;
- Long-term effectiveness of devices;
- Lifecycle cost analysis of devices; and
- Deicing effects on threatened and endangered species, amphibians, and other sensitive species.

Retrofitting and Site Selection on a Watershed Basis

Just under one-third of the DOTs have retrofitted existing stormwater facilities for stormwater quality control. DOT individual respondents identified the following topics as the most important areas of needed research that could lead to an increase in their agency's ability to improve water quality in retrofitting and site selection for retrofitting:

- An easy-to-use guide for measures that are best to use, by region;
- A synthesis of best practices;
- Models or data, or both, that will help distribute limited funding for retrofits that will achieve the greatest overall environmental impacts;
- Research on improved flood control downstream of stormwater ponds;
- Retrofits in space-limited, ultra-urban areas;
- Requirements for below-ground storage of water; and

- Watershed assessment and prioritization techniques that incorporate roadway and water resource characteristics.

Watershed Approaches

State DOTs listed the following areas as needing more research with regard to alternative mitigation (offsite location of stormwater mitigation measures) and prioritization on a watershed scale:

- A standard method for establishing critical needs within a watershed to prioritize areas for BMP implementation;
- The need to establish equivalency and to quantify based on ecosystem or habitat, determining when a threshold is met to select an alternative site;
- Mitigation to decrease areas of flooding;
- An easy-to-use guide for measures that are best to use, by region;
- A synthesis of best practices and a compilation of applied knowledge; and
- Use of water quality banking or water quality trading by state DOTs.

DOTs also listed watershed-related research priorities under related categories, such as retrofit prioritization.

Runoff Characterization

DOTs suggested further research on the contribution of runoff to water quality degradation and development of a policy regarding Manning's "N" for various pipe types and sizes (also listed under the Guidelines and Protocols section in this chapter).

Receiving Waters Impact Assessment

When asked to identify research needs in their own words, pertaining to impacts on receiving waters, DOT respondents suggested the following:

- Atmospheric deposition,
- Ambient conditions of receiving waters,
- Strategies or models for design and location of BMPs and stormwater retrofits to have the maximum impact on receiving waters,
- The BMP standard for abating temperature of water discharged to cold water streams,
- The contribution of bridge runoff to water quality degradation,
- Effectiveness of catch basin hoods,
- Effects and effectiveness of underground BMPs,
- The use of sound scientific methodology (more than just laboratory data) to determine the effectiveness of underground innovative BMPs in capturing stormwater contaminants,
- Bacteria and mosquito survivability and propagation within underground BMPs (especially innovative devices), and
- Metals fractionation within underground BMPs (due to anoxic conditions).

Guidelines and Protocols Used by State DOTs

Many state DOTs have developed design guidelines for BMP selection and development of stormwater management plans. In a few cases, state environmental protection agencies have taken the lead in developing guidelines; guidelines are even outlined in state law. State DOT hydraulic engineers and NPDES staff identified the following as the most important remaining research areas pertaining to design guidelines:

- Design considerations, coordination, and BMP selection and decision support to meet NPDES Phase II requirements; development of standards for protecting different levels of environmental sensitivity;
- Documented BMP efficiency and effectiveness information (including access to BMP research and test results;
- Short-term and long-term cost information on BMP performance;
- Better tools to model performance in relation to TMDLs;
- Maintenance facility BMP design guidance;
- Temporary water management design;
- Contractual methods to improve BMP implementation, including incorporating BMPs as line items into the contract;
- More information on and understanding of techniques for maintaining BMPs;
- Policy regarding Manning's "N" for various pipe types and sizes;
- An EMS that ties together many existing standard operating procedures in an operation and maintenance area into one EMS; and
- A standard, approved post-construction BMPs inspection and enforcement program for erosion control measures.

In a few cases, the research team also was referred to faculty from universities cooperating with the DOTs to perform research. The university researchers indicated the following as unaddressed needs:

- Methods and technologies to promote the re-use of stormwater;
- Public health-related measures;

- Performance of various proprietary devices under specified criteria—decision support system, data on pollutant removal efficiencies of various green/LID/ESBCM technologies, infiltration rates and water quality in exfiltration devices, and in situ removal of pollutants using replacement media;
- Effectiveness of plants in ponds;
- Green roofs, injection wells water quality, storm surges along coastal areas as they affect the pollution removal characteristics of ponds, and updated rainfall data;
- Phosphorus reduction;
- Weir performance;
- Effects on receiving waters, in particular, algae blooms related to stormwater discharges;
- New technologies and improvements on existing designs for the removal of pollutants to assist in reaching necessary pollutant removal levels for TMDLs (sediment, nutrient, and metals reductions) and to respond to the space limitations in ultra-urban environments, including development of biological in situ methods that will treat discharge to TMDL-impaired waters; and
- Modeling pollution plumes in a 3-D environment.

CONCLUSION

The survey yielded some interesting and perhaps surprising results given the panel and GKY's previous emphasis on research pertaining to receiving water impacts. Although there is arguably a logical progression of activity that often starts with fundamental research, progresses through applied research, addresses technology transfer, and then is applied through proof in practice, DOTs indicated less interest in prioritizing continued research on impacts to receiving waters and understanding fundamental physical, chemical, and biological or ecological processes operating in receiving systems and more interest in the immediate questions on BMP costs and effectiveness. The research areas recommended in the executive summary of this report reflect this direction.

The survey also pointed out the importance of improving the transfer of available research to practicing transportation staff. For example, BMPs for confined areas and construction-type BMP information were listed as priorities for research. These two areas have received a large degree of research attention already. Therefore, the survey results highlight the need to improve information sharing and dissemination.

CHAPTER 3

REVIEW OF PUBLISHED LITERATURE AND POTENTIAL RESEARCH NEEDS

As mentioned previously in section 1.4, Research Methodology, more than 900 of the most relevant annotated citations from the 2,500-plus documents incorporated into the research database were reviewed, and nearly 300 full documents were obtained. During the review process, citations were categorized according to the following broad research areas: Evaluation of Stormwater Control Facilities and Programs, Watershed-Based Approaches, Highway Runoff Characterization and Assessment, and Receiving Waters Impact Assessment. After a brief review of some of the major syntheses of highway runoff/urban stormwater quality research, each of these subsections and subcategories are discussed. Instead of including a discussion of every document in the review, only a selected subset of the most comprehensive documents (i.e., results either were included in the abstract, or the full document was acquired successfully, or both) have been summarized. Nonetheless, all of the categorized documents were considered in identifying potential research gaps and needs.

3.1. BRIEF REVIEW OF RECENT MAJOR SYNTHESES OF HIGHWAY RUNOFF/URBAN STORMWATER QUALITY RESEARCH

Several researchers have attempted to compile and summarize highway runoff/urban stormwater quality research and data, including BMP evaluation studies and performance data. A few of the most notable efforts are described below.

3.1.1. National Highway Runoff Water-Quality Data and Methodology Synthesis

The National Highway Runoff Data and Methodology Synthesis (NDAMS) is an effort by the U.S. Geological Survey (USGS) and FHWA to compile and readily make available highway runoff research and guidance information. Three volumes were published recently (July 2003) as a result of the NDAMS:

- Volume I—Technical Issues for Monitoring Highway Runoff and Urban Stormwater, FHWA-EP-03-054;
- Volume II—Project Documentation, FHWA-EP-03-055; and
- Volume III—Availability and Documentation of Published Information for Synthesis of Regional or National Highway-Runoff Quality Data, FHWA-EP-03-056.

Volume I is a compilation of "expert chapters" designed to address different technical issues for monitoring highway runoff and urban stormwater. Volume II provides an overview of the bibliographic database design, the project, the catalog of available information, the efforts to evaluate available information, the project quality-assurance and quality-control (QA/QC) program, and the directory structure and files on a CD-ROM accompanying the volume. Volume III is a report describing the NDAMS report–review process and summarizes and interprets the results of the metadata review process. As a product of this synthesis, a bibliography of more than 2,600 relevant references with more than 1,300 selected abstracts (or previa—an abstract written by someone other than then author) and 252 reviewed and classified references were compiled and are available as an online searchable database (http://ma.water.usgs.gov/FHWA/biblio/default.htm).

NDAMS noted that FHWA, USGS, the Environmental Protection Agency (EPA), and many state highway departments and universities have sponsored or conducted research on the nature and impacts of highway runoff on water quality, but a centrally available composite of these data was still lacking, and the existing data present conflicting information. Existing data and studies from FHWA, USGS, state departments of transportation (DOTs), and other sources were compiled and evaluated to determine whether the information needs of highway managers, practitioners, and researchers are being met and whether this information will meet future needs. The primary goal of the effort was to determine whether the quality of highway runoff and processes contributing to water quality constituents in highway runoff could be characterized adequately nationwide, based on published information. FHWA sought to check the validity of the existing data and procedures to assess and predict pollutant loadings and impacts from highway stormwater runoff as a first step toward indicating whether current guidelines for highway runoff quality are up-to-date and technically supportable. FHWA wanted a catalog of existing studies and available data as well as indications of the robustness of the data, the sufficiency of the data to characterize pollutant loadings and impacts from highway and urban stormwater runoff, and the changes in atmospheric deposition around the country since the mid-1980s. To this end, and to assess the suitability of available data to validate runoff quality models developed by FHWA, a catalog of available data and investigations was developed.

3.1.2. International Stormwater BMP Database

Probably the most widely recognized resource on BMP effectiveness data is the award-winning International Stormwater Best Management Practices (BMPs) Database at http://www.bmpdatabase.org/. The database was known formerly as the National ASCE/EPA Stormwater BMP database (the name of the database was changed to recognize and acknowledge data contributors outside of the United States). This database provides access to BMP performance data in a standardized format for roughly 200 BMP studies conducted over the past 15 years. This database is intended to provide a consistent, scientifically defensible set of data on BMP designs and related performance. The database team has made an extensive effort to assess the quality of the data entered for consistency and accuracy. However, in compiling such a large set of data, and because of limits on resources for data QA/QC, the developers acknowledge that some data may contain errors.

The database may be searched on or downloaded from the website and also is available on CD-ROM. The database was developed by ASCE's Urban Water Resources Research Council under a cooperative agreement with EPA. In 2003, new structural BMP storm event and analysis tables were added to the data search page. These tables allow for parameter-specific searches on all structural BMPs analyzed by the project team.

A summary of the number of data records currently residing in the BMP database is shown in Table 3-1. The database is relational in design, and Table 3-1 describes the number of records present in various tables within the database. Note that some of the sites in the database include multiple BMPs (e.g., filters and detention), and therefore the total number of sites is less than the total number of BMPs.

A summary of data stored in design tables and associated flow and water quality records is provided in Table 3-2. The event monitoring summary information provided in Table 3-2 does not include grab samples or flow measurements and precipitation data that are not associated with measured or calculated event mean concentrations. As demonstrated in Table 3-2, retention ponds are the best-populated BMP category in the current database. At the other extreme, some BMPs have only a single site (e.g., infiltration trenches) in the database.

A summary of the geographical distribution of BMPs is provided in Table 3-3. Based on analyses of the data stored in the BMP database, the database team has come to the following conclusions with regard to evaluating BMP performance (Strecker et al., 2000):

- Substantially more data are needed for many BMP types to be able to explore meaningfully design versus performance.
- Removal percentages are not very useful for characterizing performance, unless looked at much more carefully (e.g., with treatability information). As a result, BMP performance requirements generally should not be specified in terms of percent removal.
- Effluent quality among BMPs of the same type is much more consistent then percent removal and is thought to be a better way of characterizing efficiency; although, at an individual site, it is important to test whether the BMP had a statistically significant effect on water quality.
- As effluent quality is fairly consistent, some BMP types may have been mischaracterized as less effective because of cleaner influent. For example, BMPs that rely on settling as a primary removal mechanism cannot have high percent removals where suspended solids concentrations are low in the influent. The influent data in the dry-extended detention ponds in the database are relatively

TABLE 3-1 Summary of records found in ASCE/EPA BMP Database (as of August 2002)

Category	Records in Database
General Test Site Information	158 Sites
Sponsoring and Testing Agencies	60 Agencies
Watershed Information	167 Watersheds
Nonstructural BMPs Information	28 BMPs
Structural BMPs Information	170 BMPs
Monitoring Stations	557 Monitoring Stations
Precipitation Data	3,396 Precipitation Events
Flow Events Monitored	6,563 Flow Events Monitored
Water Quality Sampling Event Data	8,588 Water Quality Events Monitored
Water Quality Laboratory Analyses	122,265 Analyses Conducted

TABLE 3-2 Summary of data by structural BMP type (as of August 2002)

BMPs Type	Number of BMPs in Category, Including Design Information	Precipitation Records for BMPs Type[1]	Flow Records for BMPs Type[1]	Water Quality Records for BMPs Type[1]
Detention Basin	24	129	229	4,209
Grass Filter Strip	32	227	385	6,251
Media Filter	30	187	327	6,144
Porous Pavement	5	5	5	55
Retention Pond	33	378	817	14,293
Percolation Trench and Dry Well	1	3	3	21
Wetland Channel and Swale	14	53	113	1,241
Wetland Basin	15	221	681	7,320
Hydrodynamic Devices	16	169	309	6,186
Total	170	1,372	2,869	45,720

[1] Only events that included the collection of event mean concentrations have been included in the summary statistics presented in this table.

cleaner than other BMPs, and therefore they have been reported as achieving lower percent removals. In fact their effluent quality is relatively close to wet ponds and wetlands.

- Long-term trends in receiving water quality, coupled with biological assessments, probably would be a much better gauge of the success of the implementation of BMPs, especially on an area-wide basis.

Strecker et al. (2003) reanalyzed the data in the currently expanded database and found that in addition to effluent quality, BMPs are best described by their ability to reduce runoff volumes (i.e., how much stormwater can the BMP prevent) and process variable flows (i.e., how much is treated by the BMP). Table 3-4 compares the ability of some BMPs to reduce stormwater runoff volumes. Notice that biofilters and detention basins have the ability to reduce significantly runoff volumes, making them effective controls for reducing overall runoff volumes; wetland channels and basins do not have this ability.

Even with the expanded database there are still many limitations:

- The data are for storm event means only, making it impossible to do intra-storm processes analyses; although, for the sites that have included more detailed data, intra-storm data may be available. Some grab samples are included in the data sets.
- Source reports of the data must be obtained by contacting the project team and requesting a paper copy of the source information.
- Few cost data are available.
- The only summary results on the web site are cross-sectional performance data for a selected BMP based on aggregating the individual storm event data for some or all of the events.

TABLE 3-3 Total number of BMPs by state (as of August 2002)

State	Number of BMPs	State	Number of BMPs
Alabama	13	North Carolina	6
California	41	Ohio	1
Colorado	4	Oregon	3
Florida	24	Texas	19
Georgia	2	Virginia	29
Illinois	5	Washington	20
Maryland	4	Wisconsin	10
Michigan	5	Other	2
Minnesota	7	**Total**	**198**
New Jersey	3		

TABLE 3-4 Comparison of average of mean outflow to mean inflow for selected BMP types contained in the BMP Database

BMPs Type	Mean Monitored Outflow/Mean Monitored Inflow for Events Where Inflow is Greater Than or Equal to 0.2 Watershed Inches
Detention Basins	0.70
Biofilters	0.62
Media Filters	1.00
Hydrodynamic Devices	1.00
Wetland Basins	0.95
Retention Ponds	0.93
Wetland Channels	1.00

- All of the interpretive results depend on the storm event definition.
- The database is not structured to handle time series data efficiently.
- Relatively few studies have data on bypass flows versus those treated.

The database research team is actively pursuing new data sets compatible with its requirements. To facilitate this compatibility, the site recommends use of *Urban Stormwater BMP Performance Monitoring: A Guidance Manual for Meeting the National Stormwater BMP Database Requirements*, of which there have been more than 25,000 downloads to date. In addition to the detailed BMP monitoring and data analysis guidance provided in the manual, the guidance manual includes lists of required and recommended data elements, or metadata, that should be reported with BMP performance data, including specific information for individual BMP types. The manual also includes sample BMP metadata forms to ensure that all of the necessary data elements are recorded. References to other BMP performance guidance manuals are included in Appendix B.

The database team's tasks have not included and will not include recommendations of one BMP type over another; however, the team does report on the performance characteristics of BMPs based on the entered data and information in the database. Peer-reviewed performance assessment techniques are included. The database is intended to provide a data-exchange tool that permits characterization of BMPs based solely on their measured performance using the same protocols for measurements and reporting information.

3.1.3. *Caltrans' New Technology Report*

One of the best consolidated sources of evaluative information on BMP technologies, and on new and ultra-urban BMPs in particular, is the California Department of Transportation's (Caltrans) *Caltrans' New Technology Report*. The report, issued twice (with revisions, updates, and new information) in 2003, consolidates and standardizes information on new technologies developed or identified as part of the Caltrans process for BMP identification, evaluation, and approval. Since 1996, the Caltrans stormwater program has evaluated and approved a wide range of BMPs for use on Caltrans facilities and has approved more than 110 separate BMPs. New technologies—including the latest innovations in permanent stormwater treatment and control and the existing technologies used but not selected (approved) previously as a BMP by municipal or DOT stormwater management programs—are evaluated and described for practitioners in a standardized format. New technologies are identified from the literature, consultants, manufacturers, regulators, third parties, Caltrans personnel, or through the agency's formal New Product Review Process. Fact sheets for new technologies summarize constituent removal effectiveness and the advantages and constraints of each type of new technology presented in the report. Many of the new technologies identified are appropriate for ultra-urban environments.

Favorable evaluations of promising BMPs often lead to pilot studies for gathering definitive performance data. So far, there have been 121 full-scale and small-scale pilot studies. Five of the most recent pilot studies addressed low impact development (LID) areas such as bioretention and constructed wetlands, Direct Flow Inclined-Screens Gross Solids Removal Devices (GSRD), Forward Sloping Screens GSRD, and Reverse Sloping Screens GSRD. Austin filters with alternative media and infiltration basins with alternative media are being considered for pilot testing. Successfully piloted technologies may be approved and listed in the statewide management plan (SWMP) as a permanent BMP to be used where applicable by all Caltrans project engineers as part of significant construction and retrofit projects.

Also, fact sheets are developed for each newly identified technology that is not approved as a BMP by Caltrans. Each fact sheet presents summary information to be used by Caltrans Soil Water Assessment Tool (SWAT) members to evaluate the potential applicability, as well as specific advantages and constraints, of a given BMP to various DOT facilities, including for design parameters, operations, maintenance, treatment effectiveness, and costs. All fact sheets use a standard format to facilitate comparison among various BMP types. Each fact sheet is divided into a standard series of discussion topics.

These topics, and the relevant information included under each topic, are discussed below.

1. **BMP Description.** A description of the BMP is presented at the top of each fact sheet. The description provides a summary of the BMP configuration and a general overview of the treatment process, how the BMP operates, and considerations that need to be addressed for promoting maximum treatment effectiveness and functionality.
2. **Constituent Removal.** The relative degree each BMP is able to remove selected groups of constituents from stormwater runoff is provided. The groups of constituents examined were selected based on the likelihood of occurrence at transportation facilities at levels that would require treatment consideration. For each of the selected constituent groups [total suspended solids (TSS), TDS, total metals and dissolved metals, pathogens/BOD, nutrients, litter, and pesticides], a level of confidence in the available data and a general assessment of the BMP's ability to remove various categories of pollutants are provided. The fact sheets report relative removal efficiencies (high, medium, or low) for each of the nine general categories of constituents, derived from the literature review. Constituent removal was quantified by first calculating the average removal percentage for all constituents within a given category (sediment, nutrients, pesticides, metals, pathogens, and litter) and then defined using the following criteria:
   - *High*: average removal percentage was equal to or greater than 75%,
   - *Medium*: average removal percentage was between 40 and 75%, or
   - *Low*: average removal percentage was less than or equal to 40%.

   The fact sheets provide notes with additional information regarding how the removal assessment was assigned to a given BMP.

   A caveat is that the level of confidence in the constituent removal data found in the literature depended on the type and amount of information. Assessing constituent removal from stormwater BMPs is not a precise science. In fact, the National BMP Database project found that percent removals are not an accurate measurement of performance (Strecker et al., 2000). Water quality monitoring studies have demonstrated the wide variability in water quality concentrations in stormwater runoff; with more consistent effluent quality from BMPs, percent removal becomes a function of how polluted the inflow is.

   To ensure that data of the highest quality are produced, storm event monitoring requires that samples be collected according to standard protocols. The criteria applied for defining the confidence level were
   - *High*: The information came either from a Caltrans research study or from a study that met the Caltrans QA/QC monitoring protocols.
   - *Medium*: Constituent removal rates were established from the results of a scientific monitoring study or studies conducted independently of equipment manufacturers, and the BMP technology has a documented history of application for treating stormwater; or the treatment process was a known technology for treating other types of wastewater discharges; or the BMP technology provided no discharge to surface waters under design conditions. Constituent removal was assumed to be 100% removal, although it was recognized that certain large storm events would not receive treatment.
   - *Low*: The BMP monitoring program used to quantify the removal percentages and the applied monitoring protocols could not be substantiated.
3. **Caltrans SWMP Category.** Caltrans has developed the following categories for BMPs:
   - Category I BMPs: Technology-based pollution prevention BMPs to meet the maximum extent practicable (MEP) requirements for designing and maintaining roadways and related facilities;
     - Group A: The BMPs applicable to all maintenance operations, and
     - Group B: The BMPs used in the design of new facilities or major renovations of existing facilities.
   - Category II BMPs: Controls to meet BCT/BAT requirements for construction projects; and
   - Category III BMPs: Treatment BMPs to meet MEP requirements.
4. **Key Design Elements.** Elements that have been highlighted by vendors in the literature or as a result of testing. Ancillary facilities assumed to be used in conjunction with the new technology also are listed in this section. An example would be including a detention basin downstream of a chemical treatment technology to capture flocculated particles.
5. **Schematic Figure.** If appropriate, a schematic figure is provided to depict graphically a typical design plan or cross-section, or both, with the major components identified.
6. **Capital, Operational, and Maintenance Cost Assessments.** Assessments pertaining to the costs of building, operating, and maintaining each BMP also are provided, with the level of confidence in the available data and a general assessment of the BMP's overall costs.

The level of confidence in the costs to build and operate a BMP depends on the type and amount of information found in the literature. Using the cost information developed for municipal stormwater programs was not considered by Caltrans to be directly relevant to Caltrans facilities. The right-of-way costs and construction costs of major highway transportation projects are typically much greater than the typical suburban street or arterial road that might be constructed by a municipal public works department. Furthermore, operations and maintenance costs of facilities along major freeways can be much more expensive than similar municipal facilities because of limited access and the need to provide traffic control. The criteria applied for defining the confidence level of the cost estimates were

- *High*: Unit cost information was available from a facility designed and constructed by Caltrans or a similar state transportation department.
- *Medium*: Cost information was available from several similar facilities constructed under municipal stormwater programs.
- *Low*: No cost information was available from a similar BMP facility that could be verified independently. Construction costs were extrapolated from available pricing information.

The cost-effectiveness for each BMP was assessed in terms of its equivalent uniform annual cost (EUAC) relative to a detention basin. A four-quadrant system was used as a tool to rate each BMP. The cost estimates were defined by first calculating the typical range of costs for constructing or operating a BMP on a per acre basis. The acre represented the drainage area served by the BMP. Operation and maintenance costs based on the BMP's design life were then added. The EUAC for a particular BMP was estimated and then compared qualitatively to that of a detention basin. If the EUAC was higher than a detention basin, it was marked as a higher cost using the quadrant rating key. The benefit of the BMP was evaluated relative to the performance of a typical detention basin. If the constituent removal was greater than that of a detention basin, the BMP was marked as having a greater benefit.

7. **Issues and Concerns.** Issues and concerns presented information to be considered in maintenance and in project development, with a standard set of topics in each category facilitating comparisons between various BMPs. Under the maintenance category, the standard topics include
   - *Requirements*: summarizes routine maintenance tasks required to keep the BMP functional;
   - *Nuisance Controls*: identifies whether the BMP has the potential to create odors, breed mosquitoes, or attract pests;
   - *Traffic Safety*: identifies the level of potential traffic control during BMP servicing; and
   - *Staffing/Equipment*: identifies the level of staff, and their skills, required to perform the maintenance, as well as any specialty equipment.

   For the project development category, the topics include
   - *Right-of-Way Requirements*: identifies relative space requirements to install the BMP;
   - *Siting Constraints*: identifies siting considerations and limitations, such as soil types, slope of the land, distance from existing infrastructure or other natural features, and regulatory requirements;
   - *Design Complexity*: identifies major components and equipment requirements and operational controls or limits; and
   - *Retrofit Potential*: identifies the potential for retrofitting existing Caltrans facilities.
8. **BMP-Specific Advantages and Constraints.** BMP-specific advantages and constraints lists additional advantages and constraints of the BMP that were not covered in the previous sections, including hydrologic characteristics and regionally specific weather conditions, experiences from actual installations, and expansion of particular points discussed in previous sections of the fact sheet.
9. **Sources of Information.** Sources of information are provided when appropriate (e.g., vendor contact information is provided for proprietary technologies).

3.1.4. Urban Wet Weather Flow Literature from 1996 through 2002

Clark et al. (2003) compiled and organized wet weather flow (WWF) literature reviews that were published originally in the annual literature review issues of *Water Environment Research* from 1996 through 2002. The document includes approximately 3,350 references from the 7 years alone. Over this 7-year period, the field of urban WWF research expanded dramatically, in part due to increased interest in the United States due to the Clean Water Act (CWA) NPDES stormwater permit program and increased awareness of the seriousness of urban WWFs throughout the world. The document is organized according to the following primary topic categories: characterization, pollution sources, monitoring and sampling, surface-water impacts, groundwater impact, decision-support systems, regulatory policies and financial aspects, and control and treatment technologies. Each section is divided further into subcategories. For instance, highway and other roadway runoff is a subcategory of pollution sources.

3.1.5. Center for Research in Water Resources: Highway Runoff Literature Review

Barrett et al. (1995) conducted a literature review that evaluated the impact of highway construction and operation on surface water quality and on recharge of groundwater aquifers. The types of barriers for containment and retention of sediment and pollutants from runoff and the effectiveness of each device were discussed. The report also addressed the quantity and quality of highway runoff from different types of road surfaces, drainage and conveyance systems, and various types of highways. In addition, methods and strategies for the handling and control of highway runoff and effectiveness of pollution control devices were reviewed.

3.1.6. Identification of Research Needs

Clearly there is a need to compile major syntheses of stormwater runoff research, such as the major examples presented above and this current research effort. The NDAMS effort, with the generation of the bibliographic database is a good starting point for such a compilation of research literature. However, since only 252 references out of the 1,300 abstracts in the database were reviewed and classified, a more extensive effort appears to be needed. Also, the classification of documents could be extended and refined to include subcategories within the major categories.

The International Stormwater BMP Database currently contains primarily BMP design and monitoring data with no direct link to published literature. A research project that attempts to link an extensive bibliographic database (such as a refined NDAMS database) to a water quality and BMP performance database (such as the International Stormwater BMP Database) would result in a very useful tool for stormwater practitioners. Such a project would likely require the participation of several state and federal agencies, as well as private organizations, in order to produce a user-friendly database. However, this type of project could be limited only to highway runoff-related studies, substantially reducing the size of the final database and the costs associated with its development.

3.1.7. Primary References

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3.2. EVALUATION OF STORMWATER CONTROL FACILITIES AND PROGRAMS

Over the past 30-plus years, stormwater researchers have evaluated the performance of stormwater BMPs. These evaluations have come in many forms and permutations. For instance, some evaluations simply may investigate the pollutant removal effectiveness of a BMP by monitoring the influent and effluent concentrations or loads, or both, and comparing results at the storm event, seasonal, or annual scales. More advanced evaluations have included attempting to associate performance with specific site conditions or design variables, evaluating methods to improve pollutant removal in existing drainage systems, and characterizing the water quality achieved rather than the removals. Furthermore, some BMP evaluations may have looked beyond the pollutant removal effectiveness through the use of surrogate performance measures, such as the hydraulic regimes (hydraulic residence, bypass volume, etc.), retention of previously captured pollutants, maintenance requirements, or even biological indicators.

Because of the increasing use of stormwater BMPs by state DOTs, the evaluation of stormwater control facilities and programs will be an area of increasing interest for DOT stormwater managers. The survey of state DOTs revealed that a large portion of transportation agencies across the country implement stormwater control practices. Table 3-5

TABLE 3-5 Categories of stormwater control practices in use at state DOTs

Stormwater Quality Practices Used	Number of States Using	Number of States Indicating that They Do Not Use
Temporary erosion soil control	50	0
Permanent stormwater facility	40	10
Stormwater retrofit	17	33
Stormwater monitoring	26	24
Water quality BMPs in operations and maintenance	35	15

shows the number of states that currently implement standard stormwater control practices, and Table 3-6 shows the number of states that currently implement specific controls.

Of the nearly 900 documents and abstracts reviewed, the project team identified more than 400 studies that generally evaluated stormwater control facilities and programs. These evaluative studies were further categorized according to the primary subtopic area of the study. As studies that evaluate different BMP types often have similar objectives, the primary subtopic areas were based on the primary objectives of the study rather than on specific BMP types to assist in identifying research gaps and needs with regard to BMP evaluations. This section is organized according to the following primary topic areas:

- General Evaluation,
- Gross Pollutant Removal,
- Hydraulic Assessment,
- Pollutant Retention,
- Methods to Improve Pollutant Removal in Existing Stormwater Systems,
- Erosion and Sediment Control,
- Design Variables, and
- Unit Processes.

3.2.1. General BMP Evaluation

Although there are several different ways to evaluate BMPs, the most common methods monitor the effluent and influent water quality. The literature shows significant variation among the methods used to collect and analyze such water-quality data and make inferences about BMP performance. ASCE, in cooperation with the EPA, attempted to develop a standard BMP performance monitoring protocol through the publication of *Urban Stormwater BMP Performance Monitoring: A Guidance Manual for Meeting the National Stormwater BMP Database Requirements* (GeoSyntec Consultants, 2002). However, the methods and terminology recommended in the manual have yet to be adopted widely by the stormwater community. Many state DOTs have evaluated BMP performance, but without agreed-upon methods and terminology, it is difficult to compare meaningfully the evaluations.

The survey of state DOTs revealed that 15 of the responding DOTs have conducted studies or have prepared reports that evaluate the effectiveness and efficiency or performance, or both, of source control or treatment control stormwater management measures at DOT facilities. As more DOTs begin monitoring the effectiveness of their BMPs, more statistical summarizations and comparisons of performance data should be completed; however, this will not be easy if different methods are used to evaluate and report BMP performance. There is a need for reaching a consensus on standard BMP performance measures and terminology.

As discussed in *Guidance Manual for BMP Monitoring*, efficiency is a measure of how well a BMP or BMP system removes or controls pollutants, performance is a measure of how well a BMP meets its goals for the stormwater the BMP is designed to treat, and effectiveness is a measure of how well a BMP system meets its goals in relation to all stormwater flows (ASCE/EPA, 2002). In other words, performance and effectiveness are project and site specific, in that they are measures relative to specific goals, such as meeting a predetermined effluent quality. Efficiency, on the other hand, is an absolute measure, independent of effluent quality expectations. Cost efficiency is not included in any of these measures. However, a systems analysis approach to stormwater management should consider capital investments and operation and maintenance costs when evaluating the overall efficiency of various treatment alternatives. Efficiency as defined above will be the only measure discussed herein.

In addition to clarifying differences in terminology as discussed above, the primary research questions with regard to measures of BMP performance appear to be

- What are the various measures of BMP performance?
- What are the positive and negative attributes of each?

3.2.1.1. Historical BMP Efficiency Calculation Methods

Many publications reporting efficiency values do not provide adequate information (such as the equation or even the parameter values) to determine the method used. When removal efficiency calculation methods are reported, values can be based on a number of different methods. Historically, the methods used to calculate BMP efficiency include the efficiency ratio (ER), summation of loads (SOL), regression of loads (ROL), mean concentration (MC), efficiency of individual storm loads (ISL), and reference watersheds and before-and-after studies, plus various alterations of the aforementioned methods. The efficiency method used most often is the ER method, which has serious shortcomings, as do all of the others listed. Recent research indicates that BMPs are effluent-limited, and the effluent concentration of some BMPs, including extended detention basins, has little to no

TABLE 3-6 Stormwater control technologies in use at state DOTs*

Innovative Technique or Technology	Number of States Using Practice	Number of States Not Using Practice
Water quality inlets	16	32
Constructed wetlands	32	16
Grassed/vegetated swales and buffer strips	43	5
Wet ponds	31	17
Dry ponds	39	9
Wet vaults/tanks	9	38
Dry vaults/tanks	6	41
Porous/permeable pavement designs	5	42
Oil and water separators	27	21
Silt fences	31	16
Infiltration basin/trench	32	15
Sand filter	15	32
Low impact design	11	36
Hydrodynamic ultra-urban BMPs	9	38
Filtration ultra-urban BMPs	14	33
Natural stream channel design and stabilization	24	22
Herbicide alternatives for roadside vegetation maintenance	23	23
Gross solid separators (trash)	16	30
Dry weather diversion	9	38
Flocculating agents	10	37

*Not all state DOTs responded to every question

dependence on the influent concentration. Therefore, efficiency calculation methods using influent concentrations tend to overestimate the efficiency of the BMP when influent concentrations are high and to underestimate the efficiency when the influent concentrations are low. The paragraphs below describe briefly the most common and currently accepted methods used to calculate efficiency. A more complete description of historically used BMP efficiency calculation methods can be found in *Guidance Manual for BMP Monitoring* (ASCE/EPA, 2002).

Efficiency Ratio Method. As indicated above, the ER method is the most commonly used method and is accepted by various organizations including the EPA (U.S. EPA, 2002). As opposed to a storm-by-storm estimate, this method tends to minimize the influence of clean influent concentrations at underestimating BMP efficiency by averaging the event mean concentrations (EMCs) of several storms. By definition, the ER is the ratio of the difference between the average EMCs of the inlet and outlet to the average inlet EMC. It can be expressed mathematically as

$$ER = 1 - \frac{\text{average outlet EMC}}{\text{average inlet EMC}}$$

Summation of Loads. The SOL efficiency calculation is used often to evaluate long-term performance of a BMP. Summing loads over a period greater than the residence time reduces the inherent outlet independence to inlet concentrations for detention–storage BMPs. This method, recommended by the Bay Area Stormwater Management Agencies Association (BASMAA, 1996), has been used by Texas DOT to evaluate the treatment effectiveness of the DOT's highway runoff controls (Keblin et al., 1997). By definition, the SOL is equal to the difference in the sums of the inlet and outlet loads divided by the sum of the inlet loads over a specified time period. Individual loads are calculated by multiplying the EMC by the entire flow volume of the storm. The SOL can be calculated mathematically as

$$SOL = 1 - \frac{\text{sum of outlet loads}}{\text{sum of inlet loads}}$$

Regression of Loads. In this method a least squares linear regression of the influent and effluent loads is conducted, with the regression line constrained at the origin. Percent removal then is defined as the compliment of the slope (β) of the regression line, or mathematically as

$$\text{ROL} = 1 - \beta$$

Over a large range of loadings, there is sufficient evidence to demonstrate that outlet concentrations are not correlated linearly to inlet concentrations. Therefore, this method is not a recommended method. Endorsement of the ROL method could not be found during a review of current literature (i.e., within the last 5 years).

Mean Concentration. The MC method generally is not a recommended method; however, when flow-weighted data or storm volumes are not available (such as from grab samples, which are required when sampling for oil and grease), this method may be of some value. Data transfer is not advisable when this method is employed because of the general lack of storm information. The MC equation is identical to the ER equation except that average outlet concentrations are used instead of average EMCs. Thus, an inherent assumption of this method is that the grab sample is representative of a flow-weighted composite sample.

Efficiency of Individual Storm Loads. The ISL method is a ratio of the loads removed to the loads entering a BMP during a single storm event. The mean ISL efficiency of several individual events is then considered to be the average efficiency of the BMP. This method weights all storms equally and does not account for pollutant storage and release during successive storm events. The most serious shortcoming of this method is the assumption of effluent quality dependence on influent quality, particularly when applied to detention storage BMPs that have residence times greater than the storm event duration.

Reference Drainage and Before-and-After Studies. These two methods differ slightly; however, the inherent assumptions are essentially the same—characteristics of the reference drainage, or the study drainage, before BMP implementation are the same as the study drainage with the BMP. The reference drainage method assumes spatial transferability of drainage characteristics, and the before-and-after method assumes temporal transferability of drainage characteristics. Because of site constraints or poorly defined inlet or outlet structures (such as infiltration facilities), these two methods are often the only methods available for analysis. Fairly recent examples of reference drainage studies include those of Legret and Colandini (1999), where the effectiveness of porous pavement at removing heavy metals is evaluated, and of Sansalone (1999), where the effectiveness of a partial exfiltration trench (PET) on a highway shoulder is evaluated. The major difficulty of this method is the large number of parameters that need to be consistent between the two drainages in the reference watershed method or constant in time in the before-and-after studies.

3.2.1.2. Innovative Approaches and Variations of the Historical Approaches

In the past few years of stormwater BMP data collection and assessment, the shortcomings of the historical BMP efficiency calculation approaches have become more apparent. Also, inconsistent use of the several available methods has led to a wide range of efficiency values for BMPs, as well as inappropriate transfer of data. In an effort to overcome some of these shortcomings, several stormwater quality professionals have proposed alternative methods for calculating efficiency. Most of the newer methods are variations on the historical approaches; however, some innovative methods have been proposed. All of the more recently proposed methods attempt to address the shortcomings of the historical approaches and to increase the transferability of BMP data.

During a review of the most recent literature on BMP performance monitoring protocols, four promising alternative methods were found.

Effluent Probability Method. The effluent probability method was the recommended method in the ASCE/EPA National Stormwater BMP Database *Guidance Manual*. This method evaluates statistically the influent and effluent EMCs to determine if the differences in concentrations are statistically significant and, subsequently, to discover trends or characteristics in the two data sets by analyzing cumulative distribution functions or standard parallel probability plots. Useful information, such as ranges in influent values that yield the greatest percent removal, is provided by this method. Because of the relatively large amount of analytical information generated, as well as the relatively more complicated analysis as compared to the historical approaches, BMP efficiency estimates may be more difficult to include in a user-friendly database. Instead of a single efficiency value, a range of values at specific influent conditions or graphical plots would need to be reported. Nonetheless, this method provides the most innovative assessment of BMP efficiency and has the potential to generate widely transferable data.

Flow-Dependent Removal Efficiency Method. This method, which is a variation of the ER method, uses partial EMCs. Storm hydrographs are bracketed into storm sampling periods, during which flow-weighted composite samples are collected. Partial EMCs are then averaged according to average inflow rates. Therefore, instead of reporting a single efficiency value, as in the ER method, the removal efficiency is calculated at various inflow rates. This method has been proposed by the Environmental Technology Evaluation Center and David Evans and Associates (EvTEC and DEA, 2000) and endorsed by the Washington State Department of Environmental Quality (WADOE, 2002). A serious assumption of this method is that the flow rate is essentially steady during the storm sampling period. Also, as with the ER approach, this approach neglects the fact that outflow concentrations are often independent of influent concentrations over the course of a storm event.

Minimum Influent Concentration. The concept of this method is similar to the previous method, in that it is an attempt to discretize the efficiency according to influent conditions. In this method, influent concentration, instead of flow rate, is used to provide an efficiency ratio with a lower limit on the influent quality. Specific guidance on this method has not been found. However, it was referred to in *Stormwater Best Management Practice Demonstration Tier II Protocol for Interstate Reciprocity* as an appropriate BMP performance claim (Tier II Protocol, 2001). For example, a stormwater BMP performance claim could be "The Model X system can capture and treat the first half-inch, 24-hour storm for a 10-acre runoff area. Under these conditions, a TSS removal rate of 85%, ±5% (at a 95% confidence interval), can be achieved with inflow TSS concentrations greater than 100 mg/L." Placing a lower limit on influent quality addresses the fact that the efficiency of BMPs tends to decrease as influent concentrations are reduced.

Pollutant Flux Ratio. This method is a variation of the SOL method with average event flow rates being used instead of flow volumes. This modification results in a pollutant flux ratio instead of a loads ratio. This method likely would result in similar values as the SOL method, depending on how event flow volumes are calculated. The WADOE guidance document does not provide any preference to either method (WADOE, 2002). However, the appropriateness of summing flux values from individual storms is questionable.

3.2.1.3. Identification of Research Gaps and Needs

Of all the BMP efficiency calculation methods analyzed, the most promising methods are the effluent probability and the minimum influent concentration removal efficiency methods. The former provides greater detail of the actual performance of a BMP. The latter provides an easier-to-understand and transferable measure of BMP efficiency. Neither method can be used adequately to estimate the efficiency of BMPs without well-defined inlets and outlets, such as infiltration-type facilities or even source controls. As mentioned above, reference watersheds and before-and-after studies have been used to estimate infiltration performance. In other performance estimates, infiltration is considered to be 100% efficient at removing pollutants and is, therefore, based solely on the amount of stormwater infiltrated. This type of efficiency measure is appropriate for some pollutants such as suspended solids; however, it is inappropriate for highly mobile pollutants, particularly when groundwater resources are threatened. Alternative estimates could be based on changes to groundwater quality or in soil concentrations. For large infiltration operations, efficiency could be based on changes to local groundwater quality. For small infiltration operations, such as roadside ditches, calculating the percent removal before the introduction to the groundwater would be necessary. Changes in soil concentrations would provide an idea of the pollutant removal; however, the transport and chemical transformations of the pollutant of concern would need to be assessed adequately.

Based on the review of the many methods for evaluating and reporting the efficiency of BMPs, consensus and clear guidance are needed.

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3.2.2. Gross Pollutant Removal

The subtopic of gross pollutant removal generally refers to stormwater treatment facilities or programs designed to reduce the amount of trash, debris, or large sediments discharged from constructed road surfaces or storm drain systems. Erosion controls, which are designed to hold soils in place either temporarily during construction or permanently on cut–fill slopes, will be addressed in a separate subsection. Some common research questions with regard to gross pollutant removal include

- How effective are source controls—such as street sweeping, catch basin cleaning, and public education—at reducing trash and debris in transportation facility runoff?
- How effective are trash racks, screens, or other GSRD at removing and retaining bulk pollutants?

Several state DOTs have participated in recent studies that try to answer these research questions. Caltrans has taken a lead role with impetus from new TMDLs for trash; however, survey results showed only 16 DOTs use gross solid separator devices. The surprisingly low implementation of this simple treatment technology indicates a potential need for education and outreach in this area.

To investigate the characteristics of litter in freeway stormwater and the effectiveness of various BMPs, Caltrans conducted a 2-year litter management pilot study in the Los Angeles area (Lippner et al., 2001). New litter sampling and monitoring protocols were devised to characterize litter and to test BMP effectiveness. Twenty-four freeway catchments were monitored. Half of the catchments were treated with one of five BMPs; the others were controls. Tested BMPs included increased street sweeping frequency [the results of which were included in Lippner and Moeller (2000), discussed at the end of this section], increased frequency of manual litter pick up, a modified drain inlet, a bicycle grate inlet, and a litter inlet deflector developed during the study. Litter discharges were quantified by weight, volume, and count and were further classified by composition. Roughly half the freeway stormwater litter was found to consist of paper, plastic, and Styrofoam. With the exception of cigarette butts, the origins of most litter items could not be identified because of their small size. Of the five BMPs tested, only increased litter pick up and the modified drain inlet demonstrated some reduction of litter in stormwater runoff, although the data are highly variable. Increased frequency of sweeping, the bicycle grate, and the litter inlet deflector did not effectively reduce litter in stormwater discharges monitored during the study, although the trash bags placed on the outfall to evaluate what trash was leaving the system were effective.

Street-sweeping efficacy studies have been conducted by several researchers with variable results. One of the conclusions of the EPA-sponsored Nationwide Urban Runoff Program (NURP)—in which more than $30 million was expended in an intensive 3-year investigation of urban runoff quality at 28 locations throughout the United States (U.S. EPA, 1983)—was that street sweeping was generally an ineffective technique for improving the quality of urban runoff. Similar results were reached by Pitt (1979) and Pitt and Shawley (1982). Nevertheless, recent studies suggest that street sweeping programs can be optimized to reduce significantly pollutant washoff from urban streets (Sutherland and Jelen, 1997)

Lippner and Moeller (2000) conducted a paired watershed study to evaluate how end-of-pipe litter discharges were affected by street sweeping frequency and the type of sweeper used. The study included field-tests of vacuum, regenerative air, and high-efficiency and mechanical broom sweepers to determine which sweeper type would be most appropriate for sweeping frequency analysis. Results of the tests found that while the high-efficiency and regenerative air sweepers left the pavement cleaner than the broom sweepers, large material often was lodged in the air intake hoses of regenerative air sweepers or was pushed in front of the suction head of the air machines rather than being sucked up. Also, Caltrans was concerned that the maximum operating speed of the high-efficiency sweeper precluded it from being used in freeway applications; thus, the agency chose a broom sweeper (Mobil model M-8A) for the sweeping frequency study. The analysis indicated that litter reduction from sweeping monthly as compared to weekly was not statistically significant at the 95% confidence level. Analysis of conventional water quality constituents such as metals, nutrients, oil and grease, TSS, and coliform bacteria showed that increasing sweeping from monthly to weekly actually may have increased the concentrations of hardness, total and dissolved copper, dissolved nickel, and total petroleum hydrocarbons (diesel). The cause of this is unknown, however, it could be due to the abrasive action of the sweeper on the road surface, the pollutant sorption ability of street litter no longer available once removed, or simply the random variability of the data.

In another study, Smith (2002) evaluated the street sweeping effectiveness of mechanized street sweepers for particulate removal. The first mechanized street sweeping had no observable effect on subsequent storm loads of suspended sediment. Following the second sweeping, a net increase of the suspended-sediment load was observed at one station, and a net decrease of the suspended-sediment load was observed at the second station; however, these effects were only temporary. The highway was swept a third time after continuous monitoring was terminated. The particle-size distribution in sweeper samples for the size fraction <4 mm in diameter was similar to the particle-size distribution in bottom sediment in the catch basin. The concentration of particles >0.5 mm in diameter was higher in sweeper samples than in samples from the oil–grit separators, allowing for the conclusion that the sweepers were successful in removing the larger particles.

The Wisconsin DOT Bureau of Highway Operations conducted a research project to study the effectiveness of a high-efficiency street sweeper used on an urban freeway section to control the quality of stormwater runoff from the pavement surface (Martinelli et al., 2002). The research process used a paired basin approach on a test section that was swept once per week and on a control section that was not swept during the study period. The results of the study indicated with a 90% confidence interval that there was a difference of 1% and 280% in suspended-sediment concentration (SSC) between the control and test sites. This upper limit indicates that the control site may have had higher average baseline conditions than the test site, which is one of the problems with paired watershed studies.

To eliminate the spatial variability, a before-and-after study could have been conducted (though this approach introduces temporal variability). Alternatively, a calibrated simulation model—such as the Simplified Particulate Transport Model (SIMPTM) developed by Sutherland and Jelen (1993) or the Source Loading and Management Model (SLAMM) developed by Pitt and Voorhees (2002)—could have been used. These models have been calibrated and applied successfully by some researchers to estimate loads and concentrations, as well as to evaluate the BMP effectiveness, including street sweeping. Please refer to section 3.2.10, BMP Modeling, for descriptions of studies that have calibrated and successfully applied these models.

Catch-basin cleaning is considered a source control BMP designed to reduce the potential for stormwater bypass and resuspension of previously captured pollutants and subsequent discharge to receiving waters. Dammel et al. (2001) conducted the Drain Inlet Cleaning Efficacy (DICE) Study for Caltrans to evaluate whether catch-basin cleaning improves the water quality of highway stormwater runoff. The runoff water quality was monitored and analyzed to determine any difference in water quality between stormwater discharge from a drainage system with clean drain inlets versus discharge from unclean systems. Results from 4 years of monitoring have not indicated a statistically significant difference between cleaned and uncleaned catchments for all 21 monitored cases. The DICE Study is continuing with additional sampling sites and with the sampling of litter and other macro debris from the flow stream added to the list of monitored constituents. As additional data become available, efforts will be made to determine if cleaning drain inlets has a measurable impact on the water quality of effluent emanating from Caltrans freeways.

Another Caltrans study tested three nonproprietary in-line devices that could be incorporated into existing or future highway drainage systems to remove trash from stormwater discharges, subsequently meeting the waste load allocation of the trash TMDL (Endicott et al., 2002). The pilot study included conceptual design of trash removal devices, site selection, development of device design criteria, construction, monitoring, and assessment of the performance of each device. The peak runoff generated by a 25-year storm event was set as the minimum hydraulic design criteria for the pilot GSRD. Design criteria to address operation and maintenance concerns included adequate parking and access for maintenance and monitoring vehicles; no lane closures for servicing or monitoring a device; minimized shoulder closures for major device maintenance activities; maintenance equipment, limited to equipment commonly available in the Caltrans maintenance fleet; and an annual maintenance cycle for removal of accumulated gross solids.

For this study, device effectiveness was defined as the percentage of total litter captured by the device. The pilot GSRD removed a combination of gross solids, including solids, vegetation, and litter. Removal efficiencies for gross solids ranged from approximately 82 to 100% on a wet mass (weight) basis and from approximately 55 to 100% on a wet volume basis. Removal efficiencies for litter ranged from approximately 66 to 100% on a dry mass (weight) basis and from approximately 66 to 100% on a dry volume basis.

Key findings from this pilot study include the following: (1) GSRD are sensitive to gross solids loading rates; (2) design loading rates must consider total gross solids (solids, vegetation, and litter), because the simple screening technologies used in these devices do not automatically segregate the litter component regulated under the TMDL from overall gross solids; (3) litter is a relatively small component of gross solids on both a total mass and total volume basis; (4) gross solids loading rates require further study to define the average and range of expected values; (5) screen blinding, and subsequent bypass, is the most common cause for a device to exhibit a low level of effectiveness for litter removal; and (6) gross solids storage and screen blinding prevention must be considered individually during design.

Virtually every municipality and several state DOTs have public education and outreach programs that discourage littering. However, the effectiveness of this type of source control is difficult to evaluate and therefore done rarely. Caltrans has embarked on an extensive Public Education Litter Monitoring Study (PELMS) to implement and assess a public education program targeted at reducing stormwater litter pollutants (Caltrans, 2002). Public education media rollout for the Public Education Resource Study (PERS) started in mid-February 2002, so the effectiveness of the program has yet to be determined. Stormwater litter monitoring is one of several methods that will be used to gauge public education effectiveness. Other methods include public opinion surveys and an assessment of roadside litter collection before-and-after program implementation.

3.2.2.1. Identification of Research Needs

Based on the literature review pertaining to gross pollutant stormwater control facilities and programs, litter removal using solids separation devices has been demonstrated by a number of researchers, and the effectiveness of these devices at removing large particles (>5 mm) is well documented. A smaller amount of literature is available on the effectiveness of source controls such as public education and catch-basin cleaning, particularly with regard to the overall effects of catch-basin bypass.

The effectiveness of street sweeping technologies has not been demonstrated clearly, even with numerous studies, but it appears that mechanical sweepers may be better at removing larger pollutants, and air machines may be better at removing fine particulates. The likely cause for street sweeping studies being inconclusive is that the overall reductions in runoff loads and concentrations caused by street sweeping are relatively small in comparison to the high degree of noise or variability of the data. Such noisy data require many more samples to detect differences than are collected typically. Most studies do not have the resources to collect and analyze this many samples.

One potential research need is identification of a uniform definition of gross solids (and the related components) for the purpose of standardizing data reporting. There is an ASCE/EWRI committee working on this issue, but protocols developed for highway situations may be appropriate to help standardize BMP performance.

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3.2.3. Hydraulic Assessment

One method of evaluating the performance and applicability of a stormwater control facility is to analyze the flow rates and volumes of stormwater into, within, and out of a facility. Hydraulic residence times and the volumes of overflow, or bypasses, often are used as sizing criteria before BMP construction and as performance measures after construction. The degree of short-circuiting, which is a function of BMP design, has a direct effect on the hydraulic residence time within a stormwater BMP. The hydraulic conductivity, or flow-rate capacity, for flow-based BMPs and the design volume for detention-based BMPs have a direct effect on the bypass or overflow volume for a given rainfall-runoff event. Assessment of these hydraulic phenomena sometimes is considered when evaluating the performance of individual BMPs. Other times, researchers have reported only the treated effluent, but not the amount that was bypassed. In evaluating the overall performance of a stormwater management program within a watershed, which may include a combination of nonstructural source control and structural treatment control BMPs, it often is desirable to evaluate the amount of water stored and released slowly, evapotranspired, or infiltrated throughout the watershed. Thus, this distributed BMP approach was coined LID (see section 3.2.9).

BMP design guidelines and criteria frequently include recommended or required hydraulic residence times. For instance, the City of Portland BMP design manual specifies that the outlet of stormwater quality ponds be designed such that the pond drains to the permanent pool volume in 12 hours (Woodward-Clyde, 1995). For extended detention, which is believed to provide a higher level of treatment, the hydraulic residence time may be increased by 24 to 48 hours for detention facilities. Hydraulic residence time also is sometimes a design criterion for other BMP types, such as vegetated swales, where it is recommended that stormwater be in contact with biofiltration media 5–9 minutes (Water Environment Foundation and ASCE, 1998). Despite these recommended design parameters, the relationship between BMP performance and hydraulic residence times, as well as other hydraulic characteristics of BMPs, is not understood clearly. As such, some of the common research questions with regard to the hydraulic assessment of individual stormwater control facilities include

- How do hydraulic residence times and bypass volumes relate to BMP performance?
- What design variables influence hydraulic residence times and short-circuiting?
- What methods are available to evaluate, improve, and maintain stormwater infiltration?
- What is the potential for storage and reuse of urban stormwater?

3.2.3.1. Hydraulic Residence and Bypass

A couple of studies have shown that typically the longer the hydraulic residence time, the better the overall pollutant removal performance (Kulzer, 1989; Driscoll, 1986). With regard to particulate settling, Galli (1992) noted that several researchers have found that a large portion of suspended particulates (30–70%) settle out within the first 6–12 hours of detention. Fine silt and clay-sized particles settle out over a much longer period, on the order of days and weeks.

With regard to increasing the hydraulic residence within stormwater BMPs, Newberry and Yonge (1996) studied the factors that influence the hydraulic residence on highway grass strips. They found that a change in flow rate has a greater effect on hydraulic residence than an equivalent percent change in slope and that a lower degree of soil compaction would allow for more subsurface flows and a longer average hydraulic detention time. A tracer study by Price and Yonge (1995) found that the installation of a baffle at the inlet of a detention basin would reduce short-circuiting and increase hydraulic residence. Increased sediment and adsorbed metals removal also were observed.

As a flood-control precaution or to protect the BMP, water quality BMPs often are designed to bypass stormwater runoff that exceeds their design capacity. Sometimes, bypass occurs unintentionally when filter media or inlet structures become clogged or blocked. Ultra-urban BMPs—such as storm drain inlet filters, oil–grit separators, and infiltration facilities—are the most susceptible to bypass. The overall effect of bypass on BMP performance, and ultimately receiving water quality, is relatively unknown. Consequently, several BMP performance evaluation protocols require an evaluation of BMP performance with the inclusion of bypass volumes. Very few studies were found that evaluated the effects of bypass on BMP performance.

A study by Greb et al. (1998) evaluated the effects of bypass in a Stormceptor® and a multi-chamber treatment train (MCTT) installed in public works maintenance yards. For the Stormceptor, 11 out of 45 storms bypassed the unit; the total water volume that bypassed equaled approximately 9%. The reported percent removal including the bypass volume was 22% for TSS, as compared to 25% when excluding the bypass volume. For the MCTT, the overall TSS removal efficiency was impossible to measure directly because of the water loss problems. However, it was estimated that the overall percent removal of TSS including bypass was 78%, as compared to 98% when excluding bypass.

Keblin et al. (1997) studied the effects of bypass on the removal efficiency of the Texas DOT's Seton Pond facility in Austin, which includes a sedimentation basin and a sand filter. Of the 10 storms that were monitored, the authors observed that 20% of the total runoff volume bypassed the facility, resulting in the total TSS load removal efficiency being reduced from 89% excluding bypass to 71% including bypass.

3.2.3.2. Hydraulics of Infiltration Facilities

Rather than maximizing residence time, infiltration facilities usually have the goal of maximizing percolation rates. Common types of infiltration facilities include porous pavement, infiltration basins and trenches, sand filters without an underdrain, and PETs. Sand filters or other media filters that have an underdrain are not considered infiltration facilities. Infiltration practices are one of the most valuable urban stormwater BMPs, because they help to reduce not only stormwater pollutants but also stormwater volume, which increases groundwater recharges and reduces the potential for scour and bank erosion in receiving waters. Livingston (2000) provides a comprehensive review of the successes and failures of stormwater infiltration, a summary of the lessons learned about the use of infiltration practices, and a list of recommendations of when and how they should and should not be used.

The review of highway stormwater literature revealed several studies that evaluated the hydraulics of porous pavement (Nawang et al., 1993; Goforth et al., 1984; Dempsey and Swisher, 2003; Bond et al., 1999; Pratt et al., 1995; Wada et al., 1997; and Backstrom and Bergstrom, 2000). The model simulation study by Wada et al. (1997) found that the construction of permeable pavements with infiltration pipes (a perforated pipe within a gravel bed beneath the pavement) significantly increased the percolation rate of the pavement. The study by Backstrom and Bergstrom (2000) that evaluated the hydraulics of porous pavement in cold climates found that when porous asphalt was exposed alternatingly to melting and freezing over a 2-day span (conditions similar to the snowmelt period), the infiltration capacity was reduced by approximately 90%. Based on the results of this study and previous studies, the infiltration capacity of porous asphalt was estimated to be 1–5 mm/min for snowmelt conditions. These results have serious implications with regard to the use of porous pavements in cold climate areas.

An increasing concern, especially with the implementation of EPA's UIC regulations is that if infiltration rates are too high, many pollutants could be introduced to groundwater. This issue is addressed in section 3.4, Highway Runoff Characterization and Assessment.

3.2.3.3. *Identification of Research Needs*

Based on the literature review addressing the hydraulic assessment of stormwater control facilities in relation to BMP performance, the most pressing gaps appear to be in the evaluation of the characteristics and effects of short-circuiting and bypass or overflow (e.g., ponds or wetlands discharging over the low-flow outlet or bioswales when depths and velocities for good treatment are exceeded). The influence of hydraulic residence time on BMP performance has been studied well, and it has been confirmed that detention time is correlated positively with pollutant removal (at least for particulate-bound pollutants). However, no studies were found that investigated the nature of the correlation (linearly, asymptotically, and others). Also, hydraulic residence usually is calculated simply by dividing the permanent pool volume by the average outflow discharge rate of a BMP. The true hydraulic residence time depends on the flow path through the system, which requires some means of estimating the velocity field of the system, such as the use of tracers, ultrasensitive velocity meters, or two-and three-dimensional hydrodynamic models.

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3.2.4. Pollutant Retention

Pollution retention is another import criterion for evaluating the performance of stormwater quality control facilities. During large storm events, pollutants may be flushed out of sedimentation systems, particularly in-line systems such as catch basin sumps, and be discharged inadvertently into receiving waters. Changes in water chemistry also may have an effect on pollutant mobility. For instance a decrease in pH or a change in oxidation-reduction potential, or both, may cause solid-phase pollutants to become soluble, and therefore mobile. Dry weather flows into BMPs may have a different chemistry, or the BMP, through biochemical processes, may alter water chemistry to the point that pollutants are released and remobilized. Resuspension of pollutants within stormwater BMPs can cause the BMPs to be a source of pollutants, which may translate into negative percent removals in BMP evaluation studies if mobilization occurs during storm events. If pollutants are mobilized via dry weather flows, BMP studies that focus on stormwater event monitoring alone would not detect this.

Potential research questions with regard to pollutant retention are

- What is the potential for resuspension of previously captured sediment?

- What conditions influence pollutant mobility in BMP systems, and how can these conditions be reduced?
- What need is there for more continuous monitoring of wet BMPs to assess the potential for pollutant remobilization between storm events?
- How sequestered are captured pollutants in BMPs?

Smith (2002) investigated the sediment retention of oil–grit separators and a deep-sumped catch basin. Despite the presence of bypass pipes at the inflows to the separators and the fact that the depth of bottom sediment retained in the catch basin was less than 25% of the sump depth, previously captured sediments from the separators and the catch basin sump were resuspended during several monitored storm events. For the separators, resuspension of sediments was detected at and above rainfall intensities of 0.04 in. per 5-min interval and flows >0.46 ft^3/s. The amount of resuspended sediment estimated for the separators represented about 8% of the suspended-sediment loads retained at the end of the monitoring period. The estimated quantity of suspended sediment that bypassed the separators was 16–20% higher than the amount of sediment resuspended (<0.062 mm in diameter). For the catch basin sump, the frequency of cases in which resuspension was detected did not increase with an increase in captured sediment. The estimated amount of resuspended sediment represented 18% of the final mass of retained sediment in the sump.

Results of experiments conducted by Clark et al. (2001) to determine if four potential filter media (sand, activated carbon, peat moss, and compost) could retain previously trapped pollutants indicated that permanent retention of heavy metals (copper, lead, iron, and zinc) may occur even in an anaerobic environment. However, retention of nutrients may not occur under these conditions.

In a BMP performance study by Yu and Stopinski (2001), four ultra-urban BMPs—three oil–grit separators (Isoilater, Stormceptor, and Vortechs Stormwater Treatment System) and a bioretention area—were evaluated. Monitoring results indicated that resuspension of sediment from the bioretention occurred during three of the larger monitored storm events, presumably because of minimal vegetation establishment before the study's onset. Negative removals for total nitrogen also were observed in three events of the Stormceptor monitoring. However, these events did not correspond to large events. In fact, the largest negative removal occurred during the smallest storm event. The authors hypothesized that the negative total nitrogen removals were due to a decrease in the amount of aeration inside the BMP, which would limit the oxidation of ammonia. Analysis of accumulated sediment depths in the oil–grit separators showed that the Isoilator unit lost captured sediment during 5 out of 15 storm events, with the highest loss of sediment (21.8 cm) occurring during the largest monitored rain event (87.6 mm on 3/31/00). The observed sediment depth never reached the manufacturer's recommended clean-out depth (34.5 cm and 43.2 cm, respectively). Similarly, sediment accumulations in the Stormceptor and Vortechs units were monitored. The Stormceptor unit showed consistent accumulation, except 10.2 cm were lost during the large 87.6 mm rainfall event. The Vortechs unit did not show sediment accumulation during the study, which was attributed to the unit not being installed properly.

Because of the increased use of porous pavement systems in LID designs, the pollutant retention capacity of porous pavement is of particular interest to stormwater managers. A study by Dierkes et al. (2002) investigated the pollutant retention capabilities of four different systems of paving stones: pavers with infiltration joints, porous concrete pavers with a filter-layer, greened (grass) porous pavers, and pavers with greened infiltration joints. All four systems showed very high pollution retention capacities for cadmium, copper, lead and zinc, but the greened systems and the porous pavers were more efficient than the system with the infiltration joints. Copper and lead were retained more effectively than cadmium and zinc in all of the pavement systems. In another study, the pollutant retention of the subbase of porous concrete pavers was investigated. Differences in pollution retention capacities between the subbase materials existed, with the highest pollutant retention capacities being reached by crushed stones with high contents of $CaCO_3$. Overall, the pH in the porous concrete effluent of all system configurations showed that the buffering capacities of concrete are very high, so there is little danger of a mobilization of previously captured metals from porous concrete paving systems.

3.2.4.1. Identification of Research Needs

When evaluating the performance of stormwater control facilities, it is important to consider not only the pollutant removal capacity under a variety of hydrological and influent quality conditions but also the pollutant retention capacity over long time periods and under both storm and low-flow conditions. Few studies were found that investigated the potential for leaching or resuspension of previously captured pollutants. The studies that were found indicate that resuspension of sediments in catch basin sumps and oil–grit separators may be significant. Resuspension also may occur in bioretention areas before complete establishment of vegetation. Heavy metals do not appear to go easily into the dissolved phase once captured, but nutrients do, particularly if there is a change in the oxidation-reduction potential. The pH of the stormwater likely has some effect on the solubility of captured metals; however, concrete and other construction materials containing high concentrations of $CaCO_3$ have a high buffering capacity and tend to raise the pH of stormwater on contact. Therefore, a slight decrease in the pH of rainwater is not expected to cause a substantial increase in dissolved metals concentrations, especially if the stormwater flows over or through porous concrete.

This is a research topic area requiring a more detailed literature review before substantiating a research need, but it is more appropriately discussed under the section Highway Runoff Characterization and Assessment. For the subtopic of pollutant retention, it appears that the primary research needs and gaps are in identifying the conditions—such as pH, oxidation-reduction potential, hardness, and organic content—that affect desorption or dissolution, or both, of captured pollutants in stormwater treatment systems.

3.2.4.2. Primary References

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3.2.5. Methods to Improve Pollutant Removal in Existing Stormwater Systems

Caltrans is conducting a multiyear study in Los Angeles and San Diego to examine the technical feasibility, costs, and operation and maintenance requirements of retrofitting structural BMPs into existing highway and related infrastructure (Currier et al., 2001). Thirty-three locations are being retrofitted with 39 BMPs using 12 different types of BMP technologies. Automated monitoring stations have been installed upstream and downstream of each BMP to determine removal efficiencies from flow weighted composite samples. Constituents monitored in the runoff include suspended solids (e.g., sediment), metals, nutrients, and organics (e.g., gasoline). To date, most projects have been sited, designed, constructed, and monitored for at least one year. The purpose of the program has been to identify the problems and solutions that occur with structural BMP retrofits and to collect operation, maintenance, and performance data for the BMPs. Results have indicated the existence of substantial construction, maintenance, and cost challenges in retrofitting existing infrastructure with conventional structural BMP technology. Water quality monitoring results have indicated that average pollutant removal efficiencies are consistent with published values. The information collected on completion of the study will enable more accurate prediction of BMPs cost and performance for treating highway runoff.

3.2.5.1. Flood Control Retrofits for Water Quality Enhancement

Only eight states have conducted studies or prepared reports on the retrofitting of existing stormwater management measures at DOT facilities.

Before the CWA, stormwater management primarily involved protecting people and property from floods through the construction of flood conveyance and detention facilities. Over the past few decades, however, the emphasis of stormwater management has broadened to include quality control and quantity control. In response to these dual stormwater management objectives, existing flood control basins often are retrofitted for water quality enhancement. The primary research question with regard to retrofitting flood control basins is how can detention facilities be modified to provide water quality benefits without compromising flood control objectives?

Walesh (1991) presented approaches for retrofitting existing stormwater detention facilities to improve quantity control, add quality control, improve operation and maintenance, reduce safety hazards, enhance aesthetic attributes, and add recreation features. A matrix was used to illustrate retrofitting objectives for stormwater detention facilities versus available retrofitting measures. Examples presented were all based on actual facilities.

Barth (2000) discusses the conversion of existing detention facilities (dry detention basins) into more functional treatment practices. The author states that the modification of older basins into stormwater wetlands or wet ponds is perhaps the easiest retrofit option for the following reasons: (1) stormwater is already managed in a distinct location, (2) there is already some resident acceptance and understanding of stormwater management, and (3) it usually involves minimal impacts to secondary environmental resources. Modification options include (1) excavating the pond bottom, (2) raising the embankment, (3) modifying the outlet structure, or (4) increasing the flowpath by using baffles, berms, and other treatments.

The conversion of a dry detention pond at Villanova University in Pennsylvania to a constructed wetland was presented by Traver (2000). The steady, year-round base flows necessary for wetland establishment previously were piped through an underdrain below the detention basin. In the design and construction of the extended detention wetland, multiple meanders and gravel berms were placed to maximize water storage. A sediment forebay was installed off-center to allow for sedimentation of small to medium-size storms, but to be bypassed by larger storms, so that resedimentation was avoided and flood protection was maintained. Several wetlands plants were sown throughout the site to allow for competitive selection and maximum nutrient uptake. The outlet was modified slightly to sustain the wetland water surface elevation and to maintain the original flood control hydraulics of the original detention basin design. The site is being monitored for both water quality and water quantity data.

Decker and Guo (2003) evaluated the feasibility of retrofitting with the installation of a new subsurface flow gravel-bed wetland system to enhance water quality treatment of two existing dry detention basins within a single-family residential development in Morris Township, New Jersey. An overall model of the entire project area was prepared using the U.S. Army Corps of Engineers HEC-1 Model with the Natural Resources Conservation Service Methodology to facilitate calculation of peak flows and hydrographs, routing through the detention basins, and combination of hydrographs. The model was calibrated and verified based on previously measured storm events. Based on the modeling analysis, the researchers concluded that the initial preferred retrofit plan should be rejected for the following reasons:

- The loss of flood storage due to the filling inside the basin would result in an increase in peak flows downstream.
- The flat slope of the existing basins prevented the provision of a positive slope from the inlet to the outlet or the installation of any peninsulas to increase particle flow distance.
- Cost of an underground concrete forebay system would be excessive.
- Introduction of the forebay would result in additional friction and head loss that would cause an increase in flood elevations upstream of the upper basin.
- The proposed 762-mm diameter overflow pipe from the flow splitter would be required to be raised to provide a positive slope to the outlet. Raising the pipe would increase the upstream hydraulic grade line and would cause flooding upstream of the upper basin.

Additional alternatives to minimize hydrologic–hydraulic and environmental impacts for retrofitting at the upper basin in combination with enlarging or modifying the lower basin were evaluated and ultimately rejected because of excessive costs, site constraints, or adverse environmental impacts. An alternative site for the subsurface flow wetland between the two flood control basins was recommended.

3.2.5.2. Coagulants

Methods to improve pollutant removal in existing stormwater systems can be borrowed from technologies used at municipal treatment facilities. One of the most common technologies is the addition of coagulants—such as aluminum sulfate (alum), ferric chloride, and lime—to enhance coagulation and sedimentation rates. As compared to other coagulants, alum has been shown by several researchers to provide a high pollutant removal rate and a stable end product, as long as pH is monitored and adjusted as needed (Harper et al., 1999; Escobar et al., 1998). A study by Price and Yonge (1995) evaluated four coagulants (alum, ferric chloride, and two proprietary cationic inorganic coagulants: SWT 848 and SWT 976) for their ability to enhance removal of sediment and metals. Results indicated that alum and SWT 976 were ineffective at destabilizing the sediment suspension and initiating floc formation in the relatively short rapid-mixing period. Ferric chloride and SWT 848 exhibited rapid floc formation and good solids settling characteristics, but ferric chloride was sensitive to dose, requiring dose optimization for each of the four test flow rates; SWT 848 did not exhibit dose sensitivity over the range of flow rates studied.

In another study, one by Babin et al. (1992), researchers used lime and alum in an urban stormwater pond to reduce pH concentrations in the water column and to precipitate out particulate matter. Of the two chemical treatments, the researchers found that a lime–alum mixture was better at controlling macrophytes and shoreline filamentous algae, but alum was better at controlling planktonic algal growth and turbidity. A combination of both chemicals, lime (which elevates pH) and alum (which lowers pH), is used to maintain pH within a desirable range (6–10). Overall, water quality can be improved through the application of alum–lime mixtures; however, these applications will have to be applied routinely throughout the open-water season because of continuous nutrient inputs from point and nonpoint sources.

The Southwest Florida Water Management District, under its Stormwater Research Program, conducted a study to determine the feasibility of using an in-line alum injection facility as a stormwater treatment retrofit (Carr, 1999). The water quality constituents analyzed during the study included various forms of phosphorous and nitrogen, and several metals. Individual storm data revealed that event mean percent loads were reduced. Reductions were observed in total phosphorus (37.2%), ortho-phosphorus (42.7%), ammonia (24.5%) and nitrate-nitrite (52.2%). A detailed analysis of the potential for aluminum toxicity to various fish and benthic species was conducted, and concentrations of monomeric species of dissolved aluminum were measured at the inflow and outflow of the injection facility at levels that have been shown to be toxic or to affect adversely golden shiners, striped bass, rainbow trout, and *Daphnia magna* (a zooplankton).

An innovative coagulant and adsorbent that has not been used widely for stormwater treatment is chitosan, a biopolymer of shrimp and crab shells that is manufactured by Vanson HaloSource, Inc. Similar to alum, chitosan causes coagulation of fine sediment particles, which then allows for gravity settling, biofiltration, sand filtration, or cartridge filtration. FHWA used chitosan to reduce turbidity and enhance sand filtration in runoff from a road-widening project from a section of Big Salt Lake Road on Prince of Wales Island, Alaska (Natural Site Solutions, 2002). Application of chitosan enhanced settling and reduced turbidity in sedimentation tanks by more than 90% and enhanced sand filtration that further reduced turbidities to less than 5 NTU. In another highway construction project, Washington State DOT used chitosan for the treatment of construction site runoff from the Washington State I-90 Sunset Interchange Issaquah Project (Washington

State DOT, 2003). Chitosan, when added to settling pond effluent, caused the fine sediment particles to bind together and was removed with the sediment during sand filtration. Chitosan also removes phosphorous, heavy minerals, and oils from the water.

Other areas are considering the use of coagulants for post-construction runoff, including the Lake Tahoe area, where fine particulates and nutrients have been identified as reducing the lake's clarity. In areas where sands are used for winter traction and the applied sands are ground into fine materials, coagulants may be one of the only approaches for achieving desired suspended sediment levels.

3.2.5.3. Identification of Research Needs

The literature review addressing methods for improving pollutant removal in existing stormwater control facilities indicates a few potential research gaps. With regard to retrofitting flood control facilities to include water quality treatment, there appears to be a need for detailed design guidance that includes cost–benefit comparisons between retrofit alternatives, with consideration of the overall feasibility and potential impacts to flood protection. Sponsoring research to evaluate whether other less conservative flood control methods could be employed safely is another option. These methods could include using more refined continuous simulation approaches to assess flood detention needs.

With regard to coagulants, the literature reviewed for this study as well as the plethora of literature available in the area of wastewater management, showed that further research in this area likely is not a high priority. However, soil amendment recommendations for more passively improving performance in BMPs need to be developed. In selected locations, coagulant use may be necessary to achieve water quality goals. For these areas, more detailed design guidance for highway situations may be valuable. The potential impact of coagulants on receiving waters may warrant further research, particularly for fairly new products or products—such as chitosan—not used widely for stormwater treatment.

3.2.5.4. Primary References

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3.2.6. Erosion and Sediment Control

Erosion prevention reduces the amount of sediment generated from the land surface. Once erosion occurs, sediment-control practices are necessary to limit the downstream movement of the sediment. The review of erosion and sedimentation controls included in this section is limited to studies that have evaluated the effectiveness of stormwater BMPs designed to control the detachment (erosion controls) and transport (sediment controls) of sediment from road surfaces, right-of-ways, and banks of receiving waters. The effects of scour, sedimentation, and turbidity on receiving waters are discussed in section 3.5.2. Characterization of highway construction runoff is discussed in section 3.4.7. This review, as with the preceding and subsequent sections, does not attempt to exhaust the literature on the subject, but instead provides a brief summary of some key studies. Potential research questions with regard to erosion and sedimentation controls include

- How effective are temporary soil stabilization and erosion controls at keeping particulates in place? What is the minimum grain size effectively held in place?

- Are vegetated erosion controls more cost-effective than nonvegetated controls?
- What are the differences in erosion control effectiveness between native and nonnative vegetation?
- What are the variables that affect seed germination?
- What are some alternatives to riprap for in-stream channel stability BMPs?

The most effective erosion prevention measure is almost always minimization of the amount of land being disturbed. Once land is disturbed, erosion prevention controls must be implemented. Some common controls include erosion mats, compost and mulch, and hydroseeding.

A study by Miller et al. (2002) evaluated the effectiveness of composted yard waste mulch, sod, and erosion mats in controlling erosion and establishing permanent vegetation along Florida highways. The study found that the composted mulch can effectively control erosion but does not necessarily facilitate the growth and establishment of turf grass or other vegetation. The composted mulch can provide slope stability for periods of at least 18 months, and probably longer, with or without vegetative growth. Lack of sufficient rainfall during the study period severely limited establishment of vegetation (and also limited erosion) in compost mulch-treated plots. Sod and erosion control mat treatments had greater turf grass and vegetative cover, but all treatments effectively controlled erosion during the study. Seeding experiments indicated that seed incorporation into composted yard waste mulch may not be necessary during periods of abundant rainfall; however, it is necessary during periods of low rainfall. Erosion control mats can be seeded either above or below the mat without affecting seed germination.

In a 5-year research project by Banovich and Outcalt (2002), three test zones were established to evaluate various erosion control materials and methods on cut and fill slopes of US 40 on the west side of Berthoud Pass, a high altitude (~10,000 ft) Colorado pass. Snowmelt runoff and severe spring and summer rain storms frequently washed away the easily eroded sandy soil, preventing vegetation from establishing itself on the slopes, some of which were steeper than 1 : 1. The results of the study showed that all of the cellular confinement materials and soil retention blankets were successful in holding and reinforcing the plants' root systems. The average density of plant shoots in the test areas (blankets and geocell materials with seeding, fertilizer, and mulch) ranged from -20% to 276% of the density in the control sections (seeding, fertilizer, and mulch only).

Based on observations of the surface conditions and on quantities of plant material on the slopes, it appeared that all of the blankets and cellular confinement products provided reinforcement to the scarp-forming area of the cut slopes. Based on the plant counts in the six test areas, the effectiveness of the products ranks as follows from most effective to least: Enviro Grid, Geoweb, Armater Geocell, Enkamat 20-S, Multimat, Pyramat. The Pyramat blanket in one of the zones did not conform to irregularities in the slope as well as the other products. This is the only zone where the plant count was lower than the count in the control section. Failures occurred in the Armater test section when the anchor system failed and where the product was placed over a large boulder.

Polyacrylamides (PAMs) are water-soluble synthetic polymers widely used in furrow irrigation to reduce erosion and turbidity. McLaughlin (2002) evaluated PAM, in the laboratory as well as in the field, for construction site erosion and turbidity control. A laboratory screening was conducted for 11 PAMs on 13 sediment sources from North Carolina DOT construction sites. In addition, field tests were performed for two PAMs at two rates, with and without straw mulch and seeding, on a 2 : 1 fill slope, a 4 : 1 cut slope, and a 4 : 1 fill slope. The results indicated that no one PAM is effective for turbidity reduction on all sediment sources but that several are promising for many soils. Superfloc A-100 ranked among the top three flocculants for 10 of the 13 sediment sources. Some PAMs are equally effective but at different doses, some as low as .075 mg/L, or a few grams per 1,000 ft^3 of water. Tests of PAMs with and without mulching on 2 : 1 slopes at North Carolina DOT construction sites resulted in erosion rates that were 20 times greater on bare soil plots after the first seven events, with or without PAMs, compared to those mulched with straw and seeded to grass. During the eighth and last event, in which more than 6 cm of rain was recorded, rates of more than 50 tonnes/ha were recorded for a single, intense storm event for the bare soil plots compared to 3–9 tonnes/ha on the mulched and seeded plots. PAMs at the highest rate (11 kg/ha) were effective in reducing erosion and turbidity on the 4 : 1 cut slope with a clay loam texture, but the effect declined with each storm event. On the sandy 4 : 1 fill slope, there was no evidence of any effects of PAMs, even at an application rate of 20 kg/ha.

Nwankwo (2001) evaluated the effectiveness of PAMs at controlling erosion from three highway construction projects around Wisconsin. Comparison of CFM 2000, PAM, with other erosion-control products that are used currently by Wisconsin DOT, showed that this product is effective in controlling erosion, is applied easily, and, at a material and installation cost of approximate $1,250/ha ($500/acre), is relatively inexpensive when compared to the $11,250/ha ($4,500/acre) for Wisconsin DOT Class 1 Type A erosion mats. Also, when the manufacturer's recommended application rate is followed, the product was found to be environmentally safe. The performance of CFM 2000, PAM, in controlling erosion is based on the fact that it binds soil together into particles of a larger size; the binding makes the soil more resistant to collapse, dispersion, and shear forces. Soil infiltration rates also appear to increase with the use of PAMs, resulting in more available water for the seeds to germinate, lower runoff, and less soil detachment from erosion.

CFM 2000, PAM, performed comparably to erosion mats and better than mulch and seed on slopes of 2 : 1 or less in controlling erosion before the establishment of permanent vegetation. The combinations of the polymer, seed, and mulch performed the best for erosion control and vegetative growth. From the data of on the CTH N test plots it follows that Test Plot 2 (Class 1 Type A erosion mat plus seed) and Test Plot 3 (PAMs, mulch, and seed) produced the smallest amounts of eroded soil of all five test sections after 6 months of observation. Initial indications also showed that Test Plot 3 produced not only the most seed germination and the densest vegetation but also the tallest grass plants. Although field observations 8 months after the products were placed showed no significant difference in plant height, the test plot with PAMs, mulch, and seed appeared to have the denser vegetation.

The Georgia DOT recently completed a research study to evaluate the effectiveness of using PAMs in erosion control and runoff turbidity reduction on Georgia's DOT construction projects and to establish BMP guidelines for Georgia DOT. A report has not yet been prepared.

Caltrans (2002) initiated a series of laboratory experiments under a variety of rainfall regimes and erosion control treatments to identify and select plant species that demonstrate initial fast growth and potential long-term erosion control. The plants examined included native and nonnative naturalized species. Preliminary results indicated the benefits of using jute netting for optimum vegetation cover. Results also indicated that the type of vegetation cover (grass, legume) was affected by the erosion control treatment. The greatest water quality improvements were seen with the use of bound fiber matrix, jute, and straw. Initial results indicated that sediment amounts decreased with the hydroseeding of native seeds as compared to plug planting. Soil roughening and using crimped straw were shown to be the most effective forms of erosion control on test plots in combination with vegetation. Also, results showed that native vegetation was affected negatively when fertilizer was applied on the test plots.

California Polytechnic State University, in conjunction with Caltrans, investigated soil stabilization treatments and burial depth influences on the germination capabilities of seven native California plant species and annual ryegrass (Chiaramonte et al., 2003). Six treatments—gypsum, gypsum and wood fiber, guar tackifier, bona fide fiber matrix, wood fiber, and no treatment—were applied hydraulically to the soil surface. One hundred seeds of eight plant species (*Lotus scoparius*, *Lupinus succulentus*, *Artemesia californica*, *Eriogonum fasciculatum*, *Escholzia californica*, *Bromus carinatus*, *Achillea millefolium*, and *Lolium multiflorum*) were hand planted into each treatment. *Eriogonum fasciculatum*, *Artemesia californica*, and *Lotus scoparius* experienced less than 18% germination for all treatments. *Lupinus succulentus* experienced less than 13% germination for all treatments. *Lolium multiflorum* (ryegrass), with the highest germination rate for all species, had higher than 86% germination rates for all treatments. The bona fide fiber matrix treatment resulted in the lowest overall germination percentages, and gypsum and wood fiber treatment resulted in the highest overall germination percentages. The depth resulting in the greatest germination percentage was the 0.25-inch burial depth.

The use of nonnative species for roadside erosion and sediment control has become an issue in many states because of the related invasive and aggressive establishment. Commonly used species like reed canary grass, sweet clover, perennial rye, smooth brome, and crown vetch have led to weed problems in many areas, in some instances even leading to the plant being listed on states' noxious weed lists. This issue has prompted FHWA to prepare the handbook *Roadside Use of Native Plants* (http://www.fhwa.dot.gov/environment/handbook.htm).

Landphair et al. (2001) evaluated the benefits and performance of native plant materials compared to an introduced species commonly used in the erosion control mixes for the stabilization of roadsides in Texas. The study found that wildflower-only mixes did not prove successful; there was some germination in the first year of planting, but the vegetation appeared to be gone by the second year of the project. A recent check of the plots, however, revealed a greater persistence than was evident in 1999 and 2000. Bermuda grass was very aggressive in the first few years of planting. Where researchers originally planted native grasses and forbs, the latter began to gradually displace the Bermuda grass. This displacement likely can be attributed to shading of the low-growing invaders and the fact that mowing was being done at this time.

Native grasses will continue to increase if mowing is not permitted. However, stands of natives will still require some cultural management, such as mowing or burning, to maintain their vitality and to prevent the invasion of woody species (if woody species are not desired). The erosion control properties of native grasses do not appear to be as effective as the grass mixes currently used by Texas DOT. This is probably a function of their clump-forming growth habit and the slow-developing nature of the native species. This finding argues in favor of the practice of using nurse grasses with the native prairie species. The vegetation reached at least 70% cover by the second year. However, the aesthetics of the natives probably would not meet expectations during some parts of the year. Finally, there was no evidence that the native plant materials made any more significant difference than the other plant materials in the rate of surface erosion or contributed to any increase in tensile strength of the surface soil layer. However, in 2 or 3 years, the larger natives, such as witchgrass and Little Bluestem, will develop more mature root systems that may indeed show some increase in soil shear strength.

Riprap is used commonly for roadway protection at streams and often is used at the expenses of increased water temperature and decreased quality of stream habitat due to riparian vegetation removal. Researchers at Oregon State University investigated the potential for integrating riparian vegetation into stream bank protection designs (Klingeman et al., 2002). Based on the research, it appears that vegetation may be incorporated safely into riprap projects at the time of project construction. However, allowing vegetation to grow in existing riprap requires caution because the riprap systems were not designed with this in mind, which introduces more uncertainty and the possibility of failure. Examination of some revetments that have growing vegetation suggests that riprap rock displacement does occur and that adjacent rocks are pushed up along the trunk. However, rock displacement does not diminish the riprap integrity when the tree is part of an extensive mass of vegetation growing in the riprap, as the flow resistance provided appears to diminish the local velocities at the vegetated riprap. Isolated trees in riprap have not yet been observed, so judgment is reserved on such conditions.

NCHRP Project 24-19, Environmentally Sensitive Channel- and Bank-Protection Measures, includes the development of selection criteria; design guidelines; and techniques for the type, size, and placement of environmentally sensitive channel- and bank-protection measures. The selection criteria, guidelines, and techniques are based on engineering and environmental considerations. Vegetated riprap and riparian habitat are among the many different research areas.

3.2.6.1. Identification of Research Needs

With regard to temporary vegetation controls, there is seemingly sufficient research with respect to the erosion control effectiveness of compost/mulch, erosion control mats and blankets, and cellular confinement technologies. Also, there is sufficient guidance in this area (see Appendix B for a list of guidance manuals). The effectiveness of erosion controls at removing fine particulates does not seem to be covered adequately in the literature. However, the use of PAMs or other flocculants in conjunction with temporary vegetation controls holds promise for controlling erosion of fine particulates.

The application of PAMs as a highway erosion control BMP is fairly new, so there are a limited number of studies available in the literature with regard to highways. However, the two studies cited above indicate that the use of PAMs is indeed an effective erosion control BMP. In fact, the use of PAMs is one of the recommended BMPs in the California Stormwater Quality Association's Construction Handbook (www.cabmphandbooks.com). Furthermore, there are several studies in the realm of irrigation and agricultural practices that demonstrate its effectiveness and environmental safety (http://www.nwisrl.ars.usda.gov/pampage.shtml). Therefore, further research on the effectiveness of PAMs is not warranted, unless, as stated above, the research involves the use of PAMs to enhance the effectiveness of other BMPs.

With regard to native versus nonnative vegetation, it appears that more research on how to increase germination and survival rates, as well as overall soil coverage, of native vegetation is needed. The two studies presented both indicate that native species are not as effective at establishing themselves after being applied hydraulically to slopes. The Texas DOT study suggests that the native species are not as effective at controlling erosion as the grass mixes currently used; however, this likely is due to the density of vegetation establishment.

With regard to bank protection research, the primary research needs identified by Klingeman et al. (2002) are (1) to evaluate and compare different types of vegetation for riprap planting; (2) to study the necessary top elevation for conventional riprap as a function of velocity, turbulence, and flow duration; (3) to compare terraced versus sloping riprap in terms of hydraulic performance and planted vegetation success; (4) to evaluate alternative current deflectors that have a lesser effect on aquatic habitat than riprap, but are effective in preventing bank erosion; and (5) to conduct more-detailed inspection of riprap where vegetation is now growing or has grown in order to better understand its impacts to bank stability.

3.2.6.2. Primary References

Banovich, M., and W. Outcalt. *Evaluation of Slope Stabilization Methods (US 40 Berthoud Pass)*. Final Report, Colorado Department of Transportation Research Branch (2002) 22 pp.

Caltrans. *Rainfall Simulation: Evaluating Hydra Seeding and Plug Planting Technologies for Erosion Control and Improved Water Quality*. Vegetation Establishment and Maintenance Study, Experiments: RS2 and RS3, Central Coast District 5 (2001–2002) 131 pp.

Chiaramonte, M., Scharff, M., Hallock, B., and M. Curto. Effects of Erosion Control Treatments on Native Plant and Ryegrass Establishment. *Proc., International Erosion Control Association (IECA) 34th Annual Conference and Exposition*, Las Vegas, NV (February 24–28, 2003).

Klingeman, P., Pyles, M., Hibbs, D., and B. Kauffman. *Roadway Applications of Vegetation and Riprap for Streambank Protection*. Final Synthesis Report, Oregon Department of Transportation Research Group (2002).

Landphair, H. C., Schutt, J. R., and J. A. McFalls. *Native Vegetation or Bermuda Grass? Testing the Erosion Control and Engineering Properties of Roadside Vegetation*. Project Summary Report, Texas Department of Transportation, Austin (2001) pp. 1504–1505.

Nwankwo, K. N. *Polyacrylamide as a Soil Stabilizer for Erosion Control*. Final Project Report, Wisconsin Department of Transportation, Milwaukee (2001) 29 pp.

McLaughlin, R. A. *Measures to Reduce Erosion and Turbidity in Construction Site Runoff*. Research Project Report, North Carolina Department of Transportation (2002) 31 pp.

Miller, G. L., Black, R. J., and G. Kidder. *Erosion Control Along Florida Roadways*. Florida Department of Transportation, Environmental Management Office (2002) 88 pp.

3.2.7. Design Variables Affecting BMP Performance

The performance of stormwater control facilities is believed to be affected in large part by design variables such as geometry, surface area, outlet control structure, and vegetation density and type. Because of site- and project-specific constraints, BMPs of the same type that follow the same design criteria and guidelines may end up vastly different in terms of performance. In fact, differences in BMP designs likely account for a large amount of the variability observed among various BMP performance findings, such as those compiled in the ASCE/EPA BMP Database (www.bmpdatabase.org). The reanalysis of the BMP database conducted by Strecker et al. (2003) indicated that some design parameters (e.g., the capture volume of a BMP relative to monitored storm volume for volume-based BMPs) are found to be statistically significant with regard to performance.

Design requirements and recommendations provided in BMP design manuals (see Appendix B for a brief list of available design manuals) often are based on a limited number of studies, the majority of which are conducted in laboratories where only a limited number of design configurations are investigated under strictly controlled conditions. Alternatively, they have been based on good engineering judgment. As discussed above in section 3.2.3, Hydraulic Assessment, the positive association of BMP performance and hydraulic residence has been well documented, so BMP design criteria often are composed in terms of detention or contact time (see section 1.1.2), and design guidelines often are intended to increase hydraulic residence.

Some potential research questions with regard to design variables and BMP evaluation include

- How do BMP geometry or specific surface area, or both, affect pollutant removal?
- Other than overall size relative to incoming storms, what are the most influential design variables affecting the performance of a BMP?

A study by Barrett et al. (1997) investigated the impacts of swale length, water depth, and season of the year on removal efficiency of a highway swale in Austin, Texas. Results indicated that swale length and water depth affect the removal of constituents. TSS removal efficiency was found to be reduced as water depth increased. The reduction in removal efficiency confirmed expectations, since the filtration action of the grass blades was expected to be lower for higher water depths.

Removal of other constituents was not correlated as strongly with water depth. Pollutant removal efficiency increased with length, but the increment of increased efficiency diminished as runoff proceeded down the swale. This trend was evident especially for TSS, chemical oxygen demand, total phosphorus, and metals. The majority of removal occurred in the first 20 m of the swale for these constituents.

A study related to the one by Barrett et el. investigated the effect of a swale underdrain on the removal efficiency (Walsh et al., 1997). During nine experiments, simulated highway runoff was sampled on the surface of a swale and from the swale's underdrain pipe after percolating through a top layer of grass sod, 16 cm of topsoil, and 6 cm of gravel. Concentrations of constituents in runoff that had percolated through the soil in the swale generally were lower than the concentrations in surface runoff after 40 m of treatment by the swale. The underdrain water quality demonstrated the filtering capability of the soil and reflected water quality of recharge for groundwater in situations with shallow soils.

Petterson et al. (1999) studied the effects of specific surface area (i.e., the ratio of the pond area and the impervious catchment area, m^2/ha) on the pollutant removal efficiency of four stormwater ponds in Sweden. Each pond had a different specific surface area, but the depths were similar (1.2–1.7 m). The results of the comparison showed that the removal efficiency of TSS, phosphate, copper, lead and zinc increased up to a certain level of surface/impervious area, 250 m^2/ha, and above this level the increase was not as significant. Nitrogen showed a less significant, but similar trend. However, the pollutant removal efficiency of nitrogen was low for all of the ponds.

In a study by Horner (1990), the pollutant removal effectiveness of laboratory model-scale sedimentation pond designs was evaluated. The results of the laboratory tests demonstrated that the following design features, in concert, maximized actual water residence time to promote sedimentation: (1) length/width ratio of 5:1; (2) series arrangement of two chambers rather than a single pond of equivalent size and shape; and (3) use of a perforated riser outlet.

To verify these results in a full-scale application, a sedimentation pond was designed according to the laboratory findings, constructed in a highway right-of-way, and monitored for pollution-control performance. Another sedimentation pond without these design features was tested for comparison. Samples were analyzed for solids, metals, phosphorus, and organic content. Results demonstrated that the ponds designed according to the laboratory findings were both more efficient in pollutant removals and less costly (per unit area served) than the pond to which they were compared.

3.2.7.1. Identification of Research Gaps and Needs

Based on the review of literature, it is apparent that some of the primary design variables affecting BMP performance—such as outlet structures, baffles, berms, and vegetation density, in addition to the volume a system is able to capture—are those that control flow. Design features specific to individual types of BMPs, such as specific surface area for detention facilities and flow length for the swales, also are significant factors to consider when evaluating and comparing BMP performance. These design variables are related directly to physical treatment mechanisms of sedimentation and filtration. Other design variables that are more related to the bio- and geo-chemical treatment mechanisms—such as vegetation and soil type—also may be important design factors. However, no studies were found that compared BMP performance according to these variables, indicating a potential research gap.

One of the problems addressing research gaps in this area is that in order to provide verification with field studies, a large number of BMP studies with different BMP design attributes are needed. One purpose of the National BMP Database is to provide a repository for design and performance data to facilitate future research on BMP design versus performance. Recent ASCE database project efforts have included conducting this type of analysis, but given the relatively small number of BMPs in most BMP categories and the large number of design parameters, short-term research in this area could be premature.

3.2.7.2. Primary References

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Horner, R. *Improving the Cost Effectiveness of Highway Construction Site Erosion and Pollution Control*. Final Report GC 8286-Task 7, Construction Erosion Control-II, Washington State Transportation Commission, Federal Highway Administration (January 1990).

Petterson, T. J. R., German, J., and G. Svensson. Pollutant Removal Efficiency in Two Stormwater Ponds in Sweden. *Proc., 8th International Conference on Urban Storm Drainage*, Vol. 2, Sydney, Australia (August 30–September 3, 1999) pp. 866–873.

Strecker, E. W., Quigley, M. M., and B. R. Urbonas. A Reassessment of the Expanded EPA/ASCE National BMP Database. *Proc., National Conference on Urban Storm Water—Enhancing Programs at the Local Level*, Chicago, IL (February 17–20, 2003) pp. 555–573.

Walsh, P. M., Barrett, M. E., Malina, J. F., and R. J. Charbeneau. *Use of Vegetative Controls for Treatment of Highway Runoff*. Research Report 2954-2, Center for Transportation Research (1997) 125 pp.

3.2.8. Unit Processes

As noted in the premeeting report for the 2002 TRB Research Needs Meeting (Sansalone, 2000), with regard to modeling of BMP unit processes, sedimentation and infiltration appear to be well covered in the literature. However, other BMP water quality treatment unit processes—such as sorption processes (absorption and adsorption), phytoremediation, solar radiation, and volatilization—need to be studied further before reliable BMP performance models can be developed. The lack of information on the modeling of BMP treatment trains appears to be a knowledge gap, as does the decrease in the treatment efficiency of BMPs as a function of time.

As part of NCHRP Project 25-20(01), Evaluation of Best Management Practices for Highway Runoff Control, the project team led by Professor Wayne Huber of Oregon State University will evaluate the performance of approximately 20 different types of highway BMPs from a unit processes perspective. From a unit processes point of view, stormwater controls can be partitioned into approximately four to nine fundamental process categories (adapted from Metcalf and Eddy, 2003):

- Sedimentation—as in ponds, basins, or small storage devices—including the possibility of resuspension;
- Filtration and adsorption, trash racks, screens, sand filters, compost filters, soil, and vegetation;
- Infiltration, in which filtration is accompanied by removal (redirection to the ground) of surface water runoff, including porous pavement and concrete blocks;
- Hydrodynamic devices, as in swirl concentrators or other secondary current devices;
- Biological treatment and uptake, within storage devices or in combination with infiltration, as in bioswales and wetlands;
- Oil–water separators and devices that rely upon density differences;
- Chemical treatment to enhance flocculation, use of alum or for disinfection, and use of chlorine;
- Reduction in runoff volumes via evapotranspiration; and
- Combinations of all or some processes (e.g., in ponds, wetlands, and swales).

The final report will include a section that identifies gaps and research needs with regard to BMP performance characterization and statistical assessment.

3.2.8.1. Identification of Research Needs

Based on the fact that (1) Project 25-20(01) was initiated to begin filling highway stormwater performance evaluation and assessment research gaps identified by earlier investigators and (2) the final report will include the identification of additional research gaps and needs with regard to unit process evaluations, it is deemed premature at this time to include such an identification in this report. However, based on the opinion of the 25-20(01) project team, the most likely gap will be treatability data and information that can be used to characterize the fundamental removal processes (unit processes) in action within a given BMP, as well as the simple lack of monitoring data of several different BMP types.

3.2.8.2. Primary References

Sansalone, J. The Role of Water in Ecologically Sustainable Transportation. In *Transportation in the New Millennium*, Committee on Hydrology, Hydraulics, and Water Quality, TRB, National Research Council, Washington, DC (2000).

Metcalf and Eddy, Inc. *Wastewater Engineering—Fourth Edition*. McGraw-Hill, New York (2003).

3.2.9. Low Impact Development/ Distributed BMPs

LID technologies provide tools that can promote with maximum efficiency the dual goals of environmental protection and transportation system improvements. LID technologies are based on using the cumulative effects of multiple, redundant, decentralized stormwater management techniques to meet quantified stormwater management thresholds. LID is designed to create a multifunctional–multibeneficial use in every aspect of the urban landscape to manage runoff and, where possible, to restore or maintain effectively the natural hydrologic and water quality regimes.

The water quality and economic benefits of LID have been demonstrated successfully for residential, commercial, and industrial development applications in the United States, Europe, and the Pacific Rim nations (see www.epa.gov/owow/nps/lid for a list of studies). In many cases, LID has been shown to be more cost-effective as it makes multifunctional use of the landscape to manage runoff on site, and, therefore, reduce conventional drainage infrastructure. For linear transportation systems, LID can allow transportation agencies to maximize the use of existing rights-of-way for stormwater management, reducing the need to procure additional land to meet stormwater management objectives, and thereby can reduce project costs.

This relatively new approach shows tremendous potential, particularly in highly urbanized areas, for new development and retrofit projects. At the present time, a design manual exists for suburban residential development in Prince Georges County, Maryland (see Appendix B for this and other LID guidance references). Communities and resource agencies across the nation rapidly are adopting LID practices as a new alternative to help meet regulatory requirements and resource protection goals.

Since LID is a relatively new practice, many special considerations need to be addressed for linear transportation systems. Some of the characteristics of linear transportation systems that present challenges for LID methods are extensive cut-and-fill situations that cross multiple streams, drainage divides, limited rights-of-way, multiple project phases, and limited maintenance resources. Key planning and design LID strategies that have been used for urban retrofits and green development include impact avoidance, minimization, strategic timing and routing of runoff, uniform distributed integrated management practices, and pollution prevention. LID stormwater control practices include combinations of discharge dispersal, infiltration, retention, bioretention, filtration, impervious disconnection or removal, detention, amended soils, water reuse, and increasing surface roughness. Integrating LID design principles and practices can be incorporated into every aspect of a highway right-of-way (medians, shoulders, swales, pipes, inlets, streetscapes, slopes, green space, and others) to create a more hydrologically functional transportation system, instead of using drainage infrastructure solely for stormwater conveyance.

Economic benefits of LID come from reduced costs that result from either downsizing or eliminating end-of-pipe treatment systems. Without accurate methods to simulate the retention capacities of LID systems, end-of-pipe controls will continue to be full-sized, and much of the economic benefit from using LID will be lost. The standard base models used to estimate runoff volumes and rates may not be well suited for evaluating LID systems, since stormwater routing options may be unaccounted for, and input parameters are "hard wired" into 16 standard scenarios that fail to simulate the hydraulic response of engineered LID systems. With regard to engineered roadsides and sheet-flow dispersion, a new or modified set of parameters may need to be developed. The newest version of SWMM5, EPA's stormwater analysis model developed by Wayne Huber and others, will have routing and continuous simulation options that will be useful for designing LID systems in the future. Huber is one of the principal investigators in NCHRP Project 25-26, Development of a Low-Impact Development Design and Construction Manual for Transportation Systems. One of the gaps in LID technologies knowledge is a long-term understanding of hydrologic effects. For example, will LID-type approaches provide enough hydrological control in regions that tend to have back-to-back storms?

The Low Impact Development Center in Maryland (www.lowimpactdevelopment.org) has developed a series of case studies as part of its LID training courses on the economic and environmental benefits of LID for residential and commercial development. Future LID projects planned in Seattle (SeaStreets Project, www.ci.seattle.wa.us/util/SEAstreets) and Pierce County (Village on the Hylebos) will monitor closely design and construction costs. Evaluations of the economic feasibility of LID will determine whether or not those practices will gain general acceptance in the development industry or will be limited to features of boutique development projects. LID practices are likely to be incorporated into stormwater designs on SR 405 expansions, SR 16 HOV, and other Washington State DOT projects. Detailed economic analysis of the cost and benefits of using those LIDS should be performed, if that is feasible.

The Low-Impact Development Design and Construction Manual for Transportation Systems is under development as part of NCHRP Project 25-26. The manual will be an effective tool in designing and constructing LID facilities with consistency, which in turn leads to effective technologies that can be monitored and compared. The product will include practical design standards and practices that meet identified regulatory requirements and resource protection goals. The anticipated criteria that will be used to develop the LID methods will include regional applicability, highway safety, spatial and temporal requirements, soil characteristics, pollutant removal effectiveness, hydrologic benefits, lifecycle maintenance requirements, and resultant costs. A series of conceptual design standards will be developed for practical field evaluation and optimization. Several DOTs, including Washington

State DOT, Maryland State Highway Administration, Virginia DOT, and Caltrans expressed interest in piloting LID technology because of its potential for addressing the escalating environmental requirements that are projected.

NCHRP Project 25-26 will make recommendations on modeling programs that can simulate effectively LID systems and will develop an applicable model. Washington State DOT has an insufficient amount of funding to update its MGSFlood continuous model to allow it to route water to structures in series. These structures could be modeled as leaky, where water losses can be incorporated. As time progresses, LID practices can be input as significant leaky structures, but future field evaluations will be needed to quantify accurately the water losses in LID systems. This will take a significant amount of time and money. The SeaStreets project in Seattle found an approximate reduction of 40% in the volume of runoff, which could be incorporated into assessments of BMP performance.

The Friends of the Rappahannock and the Low Impact Development Center (www.lowimpactdevelopment.org) are developing guidance and strategies for rural communities in Virginia to incorporate LID into their local resource protection and regulatory programs (Weinstein and Tippett, 2003). The first part of this effort includes evaluating state and local codes to determine what, if any, necessary legislative, code, or local regulations need to be modified to include LID. Identifying areas in the town and land uses that are appropriate for LID technologies follow this effort. The next step will be to develop materials for developers and plan reviewers to help guide them through the development process when the use of LID is appropriate. The final step will be to design and implement a small demonstration project that showcases LID features, such as rain gardens, soil amendments, permeable pavers, and infiltration devices.

3.2.9.1. Identification of Research Needs

Pilot projects conducted by several researchers have demonstrated the potential of LID to meet regulatory requirements, but substantial work needs to be conducted on developing LID design strategies, performance standards, and specifications. LID's decentralized approach to stormwater management technology has tremendous potential to supplement or in some situations to replace completely conventional centralized stormwater BMP approaches; however, LID's applicability, efficacy, and long-term economic sustainability have yet to be determined or documented for transportation systems. One long-term research need is documenting the type of hydrologic losses that can be achieved via LID regionally and under various soil, slope, and vegetation conditions.

3.2.9.2. Primary References

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U.S. Environmental Protection Agency. *Low Impact Development (LID): A Literature Review*. Report EPA-841-B-00-005, Office of Water (October 2000) 41 pp.

3.2.10. BMP Modeling

Software modeling tools have become a vital part of stormwater management. The complexity of BMP models ranges from simple spreadsheet calculations to multitiered combinations of sophisticated models. Problems and limitations that need to be overcome in this area include a lack of consistent BMP monitoring and performance data and a better understanding of BMP treatment processes. Current sources of data used in modeling applications include the NWS, EPA, USGS, and the USDA. The monitoring and performance data limitations encountered in the modeling of BMPs could be overcome through the growth and the evolution of the ASCE/EPA BMP database. As more and more studies are added to the BMP database, BMP properties in relation to various external variables can be determined more accurately using statistical analysis and other mathematical techniques. Areas of interest and possible knowledge gaps with respect to BMP modeling include

- Unit processes in BMPs (sedimentation, infiltration, absorption, adsorption, biodegradation, photolysis, volatilization, etc.);
- Prediction of BMP longevity and BMP effectiveness as a function of time;
- Modeling of BMP treatment trains;
- Modeling of distributed BMP systems such as LID;
- Development of stochastic BMP performance models; and
- Factoring the effects of maintenance on BMP performance.

Spreadsheets are simple programs that are used widely by engineers for a variety of technical applications. Numerous spreadsheet models have been created for water quality and hydraulic models and, more recently, for BMP modeling. Hayes et al. (2003) discuss the application of the Integrated Design and Evaluation Assessment of Loadings (IDEAL) model to BMP design and evaluation issues. IDEAL is a process-based stochastic spreadsheet model that is capable of predicting and routing runoff and pollutant loadings. IDEAL is limited in the number of pollutants that can be simulated satisfactorily, though it can model vegetative strips, dry detention ponds, and wet detention ponds.

New models are sometimes created to tackle new issues. Likewise, existing models are often modified, updated, and enhanced to address new problems or to take advantage of new technologies and more efficient algorithms. SWMM, in use since 1970, has been used primarily for hydrologic and hydraulic modeling; however, the increasing emphasis on water quality and environmental regulation compliance has been a driver for the development of new tools and the enhancement of old ones. Huber (1996) presented a discussion about the use of SWMM in BMP modeling, including a discussion of model enhancements, and a case study to illustrate the use of the model. According to Baxter (2002), both SWMM and the Better Assessment Science Integrating Point and Non-Point Sources (BASINS) have BMP modeling capabilities. SWMM is particularly proficient at predicting pollutant loads. BASINS is based on an extensible, open architecture. Integration with geographic information systems (GIS) enhances the visualization of input data and model results. BASINS version 3 includes PLOAD, HSPF, and SWAT, all of which are all capable of modeling various BMPs. PLOAD is a nonpoint-source loading model. The HPSF BMP module can interface with an Access database of 34 standard BMPs, including detention ponds, infiltration systems, and manufactured systems. HSPF also allows custom BMPs to be specified and modeled. SWAT is capable of simulating a variety of agricultural practices, including tillage and pesticide application.

GIS is rapidly becoming an indispensable tool in stormwater management. In the past, GIS packages were used mostly for the post-processing of model output, mainly as a visualization tool. However, a number of researchers are beginning to integrate stormwater modeling into GIS, taking advantage of the inherent libraries, routines, and underlying programming interfaces of GIS packages. Xue et al. (1996) created a mechanism-based BMP model and successfully linked the model to Arcview 2.1 using ArcView's built-in macro language AVENUE. The integrated model had a user-friendly interface, and a sample simulation was provided to illustrate the functionality of the tool.

Melancon et al. (2000) outline the application of a GIS-based BMP model to simulate the use of BMPs in the mitigation of bacteria-contaminated runoff. The model was developed using Arc/Info and ArcView GIS software packages. Results from the model were used to determine the source of bacteria loads, and the model was found to be capable of estimating flow and load conditions with reasonable accuracy.

BMP models are used mainly in the context of water quality or flood control design; however, there are models that incorporate additional optimization parameters such as cost. Heatwole et al. (1985) present a model capable of analyzing the cost and water quality implications of selectively applying various BMPs throughout a basin and comparing different scenarios. Using the model, the authors discovered that the cost for the maximum level of BMP treatment was four times as high as the cost for a 90% improvement in water quality using the four most economical BMPs.

Detention systems and infiltration systems appear to be the most extensively studied BMPs in terms of BMP modeling. There are numerous studies that have used existing software packages like SWMM, HPSF, and BASINS to model detention ponds. Boyd et al. (1994) discuss the use of MOUSE in on-site detention design in the City of Wollongong, Australia. Wu and Ahlert (1985) discuss a trajectory model that is used to investigate sedimentation processes in detention ponds. The model used a normal distribution of sediment particle sizes to calculate sediment trapping efficiencies for various length-to-width ratios. Wong et al. (1996) discussed the use of the P8 Urban Catchment Model and dynamic programming in detention pond design. The methodology was applied to the Marley Creek watershed to obtain the most economical system of detention ponds that would meet water quality and flow goals set for the watershed. The Detention Outlet Channel Dynamic Program (DOCP) is an optimization model that helps determine least-cost locations and sizes of detention basins. Bennett (1983) demonstrates the capabilities of DOCP in an application of the model to the Brays Bayou Watershed in Houston. In a study presented by Lam and Palmer (1996), two existing detention facilities that were constructed originally for flood-control purposes were retrofitted to provide water quality treatment. The sediment removal capabilities of the retrofitted ponds were analyzed using QUALHYMO and STORM. Dynamic wave routing was accomplished with OTTHYMO, QUALHYMO, and BOSS-DAMBRK. Petterson et al. (1998) used data from an open stormwater detention pond to verify the FEM model. The authors found that the 2-dimensional and 3-dimensional analysis was in agreement with the observed data.

Modeling infiltration systems has been an active area of study. James et al. (1997) present a discussion of the use of SWMM and HSPF shallow groundwater routines as a foundation for developing alternate approaches to infiltration BMP modeling. To gain a better understanding of the clogging phenomena of infiltration BMPs, Gautier et al. (1999) investigated an infiltration basin and two groundwater recharge basins. Other studies that have made attempts to model porous pavement structures include Loughreit et al. (1996) and Goforth (1983). Morita et al. (1996) describe a conjunctive flow model that overcomes some of the simplifying assumptions made in the development of other models. The model accounts for the interaction between surface flow and subsurface flow, and the authors provide an example to demonstrate the capabilities of the model. Debo (1994) discuss the development of a model used in the design and analysis of infiltration basins, infiltration trenches, dry wells, porous pavement, and vegetated swale with check dams.

Bishop and Scheckenberger (1994) describe the use of HPS-F in the design of a constructed wetland, which was to serve as a BMP to mitigate runoff for a proposed freeway interchange. The HPS-F analysis provided information that was used in the bathymetric design and also the plant species distribution for the wetland.

SLAMM, a recently calibrated urban runoff model, was used to compare the cost-effectiveness of using combinations of source area and regional stormwater treatment practices (Bannerman et al., 2003). Model results indicated that individually the Delaware Perimeter Sand Filter, Stormceptor, Multi-Chamber Treatment Tank, bioretention, porous pavement, and infiltration trenches could reduce the solids load to Lake Wingra by 7 to 19% and that high-efficiency street sweeping could reduce annual solids load by 17%. By modeling various street sweeping–treatment control practices, it was found that nine different combinations would be able to achieve the 40% reduction goal. For example, a 42% reduction in solids load to Lake Wingra is estimated for the combination of high-efficiency street sweeping on all the streets and Delaware Perimeter Sand Filters on all the parking lots. Alternatively, the 40% reduction could be achieved by using regional detention ponds with a total of 20 acres of permanent pool area. However, it was estimated that the annual cost of the source area practices range from about $573,000 to $1,504,000, while the range for the detention ponds is $963,000 to $1,840,000, assuming a 20-year life span. The least expensive combination of source area practices would only increase the annual stormwater utility bill for the Madison taxpayers by about $6, while the most likely detention pond alternative will increase the utility bills by about $18.

Through the use of the SIMPTM computer simulation, Kurahashi and Associates (1997) evaluated the effectiveness of new high-efficiency pavement sweepers in combination with conventional sediment-trapping catch basins to determine if the combination technology provided pollutant-reduction benefits that were comparable to those of wet vaults. The results of the simulation study showed that pollutant removals obtained with high-efficiency sweeping at a weekly frequency in combination with normal catch basin inlets cleaned annually are comparable to removals obtained by wet vaults. However, the model assumes that all of the sources of pollutants can be described by a build-up–wash-off function, which is not true. Therefore, the findings regarding a BMP that acts on this function can overstate grossly the BMP performance. In fact, high-efficiency sweeping appears to be more effective than wet vaults in the removal of highly dissolved pollutants (copper, zinc, and phosphorus), but wet vaults appear more effective than high-efficiency sweeping in the removal of TSS and sediment-bound pollutants such as lead. The use of high-efficiency pavement sweepers in combination with conventional sediment-trapping catch basins would result in substantial savings for the Port of Seattle compared to the use of wet vaults (estimated lifecycle costs of $2 million for high-efficiency sweepers in combination with conventional sediment-trapping catch basins versus $18 million for wet vaults) if their treatment were equal. Street sweeping has never shown the pollutant reductions in outfall discharges that the modeling of this type has—a result that is likely due to the pollutant source assumption.

3.2.10.1. Identification of Research Needs

With regard to the modeling of BMP unit processes, sedimentation and infiltration appear to be well covered in the literature. However, other BMP water quality treatment unit processes—such as sorption processes (absorption and adsorption), biodegradation, photolysis, and volatilization—still need to be studied further before reliable BMP performance models can be developed. There also is a lack of information on the modeling of BMP treatment trains. A better understanding of BMP longevity and of the decrease in treatment efficiency as a function of time is required, so that the optimization models used in selecting cost-effective BMP systems can provide better estimates of BMP lifetime costs and benefits. Another area that could be explored addresses how the sources of pollutants are represented in models. Many models still use a build-up–wash-off approach as the only way the pollutants get into stormwater; however, this approach should be used with caution as it can lead to faulty results if the BMP acts directly on that function.

With any attempt to predict or model environmental processes, there is a general need for accurate and representative data for parameter estimation and model calibration. Thus, the ability to measure and analyze accurately unit treatment processes is essential for the development of reliable models that can evaluate or predict BMP performance. As Sansalone (2000) stated in his TRB Millennium Paper, ". . . the future for ecologically sustainable transportation will require the ability to gather sufficient temporal and spatial measurements for increasingly sophisticated and integrated hydrologic, hydraulic, and water quality treatment models." The development of a review of modeling approaches and guidance on their selection and application is a potential research topic.

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3.2.11. Maintenance and Longevity

Twelve state DOTs have conducted studies and prepared reports on the maintenance aspects of stormwater management measures during construction, as well as at DOT facilities.

A review of the literature pertinent to the role of maintenance in BMP performance and longevity shows that numerous studies have attempted to link BMP performance and longevity to maintenance practices. All BMPs, both proprietary and nonproprietary, require regular and nonroutine maintenance in order to perform well. The frequency and extent of maintenance depend on pollutant loading and the availability of pretreatment. Regular maintenance activities include removing accumulated materials and cleaning inlets and outlets. Nonroutine maintenance may include structural repairs and revegetation (Livingston et al. 2000). The Watershed Management Institute, in cooperation with the EPA, published the document *Operation, Maintenance, and Management of Stormwater Systems* that includes guidance on BMP maintenance practices and costs as well as design information (Livingston et al., 1997). This document is one of the most comprehensive BMP maintenance guidance documents available. However, because of the large number of new and innovative BMPs, as well as variations to existing BMPs, there have been several more case studies since its publication. Therefore, the topic area of BMP maintenance practices and costs is in need of further research. Areas of interest and possible knowledge gaps related to the effects of maintenance on BMP performance and longevity include

- Recommended frequency of maintenance for various BMPs,
- Determination of the most cost-effective maintenance activities,
- Maintenance requirements for natural and constructed wetlands,
- Cost and benefit analysis of BMP maintenance,
- Sediment toxicity as a function of type and frequency of maintenance, and
- Disposal of maintenance waste products such as sediment.

The current state of maintenance practices of various municipalities have been the subject of a number of studies. An extensive survey of more than 800 stormwater structures was conducted in four North Carolina cities in an effort to evaluate stormwater maintenance practices and needs (Roenigk et al., 1992). Culverts, inlet devices, channels, detention ponds, wet ponds, and infiltration systems were evaluated. Stormwater officials in 88 North Carolina cities were interviewed on the phone about maintenance issues. The results of the study indicated that maintenance practices were adequate, with the exception of detention facility maintenance. Most of the surveyed systems were designed to operate primarily at flood control capacities; hence, maintenance requirements are expected to increase with the increasing prominence of water quality issues.

The phone interviews revealed that the maintenance activities performed, in order of frequency from highest to lowest, were mowing, inlet cleaning, facilities inspections, and then sediment removal at detention facilities. The final component of the study was conducting interviews with 25 stormwater management experts, who all agreed on the importance of inspections, mowing, and sediment removal, but who did not agree as to how frequently these maintenance activities needed to be performed.

King County performed a survey of 17 wet ponds and 33 biofiltration swales to assess the state of these water quality facilities (King County, 1995). Results of the survey indicated that because of poor design, construction problems, and inadequate maintenance practices, only 35% of the wetponds and 28% of the biofiltration swales were working properly. The study attributed the unsatisfactory condition of the BMPs to the novelty of the stormwater facilities and to a lack of understanding about the effort required to sustain water quality facilities in decent working condition.

The Caltrans BMP Retrofit Program evaluated the costs of acquisition, operation, and maintenance of 39 BMPs from 12 different BMP categories (Currier et al., 2001). The study estimated the annual maintenance requirements for sand filters, extended detention basins, infiltration basins, biofiltration strips, swales, and wet basins at 93 hours, 136 hours, 193 hours, more than 200 hours, and 570 hours, respectively.

The private sector increasingly is adopting the use of BMPs for commercial, industrial, and residential development applications. Inspection and maintenance of BMPs are often the responsibility of the property owner. The City of Lacey in Washington State attests to the effectiveness of inspections and education coupled with field activities as opposed to pure enforcement (Hielema, 2001).

Infiltration facilities appear to be the most prone to failure because of inadequate maintenance practices. Consequently, many of the studies on BMP maintenance have examined infiltration facilities. The study by Nozi et al. (1999) examined various infiltration facilities (infiltration inlet, infiltration trench, porous asphalt pavement, and an infiltration well) in Japan, evaluated the effects of maintenance, and demonstrated that in most cases infiltration BMP performance can be improved significantly with maintenance. A comparison of infiltration facilities that had been in use for up to 10 years showed a decline of infiltration capacity with time. To evaluate the effects of washing and cleaning, infiltration facilities in four municipalities (Tokyo, Chiba, Nagoya, and Hamamatus) that were more than 10 years old were maintained and assessed. With the exception of one infiltration trench in Nagoya, all of the infiltration facilities showed a marked improvement in infiltration capacity.

A study of four porous pavement systems, including pavers with infiltration joints, porous concrete pavers with filter layers, greened porous pavers, and pavers with greened infiltration joints was performed to determine the pollutant retention abilities of the various systems (Dierkes et al., 2002). All four systems demonstrated high pollutant retention capabilities, but the system with infiltration joints was relatively less efficient. Field evaluation of a 15-year-old piece of porous pavement revealed no impact to soil or groundwater. A device to alleviate clogging in porous pavement was tested successfully in a school yard. As a result of the cleaning, infiltration rates were increased from 1L/(s.ha) to 1500 L/(s.ha). Researchers concluded that porous pavements do get clogged and that the device developed in this study seemed suitable for maintenance of porous pavers.

To evaluate the impacts of accumulated sediment on nutrient removal efficiencies in a pond, a field study was conducted on a submerged biofilter (Mothersill et al., 2000). Substantial removal of suspended solids (97%) from the influent stormwater resulted in a significant accumulation of sediment in the biofilter, which interfered with the system's main treatment objective—removing soluble nutrients through bacterial assimilation. Removal efficiencies of total organic carbon and suspended orthophosphate were found to decrease with time; however, the removal efficiency for ammonium nitrate (64%) appeared independent of time or sediment accumulation. Sediment accumulation was attributed to infrequent backwashing of the filtration unit.

Other studies have examined and compared the effects of maintenance on different classes of BMPs. A paper by Botts et al. (1996) presented maintenance requirements and longevity estimates for four standard BMPs, including a water quality inlet, an infiltration trench, a wet detention pond, and a sand filter. Wet detention ponds and water quality inlets are shown to have long life spans, with well-designed detention ponds operating as designed for 20 years or more and 95% of water quality inlet installations operating as designed for up to 5 years. Infiltration trenches have short life spans with less than 50% of installation failing in fewer than 5 years. Proper design and regular maintenance can prolong the life of infiltration facilities to well over 5 years.

A study by Galli (1992) in Prince George's County, Maryland, evaluated the performance and longevity of 11 types of BMPs. The BMPs studied included infiltration trenches and basins, dry wells, porous pavement, vegetated swales, extended detention dry ponds, wet ponds, constructed marshes, pocket wetlands, oil and grit separators, and dry ponds. Assessment criteria used in the study included design strengths and weaknesses, maintenance issues, and environmental considerations for each of the 156 sites included in the study. The results of the study suggested that infiltration basins, porous pavement, grass filters, swales, and "pocket" wetlands generally required modifications or improvements in order to provide reliable pollutant removal.

A King County study evaluated the effects of mowing on the performance of vegetated swales (Colwell et al., 2000). Two mowing regimes—mowing at both the beginning and at the end of the growing season and mowing only at the end of the growing season—were evaluated to determine impacts to swale treatment efficiencies. TSS and turbidity mitigation were significantly higher for the unmowed swale showing that mowing did not provide increased treatment. The two mowing strategies were found to be equivalent with respect to water quality benefits. The authors cautioned that the test systems may not be representative of all swales.

The performance of BMPs commonly used in public works practices—such as water quality inlets, sedimentation manholes, and catch basin inserts—also are dependent on the extent and frequency of maintenance. Maintenance-related information on public works practices are included under the Gross Pollutant Removal and the Drain Inlet/Gross Pollutant Studies sections of this report. Details of studies presented by England and Rushton (2003), Sedrak et al. (2001), Lippner and Moeller (2000), and Dammel et al. (2001) are all relevant to maintenance of public works-related BMPs.

3.2.11.1. Identification of Research Gaps and Needs

Based on the literature review, it is apparent that there is substantial information on maintenance practices of BMPs and how these practices affect performance. A compilation of the results of these studies in an updated BMP operations and maintenance manual, such as the document by Livingston et al. (1997), may be a potential research need. Another need is for guidance on estimating maintenance frequencies based on influent characteristics and site conditions.

BMP maintenance costs frequently are not factored in during the initial planning and BMP selection phases of construction projects. There appears to be a need for guidance on estimating the lifecycle costs that account for the maintenance required for continually functioning and efficient BMPs. A final need is for further development of methods to increase the longevity and to minimize maintenance requirements of infiltration BMPs—such as the use of presettling basins or the use of PAMs to maintain infiltration rates.

Evaluations of sediment toxicity as a function of maintenance frequency and methods for disposing or reusing BMP maintenance-generated wastes would be helpful.

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3.2.12. Use of Toxicity and Biological Indicators in Performance Evaluations

Toxicity and other biological indicators—such as bioavailability, species diversity, and biomass—are underused methods for evaluating BMP performance. This subject is not to be confused with a full receiving waters biological impact analysis. Rather, use of indicators entails applying toxicity, bioavailability, and biological communities as metrics for BMP performance. Potential research questions include

- How can biological indicators be used to assess BMP performance, and what are the limitations to their use and interpretation?
- How are toxicity and bioavailability reductions related to the reduction or speciation of chemical constituents?
- Which indicator organisms are most appropriate for evaluating BMP performance?

Pitt et al. (1991) investigated the control of stormwater toxicants through conventional treatment processes. Twelve sheet flow samples were collected from the source areas that were found previously to produce the most toxic storm runoff waters. These areas were automobile service areas, industrial parking and loading dock areas, and automobile salvage yards. The samples were subjected to a variety of benchscale treatability tests, including settling columns, sieving screens, membrane filters, aeration, photo degradation, aeration and photo degradation combined, floatation, and alum addition.

Toxicity changes were monitored using the Microtox bioassay test. The benefits of the treatment processes varied for the different samples. However, some of the treatment processes consistently provided the greatest toxicity reduction. The most beneficial treatment tests included settling for at least 24 hours (generally 40–90% reduction), screening through at least 40-micron screens (20–70% reduction), and aeration or photo degradation for at least 24 hours (up to 80% reduction). The floatation tests produced floating sample layers that generally decreased in toxicity with time. However, the benefits were quite small (less than 30% reduction). Alum additions substantially reduced the turbidity of the samples but the changes in toxicity were highly irregular.

The Port of Seattle tested four filtration media in controlled laboratory experiments to determine their effectiveness for concurrent metals removal and toxicity abatement in synthetic stormwater (Tobiason et al., 2003). Media tested included commercially available leaf compost (CSF®) media, a zeolite–perlite mix, and a polyamine sponge, as well as the recently developed citric acid modified soybean hull media.

Toxicity was assessed using acute *Ceriodaphnia dubia* (48-hr) bioassays. Results indicated that the CSF® media removed up to 75% of the zinc and reduced toxicity significantly for influent concentrations of up to about 300 ppb zinc. The soybean hull material removed 80–99% of the zinc over all influent concentrations, though it reduced pH to toxic levels. After pH adjustment, the effluent from the soybean material was nontoxic over all concentrations tested (survival was 100% in pH-adjusted effluent samples). Augmenting the soybean material with leaf compost media or activated carbon effectively buffered effluent pH to circumneutral ranges. Other media tested removed modest amounts of zinc and were capable of sufficiently reducing toxicity only in the lowest concentrations tested; some media appeared to generate toxicity (which may have been due to reductions in pH or hardness).

By studying algal communities in two stormwater management ponds, Rouge Pond and Harding Pond, Olding (2000) noted that impacts to aquatic biota decreased as stormwater passed through ponds. The greatest disturbances to biological communities were observed in the sediment forebay area for both ponds. The author attributed the absence of blue-green algae populations in both ponds to the hydraulics of the ponds, despite nutrient-rich conditions, and suggested that stormwater ponds can be engineered to limit nuisance algal communities. The reduction of impacts to biological communities observed in the pond translated to a reduction of impacts to receiving water biological communities.

The use of biological indicators for evaluating BMP performance is a relatively new method that is gaining popularity among stormwater regulators. Biological indicators such as those used in toxicity bioassays have been used extensively for evaluating potential impacts to and the contamination of receiving water systems (see EPA's Biological Indicators of Watershed Health: www.epa.gov/bioindicators). It is not difficult to extend this knowledge base to the evaluation of BMP performance, but some issues with traditional toxicity testing methods should be considered. Burton et al. (2000) points out that traditional toxicity tests may not produce reliable conclusions when used to detect the adverse effects of fluctuating stressor exposures, nutrients, suspended solids, temperature, ultraviolet light, flow, mutagenicity, carcinogenicity, teratogenicity, endocrine disruption, or other important subcellular responses. This inability to predict effects is largely a result of the complex biological response patterns that result from various combinations of stressor magnitudes, duration, and frequency between exposures, as well as from the interactions of stressor mixtures, such as synergistic effects of certain pesticides, metals, and temperature. In watersheds receiving multiple sources of stressors, accurate assessments should define spatial–temporal profiles of exposure and effects using a range of laboratory (such as WET tests) and novel in situ toxicity and bioaccumulation assays, with simultaneous characterizations of physicochemical conditions and indigenous communities.

Beginning in May 2003, the Louisiana DOT embarked on the research project *Transport, Treatability, and Toxicity of Highway Stormwater Discharged into Receiving Waters across Louisiana* (http://rip.trb.org). The primary objectives of this research are (1) characterization of highway stormwater based on hydrology, pollutant loadings, toxicity, and rainfall quality; (2) comparison of standard tests for stormwater characterization; (3) quantification of pollutant loadings as a function of hydrologic parameters and traffic characteristics; and (4) assessment of treatment alternatives. Part of this research also will include documenting toxicity reductions at three experimental sites: a site near Shreveport at the

I-220 bridge over Cross Lake, a site in Baton Rouge at the I-10 bridge over City Park Lake, and a site in New Orleans at the I-10/I-610 junction over the 17th Street canal.

3.2.12.1. Identification of Research Needs

Based on the scarcity of studies that use biological indicators for BMP performance assessment (as well as for general highway runoff characterization), it appears that this entire topic area is a research need. In fact, the top two research needs identified by GKY and Associates in the original NCHRP Project 25-20 report were to (1) identify and develop regional aquatic biological indicators to assess impacts of highway runoff and (2) research methods and develop protocols for assessing the toxicity of highway runoff. This current effort demonstrates agreement that research in this area is still needed and should be expanded to include the use of biological indicators to assess BMP performance in terms of toxicity reduction.

3.2.12.2. Primary References

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3.2.13. Public Perception and Aesthetics

Few studies have attempted specifically to evaluate the importance of public perception and aesthetics in BMP selection, design, implementation, and performance. However, a literature review pertaining to this subject shows that a fair number of BMP evaluation studies make mention of aesthetics or public perception in one way or another. Areas of interest and possible knowledge gaps in this area include

- Public perception of BMPs in terms of impacts on private-property values;
- Public perception of BMPs in terms of impacts on public safety; and,
- The role of aesthetics in the design, selection, implementation, and public acceptance of BMPs.

According to Frederick et al. (1996), residential areas with open water areas are sometimes avoided by parents with young children for fear of exposing their children to the risk of drowning. Poorly maintained ponds can become unsightly and odorous and provide a breeding ground for mosquitoes and other parasites. On<the contrary, well-designed, aesthetically-pleasing properties can cause property values to increase, vacancy rates to lower, and tenant turnover to decrease in rental properties. According to Baxter and Mulamoutti (1985), 49% of the residents in a neighborhood where retention ponds were constructed believed that the lakes had a positive impact on property values. The benefits of the ponds were perceived to be aesthetics and attraction of potential residents and recreational opportunities.

A functional, aesthetically pleasing wetland designed near a golf course is discussed by White and Meyers (1997). The nitrogen, phosphorus, and suspended sediment removal efficiencies of the wetland were estimated at up to 60%. According to the authors, proper vegetation selection can result in a beautiful wetland design that can provide bird habitat and educational opportunities.

Well-designed and implemented public education programs can improve significantly public perception of stormwater pollution control programs and BMPs. An ongoing Caltrans study (PERS) is attempting to implement and to evaluate the effectiveness of a public education program targeted at reducing litter (Caltrans, 2002). The details of this study are presented in the Gross Pollutant Removal Section of this report.

3.2.13.1. Identification of Research Needs

It is seemingly evident from a literature review that not very much work has been done on the use of aesthetics and public perception as a benchmark of BMP performance. Existing research may be less applicable to highway environments.

Studies that rank BMPs in order of public performance and provide insight as to how to improve public perception of various types of BMPs would be a valuable addition to the collection of existing BMP evaluation studies. Research that quantifies the impacts of various types of BMPs on public property values could provide a useful tool for public education programs.

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3.2.14. Economic Analysis and Assessment

Evaluating BMPs on the basis of cost is an integral part of the BMP selection process. Initial capital costs and sometimes operation and maintenance costs can become the key controlling factors that dictate which BMPs are selected and whether projects get constructed. The tools and methods used in cost estimates therefore play a prominent role in stormwater management. According to Heaney et al. (2002), most of the cost-estimation methods are based on regression equations. Cost-estimation techniques can be improved through additional funding and research and through the use of available technology. Potential research needs and knowledge gaps in the economic analysis and assessment of BMPs, some of which were suggested by Heaney et al. (2002), include

- Quantification of the benefits of urban storm systems;
- Consideration of receiving water impacts in cost–benefit analysis;
- Development of cost–benefit evaluation methodologies for nonstructural BMPs;
- The availability and application of flow and water quality data to BMP cost–benefit analyses;
- Inclusion of land use data into cost optimization analyses; and
- Cost–benefit analysis of BMP treatment trains.

Another important consideration is the assessment of cost differentials. Costs for similar needs (e.g., landscaping and maintenance) for many BMPs may have been incurred already or may be avoided (e.g., reduction of pipes and inlets via the use of biofilters). Cost studies may be misleading if these potential cost offsets are not assessed.

A review of the literature pertaining to BMP cost estimation reveals a number of documents that provide BMP cost information. FHWA (2000) provided a table of relative BMP costs. Structural BMPs that were assigned relatively high capital costs included underground sand filters and organic media filters; detention tanks, underground sand filters, organic media filters and oil-grit separators were assigned high relative operation and maintenance costs. Low-cost structural BMPs included treatment systems like bioretention, detention ponds, vegetated swales, vegetated filter strips, and porous pavement. Relative costs for new innovative BMPs range from moderate to high for systems such as alum injection, MCTT, biofilters, and vegetated rock filters.

Heaney et al. (2002) present a comprehensive collection of tables and equations for estimating the cost of drainage structures, including BMPs. Also, the document contains a review of literature pertinent to drainage system cost evaluation. Cost information for BMPs includes costs for porous parking, swales, and cost estimates for streets with swales and porous pavement. Yu and Stopinski (2001) evaluated four ultra-urban BMPs consisting of a bioretention basin and three proprietary treatment systems (Isoilater, Stormceptor, and Vortechs treatment systems). A comprehensive cost analysis was presented for each system. In order to compare the capital costs of each treatment system, researchers evaluated the cost-per-volume served, the cost-per-volume served per year, and the cost-per-percentage of TSS removal. The bioretention basin was found to be the most economical system of the four tested. The Vortechs system was not installed properly and hence provided unreliable results.

Scott et al. (1999) evaluated and compared two flood control mitigation systems: on-site detention (OSD) and on-site retention (OSR). Both flood control systems provided flood protection by attenuating peak flows of in-coming storms and discharging the effluent at lower flow rates. OSR outperformed OSD in terms of cost efficiency and environmental benefits. Cost efficiency was based on the volume of site storage required to attain peak flow attenuation.

Caltrans has assessed and approved more than 110 BMPs for use since 1996 and has included cost–benefit analysis as part of their assessment. Caltrans assessed the cost-effectiveness for each BMP in terms of its EUAC relative to a detention basin (Caltrans, 2003). A four-quadrant system was used as a tool to rate each BMP. The cost estimates were defined first by calculating the typical range of costs for constructing or operating a BMP on a per-acre basis. The acre represented the drainage area served by the BMP. Operation and maintenance costs then were added, based on the design life of the BMPs. The EUAC for a particular BMP was estimated and compared qualitatively to that of a detention basin. If the EUAC was higher for the BMP than for a detention basin, it was marked as a higher cost using the quadrant rating key. The benefit of the BMP was evaluated relative to the performance of a typical detention basin. If the constituent removal was greater than that of a detention basin, the BMP was marked as having a greater benefit.

Using published literature and cost estimation guides, Sample et al. (2003) synthesized methods for estimating costs for BMPs such as detention, retention and infiltration basins, infiltration trenches, sand filters, and vegetated swales. According to the study authors, cost–benefit analysis methodologies can be improved by considering additional parameters such as flow monitoring data, receiving water impacts, and the effects of streets and parking lots.

Sear et al. (1996) explained the development of equations used to estimate BMP cost as a function of pollutant removal. The functions were used to evaluate nine alternatives for five stormwater treatment technologies in Lakeland, Florida. Production cost functions, with respect to TSS removal percentages, were developed for street sweeping, infiltration<systems, wet ponds, dry ponds, and wetlands. The cost functions do not include property acquisition costs or operation and maintenance costs. The authors concluded that wet detention ponds and wetlands are more economical than dry detention bonds and curb-cut swales, if the cost of property acquisition is taken into account.

A number of simplifying assumptions are made and some external variables are overlooked in a lot of the available cost-estimation methods. Maintenance costs and longevity of BMPs are not considered in some BMP evaluation literature. According to England (1998), maintenance costs for retrofit projects often are neglected or underestimated. An evaluation of maintenance costs of BMPs—such as wet ponds, dry ponds, exfiltration and infiltration trenches, porous pavement, baffle boxes, inlet baskets, and sediment sumps—is presented by the authors, who recommended that maintenance needs be considered in the design and construction of retrofit projects in order to ensure that retrofits provide long-term pollutant removal.

After evaluating baffle boxes and inlet devices, England (1998b) concluded that the tradeoff for the low initial cost of the evaluated BMPs is the perpetual maintenance expense. Baffle boxes are recommended for small to medium-sized drainage basins, while inlet devices are recommended for small flows and small drainage basins.

BMPs can affect the market values of neighboring properties, so another way to evaluate BMPs is to assess the economic benefits of implementing BMPs in residential and commercial areas. Frederick et al. (1996) presented a discussion about the potential increase in property value that can be gained through the construction of detention-type BMPs. Prices of homes situated close to a body of water tend to be significantly higher than comparable properties that are not near a body of water. In addition to environmental benefits, aesthetically pleasing BMPs can improve property values, lower vacancy rates of rental properties, and make properties easier to sell.

As described in section 3.2.10., BMP Modeling, Bannerman et al. (2003) were able to find the most cost-effective combination of high-efficiency street sweeping and treatment control practices by using the SLAMM model to meet the TSS reduction goal of 40%. The annual cost of the source area practices was estimated (assuming a 20-year life span) to range from $573,000 to $1,504,000, while the range for detention ponds was $963,000 to $1,840,000. The least expensive combination of source area practices would only increase the annual stormwater utility bill for the Madison taxpayers by about $6, while the most likely detention pond alternative would increase the utility bills by about $18.

3.2.14.1. Identification of Research Needs

Based on the literature review addressing the economic analyses and assessment of BMPs, it is evident that there is cost estimation information for nearly all proprietary and most of the common nonproprietary structural BMPs. Cost regression equations have been developed for a number of BMP types that are based primarily on imperviousness, land use, and flow rates and volumes. However, lifecycle costs, opportunity costs, and externalities often are neglected in cost estimation. As mentioned under the section Maintenance and Longevity, lifecycle costs account for the operations and maintenance requirements necessary to maintain lifetime BMP functionality and efficiency. Opportunity costs are the costs of land taken out of other uses and the costs of an alternative conveyance system (which actually may be a net savings in some cases). Externalities are the effects of production and consumption activities not directly reflected in the market, such as receiving waters protection and aesthetics (Willis and Finney, 1999). There is a need to develop BMP cost-estimation tools that account for land value, site constraints, construction, operations, and maintenance, as well as receiving waters protection, aesthetics, and infrastructure savings on conventional drainage structures. Quantification of receiving waters protection requires the use of existing water quality, habitat, and bioassessment monitoring data for both the runoff and the receiving waters.

With the possible exception of street sweeping, nonstructural BMPs have been primarily overlooked. Costs associated with public education, catch basin maintenance, and road side vegetation control activities would be helpful for the optimization and adequate allocation of stormwater management funds.

Finally, although there is an abundance of cost-evaluation methodologies for individual standard structural BMPs, BMP treatment trains and distributed BMP systems appear to have been neglected. There is a need for cost evaluations and comparisons of BMP treatment trains, distributed BMPs, and large centralized regional BMP systems.

3.2.14.2. Primary References

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3.2.15. Vector Control

The potential for structural BMPs to harbor and breed nuisance- and disease-causing organisms had received little attention until recently. A vector, as used in this section, refers to any organism that can transmit an infectious disease-causing organism to another living thing (Metzger et al., 2003). Because mosquitoes are ubiquitous and their life-cycle depends on humans and other warm-blooded animals, their potential to transmit infectious disease is high. Therefore many of the studies related to vectors in BMPs focus on mosquitoes (Metzger et al., 2003; VBDS, 2001). With the ever-increasing demand for BMPs, vector issues associated with BMPs could result in exponential increases in vector populations if not addressed. A review of the literature pertinent to the incidence of vectors in BMPs shows that wetlands appear to be the most targeted BMPs, and mosquitoes are the most targeted vector in studies.

Caltrans established a comprehensive vector surveillance and monitoring study in cooperation with the Vector-Borne Disease Section (VBDS) of the California Department of Health Services. The objectives of the 2-year study were to develop vector abatement protocols and to recommend modifications to Caltrans BMPs that would minimize their potential to harbor vectors. VBDS monitored 37 structural BMPs at 31 sites with emphasis on mosquitoes. The study showed that BMP technologies that maintained permanent pools of standing water (i.e., multichambered treatment trains, continuous deflector separators, and wet basins) were more likely to support a large mosquito population. BMP technologies that drained completely (i.e., biofiltration swales, biofiltration strips, sand media filters, infiltration basins, infiltration trenches, drain inlet inserts, extended detention basins, and oil–water separators) were less likely to harbor vectors. Factors that contributed to the incidence of vectors in BMPs include BMP design, BMP location, immediate and large-scale surroundings, nonstormwater discharges (such as irrigation), and site maintenance. BMP design features to be avoided include the use of sumps, catch basins, or troughs that do not completely drain; loose riprap; automatic pumps or motors; and orifices that are prone to clogging. Recommendations for pond-type BMPs included stocking permanent pools with Mosquito Fish (*Gambusia affinis*) and providing steep sideslopes to create a less desirable habitat for vectors.

The combination of vegetation and permanent pools of stagnant water in wetlands makes wetlands prone to vector infestations. As a result numerous vector-related studies have targeted wetland locations. Studies that have evaluated the incidence and implication of vectors in wetlands include studies by Russell (1999a) and Russell et al. (1999b).

Walton et al. (1999) examined the dispersal, survival, and host-seeking behavior of mosquitoes from a constructed wetland in Southern California. The study showed that the limited dispersal and the long survival of Culex erythrothorax were important factors in the development of large populations at constructed wetlands. A study in Adelaide, Australia, evaluated 12 constructed wetlands in an attempt to understand the breeding habits of mosquitoes, especially those in urban constructed wetlands (Sarneckis, 2002). The study showed that wetlands with standing water, steep edges, and little emergent vegetation typically had fewer or no larval mosquitoes. Wetlands that supported large mosquito populations typically had sheltered shallow water, isolated pools that limited predator access, poor water quality, and low marcroinvertebrate diversities. The study concluded that well-designed wetlands were less likely to produce mosquitoes.

MacLean (1995) presented mosquito management strategies for wetlands. The author suggested mosquito control strategies that included the use of bacteria, chemical larvicides, insect eating fish, copepods, and other animals. The efficiency and availability of selected controls are presented. The author inferred that wetlands designed to optimize surface area and plant growth without excessive mosquito production result in cost savings.

3.2.15.1. Identification of Research Needs

The potential for vectors, particularly mosquitoes, to inhabit and breed in stormwater control facilities is of increasing concern to stormwater management practitioners. The evident scarcity of studies and literature pertaining to the incidence of vectors in stormwater BMPs makes this whole category a research need. Details on the kind of research that is needed include the development and evaluation of maintenance and design practices that deter vectors. Poor water quality also has been linked to the mosquito proliferation in wetlands. It is thought that nutrients provide food for the bacteria and algae on which mosquitoes feed. A better knowledge of the relationship between vectors and water quality is a necessary addition to the existing literature on vectors.

3.2.15.2. Primary References

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3.3. WATERSHED-BASED APPROACHES

As previously mentioned, using watershed-based approaches to stormwater planning and management involves coordinating and integrating human activities to implement watershed recovery efforts and to prevent further degradation of natural resources within the basin. Partnerships and negotiations among various jurisdictions and levels of government often are required to fulfill multifaceted social, economic, and environmental goals within the watershed.

Only eight states have conducted studies or prepared reports on the retrofitting of existing stormwater management measures at DOT facilities where a watershed-based approach is employed to address fish passage or other issues pertaining to receiving waters. Five states have developed research or resources in the area of programmatic or other alternatives to project-specific mitigation, including means for establishing critical needs and priority mitigation on a watershed scale.

Below, the topical areas of watershed-based approaches are divided into planning, which may involve the implementation of regional and distributed stormwater management controls and practices throughout an entire basin, and into market-driven approaches, which may involve placing monetary value on stormwater quality that can be traded on the open market.

3.3.1. Watershed Planning

In 1996, FHWA came out with *Transportation Planning—The Watershed Connection*, which provided a national focus for an envisioned relationship between transportation and watershed planning (Bank, 1996). A case study was used to illustrate how the relationship can work to maximize coordination and cooperation between watershed and transportation stakeholders.

Until TMDLs became a consideration, water-quality concerns were not a driving factor in DOTs' consideration of watershed approaches. In a survey conducted in 1997, Clean Water Section 404 permitting for wetland impacts was the primary driver in state DOT efforts to consider or incorporate a watershed approach (Venner, 1998). Concerns about endangered species were drivers in only a few states, including Idaho, Montana, Washington, and Maine; in those states, DOTs identified watershed boundaries on projects primarily to indicate red-flag potential impacts. The study also examined success stories, barriers, and lessons learned in DOTs' implementation of watershed approaches.

Washington State DOT and North Carolina DOT remain the leaders among state transportation agencies in integrating a watershed-based approach into this work, primarily as it pertains to mitigation siting. Both Washington State DOT and North Carolina DOT target mitigation funds to sites offering the greatest ecological benefits. In North Carolina, such needs are identified through a formal watershed planning process conducted by the State Department of Environment and Natural Resources and are partially funded by North Carolina DOT. The watershed-based approaches of Washington State DOT and North Carolina DOT follow:

- **Washington State DOT**

  Endangered salmonids drive watershed planning and attention to watershed impacts in Washington State.

  Washington State DOT's watershed-based approach is characterized by a community-based environmental decision-making process that coordinates and integrates human activities to implement watershed recovery efforts and to prevent further degradation of natural resources within large drainage basins. In 1996, Washington State DOT shifted from mitigating impacts on a project-by-project basis, irrespective of the top watershed needs, to analyzing mitigation opportunities based on watersheds. Now Washington State DOT's approach makes links between watershed issues and creates partnerships with public, private, and nonprofit organizations that affect and are affected by the issues.

  Initiatives directly contributing to the watershed-based approach at Washington State's DOT include the department's Wetlands Strategic Plan, the Fish Passage Barrier Removal Grant Program, the Advanced Environmental Mitigation Revolving Account, Stormwater Retrofit Grants, Flood Management Strategy, and Capital Budget Coordination. A common theme in each of these initiatives is the establishment of incentives for targeting mitigation investments to sites that protect, preserve, or restore key components of the watershed, yielding substantial benefits for the state as a whole.

Over the past year, Washington State DOT has undertaken a broad analysis of mitigation siting potential, aimed at making a tangible contribution to watershed restoration. To assist this effort, the DOT is developing landscape-based approaches and tools to systematically examine ecosystem function and identify core problems leading to degradation of water quality, increased peak flows, declining base flows, and the loss of anadromous fish habitat. These tools are pointing to more cost-effective and environmentally beneficial options when the department reaches technical limits for onsite mitigation. The approach lays the groundwork for a more flexible and less prescriptive process for achieving multiple natural resource goals, resulting in a more predictable permitting process with measurable transportation and environmental benefits.

For each project, Washington State DOT inventories aquatic and terrestrial resources on site, identifies potential impacts, and assesses the potential and sustainability of mitigating on site. On a watershed scale, the department determines offsite mitigation needs; characteristics of the predevelopment landscape; current land use and future build-out; and the condition, location, and extent of aquatic and terrestrial resources and supporting ecological processes. The DOT then identifies target areas for mitigation at multiple spatial scales. Within each spatial scale, Washington State DOT identifies the ecological processes necessary for and capable of mitigating project impacts.

To qualify as environmentally desirable offsite mitigation, the potential mitigation site and local ecosystem processes must meet targeted threshold criteria, indicating high potential to maintain ecological functions over the long term. The process identifies priority recovery areas for each targeted resource (fish and wildlife, water quality, riparian, and wetland) and opportunities and priority areas for multi-objective mitigation. Land uses that alter or decrease the success of ecological processes that the mitigation would seek to restore or enhance are a primary screen. Before candidate sites and restoration projects are chosen, a comparative assessment of ecological functions is performed along with social, economic, and environmental cost–benefit analyses for the candidate sites. From these assessments and analyses, Washington State DOT is able to develop a defensible priority list of sites capable of mitigating project impacts and maximizing environmental investment.

Washington State DOT's watershed-based approach is leading to the identification of mitigation sites on a watershed basis and the cost–benefit analysis of mitigation options. A new state law has created a goal of achieving a 50% increase in environmental benefit from mitigation at a 25% reduction in cost. To direct transportation mitigation dollars toward high-priority watershed recovery projects in the basin, the DOT is working cooperatively with other agencies to look for ways to reduce transaction costs, increase environmental benefits, and obtain a more streamlined consensus that mitigation efforts happen in priority areas within the watershed.

Washington State DOT's Snohomish Basin Demonstration Project has focused on developing methods to identify candidate transportation projects from the agency's 2-year and 6-year programs, which have mitigation needs that could be linked to watershed improvement activities. This project also provides an example of how a literature review was loaded into a GIS to collate environmental recommendations for the watershed.

- **North Carolina DOT**

  The North Carolina DOT and the Department of Environment and Natural Resources (DENR) have designed the Ecosystem Enhancement Program (EEP) to deal with a rapidly expanding transportation program that has a high volume of new alignments, impacting an estimated 6,000 acres of wetlands and a million feet of streams over the next 7 years in a state with notable nutrient-loading concerns. The state has decided to tackle these issues through a strategic progress of riparian buffer and wetland restoration. EEP is intended to protect the state's natural resources through the assessment, restoration, enhancement, and preservation of ecosystem functions and through identifying and implementing compensatory mitigation programmatically, at the watershed level. In particular, the program will

  – Enable multiple project impacts (wetlands, stream corridor, water quality, species, and habitat) to be addressed in a comprehensive manner.
  – Target mitigation resources to better protect the natural resources of the state by assessing, restoring, enhancing, and preserving ecosystem functions and compensating for impacts at the watershed level. The program will address watershed concerns, including preservation of threatened high-quality sites and restoration of wetlands and riparian buffers along impaired streams.
  – Exceed the state and the Federal Highway Administration's "no net loss" objectives for wetlands.
  – Allow implementation of mitigation years earlier than the current project-letting schedule, expediting projects and eliminating temporal loss of wetland and riparian areas.
  – Reduce permit staff workload, rework, and duplication of effort, thereby saving time and money.
  – Reduce project controversy and improve communication, planning, and environmental stewardship.
  – Serve as a model for positive interagency relationships.
  – Dramatically increase the ecological effectiveness of the investments of public dollars in compensatory

mitigation, illustrating better stewardship of public resources, and setting a nationwide standard for mitigation at the ecosystem level for unavoidable impacts resulting from transportation improvements.

The EEP evolved from a multiyear effort by North Carolina DOT, DENR, FHWA, the U.S. Army Corps of Engineers, North Carolina Wildlife Resources Commission, the EPA, and the U.S. Fish and Wildlife Service to streamline the project delivery process for transportation improvement projects, to reduce environmental impacts in concert with avoidance and minimization, and to produce the most environmentally beneficial mitigation possible. A year of multi-agency process improvement workshops determined that compensatory mitigation should be "de-coupled" from individual permits and project reviews and performed on a watershed basis, with mitigation projects constructed in advance of permitted impacts. The program has been endorsed at the highest levels of participating agencies.

Mitigation strategies under EEP embrace the concept of functional replacement for unavoidable impacts. Mitigation needs and replacement opportunities are being developed through a collaborative process that includes all interested parties with the goal of restoring and protecting watersheds throughout North Carolina. The approach evaluates cumulative impacts of all projects within a watershed and implements mitigation focused on achieving a net increase in wetland and riparian functions in the watershed and across the state. To ensure that program goals are met, a ledger of implemented projects and actual impacts will be produced for each watershed. On an annual basis these ledgers will be compared to determine if a "no net loss" of wetland and riparian functions has been achieved. Any shortfall is programmed for correction in the next annual cycle, and excess mitigation is reserved for future use. In the first year of the program, mitigation requirements were satisfied for 82 transportation projects by focusing on addressing the greatest environmental needs on a watershed basis.

An interagency team led by the state's DENR is charged with developing a watershed assessment methodology to facilitate full replacement of functions. The team recently has compared, contrasted, and evaluated existing watershed assessment methods, including the methods utilized to develop watershed restoration plans and local watershed plans. The method will assess ecosystem functions of importance and the appropriate scale and assessment methodology for each function of interest as determined by all the agencies involved. The team will oversee the adoption of standard protocols that will be used to establish goals and objectives for each watershed. These protocols also will provide the framework for identifying traditional restoration and enhancement opportunities and other actions such as preservation and BMPs that are consistent with the goals and objectives developed for each watershed. Anticipated deliverables will include

- A watershed needs assessment methodology accepted by applicable resource management agencies;
- The scale of watershed assessment for each ecosystem function of interest;
- A guidance manual outlining the watershed needs assessment process;
- Standard protocols that will be used to establish goals and objectives for each watershed;
- Protocols for the selection, evaluation, and prioritization of projects, including compensatory mitigation;
- Recommendations concerning the frequency of review and revision of watershed plans;
- Recommendations for integrating the assessment outcomes and conclusions into a statewide GIS layer;
- Criteria to measure the ecological-effectiveness and cost-effectiveness of identified projects; and
- Resources (staff and funds) necessary to implement the recommended watershed assessment procedures throughout North Carolina.

The compensatory mitigation strategy will include a sufficient amount of restoration and enhancement to ensure no net loss of wetland and riparian acres and functions, including water quality effects. The project's preservation component is preserving the highest quality and most biologically diverse wetland and riparian sites throughout North Carolina.

3.3.1.1. Identification of Research Needs

Although much literature exists to support watershed management, there is still a need for development and evaluation of techniques to integrate transportation-related runoff analysis into overall watershed management. Stream channels respond to changes in flow volume and sediment loading. Watershed change is known to have a corresponding effect on channels leading to bank erosion and head cutting. These processes are well understood and descriptions of channel morphology are well developed, but effective predictive models of channel geomorphic response are lacking, especially in response to the episodic nature of runoff. Indices and indicators specific to transportation-related runoff are lacking as well.

3.3.1.2. Primary References

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3.3.2. Market-Driven Approaches: BMP Asset Management and Pollutant Trading

One of the major barriers to water quality planning and management in urban watersheds is the imbalance between economic development and environmental protection. Environmental economists often contend that the best approach to overcoming this barrier is to devise a mechanism for placing monetary value on the quality of the environment, thus creating an economic incentive for environmental protection.

Applying this reasoning to highway runoff management, BMPs may be treated as an asset that must be maintained, along with roads. Asset management is a business process and a decision-making framework that covers an extended time horizon, draws from economics as well as engineering, and considers a broad range of assets. The asset management approach incorporates the economic assessment of trade-offs among alternative investment options and uses the information to help make cost-effective investment decisions. Little asset management information exists for BMPs.

Pollutant trading is a fairly new watershed-based, market-driven approach to improving receiving water quality while minimizing the costs associated with mitigation and restoration. Pollutant trading provides watershed managers and the regulated community more options for managing point and nonpoint source discharges. In 1996, the EPA issued *Draft Framework for Watershed-Based Trading*, which provides guidelines for establishing a market-based system of pollutant trading (U.S. EPA, 1996). Specifically, the document provides

- Background on what effluent trading is and the benefits it offers;
- A series of conditions that are necessary for trading, including those that ensure protection of water quality comparable to the protection that would be provided without trading;
- A template of regulatory, economic, data, technical, scientific, institutional, administrative, accountability, and enforcement issues that facilitates identification and evaluation of trading opportunities; and
- Worksheets and checklists for evaluating whether potential trades meet threshold conditions.

Pollutant trading has been successfully implemented in several communities. The U.S. EPA (1999) compiled a document that summarizes 37 effluent trading and offset activities that are occurring or have occurred around the country. Half of the activities are still in the early stages of development and nearly all are trades based on point source discharges, mainly by publicly owned treatment works. The majority of the pollutants traded to date are nutrients (nitrogen and phosphorus). However TSS, ammonia, temperature, pH, BOD, DO, and metals also have been traded at various implementation levels, including individual, watershed, and statewide trades.

On January 13, 2003, EPA's Office of Water released the final *Water Quality Trading Policy* (U.S. EPA, 2003). The purpose of the policy is to encourage and provide guidance to states, interstate agencies, and tribes to develop and implement water quality trading programs for nutrients, sediments, and other pollutants where opportunities exist to achieve water quality improvements at reduced costs. More specifically, the policy is intended to encourage voluntary trading programs that facilitate implementation of TMDLs, reduce the costs of compliance with CWA regulations, establish incentives for voluntary reductions, and promote watershed-based initiatives. Based on the policy, EPA supports trading that involves nutrients or sediment loads, as well as cross-pollutant trading for oxygen-related pollutants where adequate information exists to establish and correlate impacts on water quality. EPA recognizes the potential value of trading other pollutants but believes such trades pose a higher level of risk and should receive a higher level of scrutiny. EPA currently does not support trading of pollutants considered (by EPA) to be persistent bioaccumulative toxics (PBTs). EPA would consider a limited number of pilot projects over the next 2 to 3 years to obtain more information on the trading of PBTs.

Another potential approach to stormwater management at the watershed level is using tradable allowances for excess stormwater runoff. Thurston et al. (2003) proposed a tradable runoff allowance system that would create economic incentives for landowners to employ low-cost runoff management practices so that excess stormwater flow to more ecologically sound levels could be reduced. The trading mechanism requires detailed mapping information on individual properties, including size, percent imperviousness, and soil type to predict runoff using sophisticated hydrological models. Each property owner is allocated a specific quantity of annual runoff based on an assessment of predeveloped conditions and receiving water sensitivity (this is assuming a stormwater management authority is in place). Anything above this allowance is considered excess runoff and must be mitigated or traded. The costs include the cost of mitigation, which would be the cost of BMP construction, operation and maintenance, and the opportunity cost of land taken out of other uses. Based on the theory of economic systems, excess runoff could be traded within a watershed-based open market.

The Water Environment Research Foundation (WERF) currently is funding a 1-year, $100,000 research project—Common Currency for TMDL Commodities: Trading Infrastructure (RFP No. 02-WSM-1). The primary objective of the project is to generate practical tools that support the implementation of watershed-based trading efforts for use by point and nonpoint dischargers. The tools developed in this research will help trading participants to better delineate their watersheds and trading markets, allow participants and potential participants and their commodities to identify each other, and help develop transferable marketplace infrastructure to enable creation of functional markets.

Building on lessons learned in past trading efforts (WERF-funded and others) and using EPA draft policy and other trading documents as general guidelines, proposed research should advance watershed-based trading by improving the tools to accomplish trading and by providing guidance for their use. Research will develop generic infrastructure tools to assist with trading implementation. Even in places where trading has been identified as a potential solution, setting up successful trading systems is a challenging process subject to various pitfalls. Successful projects are likely to develop and improve the tools to allow trades to occur and probably will address the following questions related to trading infrastructure:

1. **Participatory Tools**: How are appropriate stakeholders and participants identified?
2. **Marketplace Tools**: What is necessary for trading markets to work? How are potential traders and their commodities brought together in a functional marketplace? How will transactions be made? How can trades and water quality improvements be tracked and managed? What tools can help meet oversight needs such as accountability and liability for trades?
3. **Regulatory Tools**: How might regulatory issues such as NPDES permitting, permit conditions, and discharge reporting, affect the potential market infrastructure? How could potential regulatory constraints be avoided?
4. **Context**: Do the tools differ? Should they differ if the trading programs are established in a pre-TMDL environment or to help meet an established TMDL?
5. **Scale**: What are appropriate scales for successful trading programs? At what point is a system too large to handle trading programs to improve water quality?

For simplicity, the research may focus on tools that work for single-pollutant programs, although ultimate extrapolation to multicredit or multimedia markets is desirable. Consideration and integration of the environmental and economic parameters necessary to accomplish trading—parameters such as administration and transaction costs—are critical in this research.

3.3.2.1. Identification of Research Gaps and Needs

Of the examples of market-driven trading programs reviewed in the literature, none were found that were specific to highways. However, the EPA does support trading for both point and nonpoint source load allocations, so the potential exists for trading of highway runoff pollutants. As highway runoff is typically higher in many concentrations than other urban and nonurban runoff, the potential exists to overtreat highway runoff relative to offsite other nonpoint sources (with some appropriate compensation). As the imperviousness of highway facilities can be estimated readily, the excess stormwater runoff tradable allowances system proposed by Thurston et al. (2003) is a potentially feasible alternative to highway stormwater management. Since market-driven watershed-based stormwater management approaches are relatively new, there exists a need for further research into the practicality of such approaches, particularly for application to highway runoff management. Once completed, the current study funded by WERF should provide information and guidance on how a market-driven, watershed management system could be applied to the highway environment.

3.3.2.2. Primary References

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3.4. HIGHWAY RUNOFF CHARACTERIZATION AND ASSESSMENT

This category refers to the hydrologic and water quality characterization of highway runoff before entering water quality control facilities or receiving streams. The knowledge gained from characterization monitoring helps DOT planners and managers understand how to establish stormwater management priorities.

The research category of highway runoff characterization and assessment has been well studied and several general characterization studies are readily available in the literature. However, this category is broad and the level of detail for any one study may range from the microscale, such as unit chemical processes, to the macroscale, such as gross pollutant transport. Furthermore, because of the variability and complexity of environmental systems, the association or correlation between different physical, biological, and chemical parameters will require several more decades, if not longer, to fully understand at a satisfactory level. Due to this fact, this assessment does not attempt to identify all research gaps, but rather identifies the gaps where there is a current need for a better understanding for the purposes of improved highway runoff management. The following paragraphs are organized according to subcategories based on perceived needs of the transportation and water resources community.

3.4.1. General Constituent Characterization

During the last three decades, researchers throughout the developed world have conducted highway runoff quality characterization studies. The primary driver for runoff quality characterization today is regulatory compliance; however, characterization also is conducted to identify pollutants of concern for the development or refinement of stormwater quality management programs. In the United States, federal and state agencies have conducted several studies to identify the type and range of concentrations of water quality constituents typically found in highway runoff.

During the 1970s and 1980s, FHWA funded several studies pertaining to highway runoff quality characterization. The following excerpt from Bank et al. (1995) summarizes the multivolume research reports concerning highway runoff quality developed by FHWA:

1. *Constituents of Highway Runoff*—This six-volume report, completed in 1981, developed a predictive procedure for determining the pollutant characteristics of stormwater draining from roadway surfaces. The procedure is composed of equations that predict the runoff volumes and pollutant wash-off coefficients of 17 water quality parameters for three types of highways.
2. *Sources and Migration of Highway Runoff Pollutants*—This four-volume report, completed in 1984, identifies the sources of potential water pollutants, their deposition and accumulation within the highway facility, and their subsequent removal to the surrounding environment. The purpose of this research was to develop methods for controlling pollutant sources and mitigation measures to lessen pollutant levels entering receiving waters.
3. *Effect of Highway Runoff on Receiving Waters*—Completed in 1985, this five-volume report analyzes the effects of highway stormwater runoff on receiving waters. Included in the effort were 1-year field studies at three sites and preparation of three user-oriented manuals that provide guidelines for collecting information to use in highway project environmental assessments.
4. *Highway Maintenance Impacts to Water Quality*—This four-volume series of reports, completed in 1985, summarizes a research project involving impacts from highway maintenance practices on water quality. Research efforts included (1) evaluating the impact potential of routine practices; (2) developing assessment methods for specific practices; (3) identifying measures to mitigate impacts; and (4) conducting field studies to better define impacts from two common practices, herbicide application and surface treatment (seal-coating).
5. *Retention, Detention, and Overland Flow for Pollutant Removal from Highway Stormwater Runoff*—This report, completed in 1987, provides interim guidelines for the removal of pollutants from highway stormwater runoff. Three general types of management measures have been determined, through previous FHWA studies, to be effective in treating highway runoff: vegetative controls (overland flow and grassed channels), detention basins (wet detention basins and wetlands), and retention measures (retention basins, trenches, and wells). These interim design guidelines were developed through the project team's experience and through a thorough review of available literature.
6. *Pollutant Loadings and Impacts from Highway Stormwater Runoff*—Published in 1990, this is a culmination of analytical effort using the results of previous water quality studies in concert with hydraulic, environmental, and related concerns. The results of this study include a probabilistic design procedure for estimating impacts to waters receiving highway stormwater runoff. The procedure used and expanded on the predictive model developed in the first series of reports. Additional runoff water quality data collected by this and other studies subsequent to the original work in the first phase were used to refine the regression analyses supporting the predictive procedure.

The 1990 effort was undertaken to improve the highway practitioner's ability to address highway stormwater runoff issues. Formulated by Driscoll and others, the model used factors such as storm event statistics and probability distribution of site event mean concentration to estimate runoff volumes, concentrations, and loads, and probability distribution of streamflow to estimate potential dilution in receiving waters. This statistical model, useful for planners and highway practitioners, uses readily available rainfall statistics and water quality data to produce a frequency distribution of concentration, loads, and effects for receiving waters.

The existing FHWA model was formulated using data from 993 separate highway runoff events at 31 sites in 11 states during the period from 1975 to 1985. In the past 20 years, automobile construction materials, technology, and fuel additives have changed, and these factors have affected the loads from highway surfaces. Research has indicated that lead may be substantially lower than in the 1970s and 1980s because of improvements in fuel formulations, emissions controls, and tire wear (even though total vehicle miles traveled has increased).

FHWA has a study underway with USGS to incorporate the existing model in a new user-friendly software platform; update the existing model with new streamflow and rainfall data; and expand the model to include the availability of dissolved concentrations, sediment size information, sediment-chemistry information, and a data quality advisory system. The final version will be an updated version of the existing 1990 model, along with a new version of the model that is designed to incorporate new highway runoff data as it becomes available. This information will benefit the municipalities and state and federal agencies charged with estimating highway runoff pollutant loads.

In addition to the FHWA-funded research, several other highway runoff characterization studies have been conducted by state DOTs and independent researchers. Stormwater samples collected by the Michigan DOT at three major highways indicated that concentrations of conventional constituents—

such as biochemical oxygen demand (BOD), TSS, and phosphorus—are comparable to the concentrations collected in the FHWA studies of the 1970s and 1980s (CH2MHill, 1998). However, concentrations of metals, lead in particular, were lower for the Michigan DOT sampling than they were for the FHWA studies. This finding can be attributed to the discontinuation of leaded gasoline and improvements in sampling and analytical techniques. The earlier FHWA data contains only limited information on the dissolved form of metals, a critical consideration regarding effects of metals on aquatic biota. Therefore, this study fills a significant gap in previous FHWA highway runoff characterization studies. Organic compounds were, for the most part, not detected in Michigan DOT runoff samples.

In a study funded by the Texas DOT, water quality of highway runoff in the Austin area was determined by monitoring runoff at three locations on the MoPac expressway, which represented different daily traffic volumes, surrounding land uses, and highway drainage system types (Barrett et al., 1996). The highest concentrations of all constituents were measured at the high-traffic site [average daily traffic (ADT) >30,000 vehicles]. The concentrations at all sites were similar to median values for similar sites compiled in FHWA's nationwide studies of highway runoff quality.

Caltrans has ongoing runoff characterization studies at several different types of transportation facilities throughout the state, including highways (congested and free-flowing), construction sites, maintenance yards, and park-and-ride stations. Caltrans' *Preliminary Report of Discharge Characterization Studies* summarizes runoff quality data collected since the 2000–2001 wet season from more than 50 sites (Caltrans, 2003). With the exception of total dissolved solids, TSS, dissolved lead, total lead, and dissolved arsenic, all of the mean concentrations from the congested highways were greater than the mean concentrations from free-flowing highways; however, none of the differences were statistically significant. For the most part, the data agree with the ranges reported in FHWA's studies as well as with studies by Texas DOT and Michigan DOT. As with Michigan DOT's study, lead concentrations were generally less in the Caltrans data as compared to the FHWA data.

3.4.1.1. Constituents Specific to the Highway Environment

Volatile Organic Carbons. Many studies to characterize concentrations of semivolatile organic compounds (SVOCs) in highway runoff and urban stormwater have been conducted since 1970 (Lopez and Dionne, 1998). To a lesser extent, studies also have characterized concentrations of volatile organic compounds (VOCs), estimated loads of SVOCs, and assessed potential impacts of these contaminants on receiving streams.

This review evaluates the quality of existing data on SVOCs and VOCs in highway runoff and urban stormwater and summarizes significant findings. Studies related to highways are emphasized when possible. The review included 44 articles and reports that focused primarily on SVOCs and VOCs. Only 17 of these publications are related to highways, and 5 of these 17 are review papers. SVOCs in urban stormwater and sediments from the late 1970s to the mid-1980s were the subject of most studies.

Criteria used to evaluate data quality included documentation of sampling protocols, analytical methods, minimum reporting limit or method detection limit, quality-assurance protocols, and quality-control samples. The largest deficiency in documenting data quality was that only 10% of the studies described where the water samples had been collected in the stream cross section. About 80% of SVOCs in runoff are in the suspended solids. Because suspended solids can vary significantly even in narrow channels, concentrations from discrete point samples and contaminant loads estimated from those samples are questionable without information on sample location or how well samplers control the quality of samples. Comparison of results of different studies and evaluation of the quality of environmental data, especially for samples with low concentrations, is difficult without this information.

The most significant factor affecting SVOC concentrations in water is suspended solids concentration. In sediment, the most significant factors affecting SVOC concentrations are organic carbon content and distance from sources such as highways and power plants. Petroleum hydrocarbons, oil and grease, and polycyclic aromatic hydrocarbons (PAHs) in crankcase oil and vehicle emissions are the major SVOCs detected in highway runoff and urban stormwater.

The few loading factors and regression equations that were developed in the 1970s and 1980s have limited use in estimating current loads of SVOCs on a national scale. These factors and equations are based on few data and use inconsistent units, and some are independent of rainfall. Also, more cars on the road today have catalytic converters, and fuels that were used in 2003 are cleaner than when loading factors and regression equations were developed.

Comparisons to water-quality and sediment-quality criteria and guidelines indicate that PAHs, phenolic compounds, and phthalates in runoff and sediment exceeded EPA drinking-water and aquatic-life standards and guidelines. PAHs in stream sediments adjacent to highways have the highest potential for adverse effects on receiving streams.

Few data exist on VOCs in highway runoff. VOCs were detected in precipitation adjacent to a highway in England, and chloromethane, toluene, xylenes, 1 2 4-trimethylbenzene, and 1 2 3-trichloropropane were detected in runoff from a highway in Texas. In urban stormwater, gasoline-related compounds were detected in as many as 23% of the samples. Land use could be the most significant factor affecting the occurrence of VOCs, with the highest concentrations of VOCs found in industrial areas; temperature is another factor. Urban land surfaces are the primary nonpoint source of VOCs in stormwater. However, the atmosphere is a potential source of hydrophilic VOCs in stormwater, especially during cold seasons when partitioning of VOCs from air into water is greatest. Tetrachloroethene, dichloromethane, and benzene were the only VOCs detected in stormwater that exceeded EPA drinking-water standards.

Polyaromatic Hydrocarbons. PAHs are a group of toxic and carcinogenic compounds rarely included in characterization studies, but often present in highway runoff due to traffic-related sources. PAHs represent more than 2000 PAH compounds; only 16 have been placed on the EPA list of priority pollutants (Pawluk et al., 2002). PAHs are ubiquitous and are emitted from practically every combustion source. Following combustion, PAHs enter the atmosphere, rivers, and lakes through wet deposition or through dry deposition, where they are washed away by stormwater runoff. Specific traffic-related sources of PAHs include tire wear, asphalt and asphalt coatings, vehicle exhausts, and lubricating oils and grease (Pawluk et al., 2002). Other sources include industrial effluents and spills or intentional dumping.

Some PAHs will evaporate from water and soil, but the majority of PAHs in stormwater usually are found in particulate form. A stormwater runoff study done by Marslek et al. (1997) found that the dissolved phase PAHs represented less than 11% of the total concentrations. In another study, Shinya et al. (2000) found that the higher molecular weight PAHs were more associated with suspended solids in the runoff and the predominant PAHs (phenanthrene, fluoranthene and pyrene) comprised about 50% of 15 quantified PAH constituents in each sample. In results from Ames' assay, mutagenicity was associated appreciably with PAHs in the particulate fraction of runoff water. The dissolved fraction also showed positive mutagenic response by unknown soluble aromatic compounds. Smith et al. (2000) collected 42 stormwater runoff samples from four sampling sites (a highway off-ramp, a gas station, and a low- and high-traffic-volume parking lot). For each sample, the suspended-sediment and water phases were separated and analyzed for 16 PAHs. The gas station site produced the highest total PAH loading (2.24 g/yr/m^2), followed by the high-traffic-volume parking lot (5.56×10^{-2} g/yr/m^2), the highway off-ramp (5.20×10^{-2} g/yr/m^2), and the low-traffic-volume parking lot (3.23×10^{-2} g/yr/m^2). In several samples, one or more PAHs were detected in the aqueous phase at concentrations above aqueous solubility. This result suggests the presence of colloidal-size particles capable of sorbing PAHs to an appreciable extent, or the presence of an oil-and-grease microemulsion.

The effects of PAHs on aquatic systems are not well known.

Platinum Group Metals. Another group of elements that have been found more recently in urban runoff are the platinum group metals (PGMs): palladium, platinum, and rhodium. PGMs are used in catalytic converters to abate the emission of aromatic hydrocarbons, CO and NO_x. Due to the thermal and mechanical conditions under which autocatalysts work (including abrasion effects and hot-temperature chemical reactions with oil fumes), significant release of the PGMs to the environment in the form of fine particles can occur (Carolia et al., 2000). This raises concern, because platinum is a known cytotoxin and tends to bioaccumulate. Because air quality regulations require catalytic converters in all new cars, the amount of PGMs released into the environment each year is expected to continue to increase. A study conducted by Rauch et al. (1999) investigated the concentrations of PGMs in road sediment samples in 1984, 1991, and 1999 and found a clearly increasing trend, especially as related to particles smaller than 63 µm.

Gasoline Oxygenates. Methyl tert-butyl ether (MTBE), a gasoline oxygenate, disperses rapidly in water and is less biodegradable than common gasoline compounds, such as benzene, toluene, ethylbenzene, and total xylene (BTEX). USGS sampled stormwater in 16 cities and metropolitan areas that are required to obtain permits to discharge stormwater from their municipal storm-sewer system into surface water (Delzer et al., 1996). Concentrations of 62 VOCs, including MTBE and BTEX compounds, were measured in 592 stormwater samples collected in these cities and metropolitan areas from 1991 through 1995.

MTBE was the seventh most frequently detected VOC in urban stormwater, following toluene, total xylene, chloroform, total trimethylbenzene, tetrachloroethene, and naphthalene. MTBE was detected in 6.9% (41 of 592) of stormwater samples collected. When detected, concentrations of MTBE ranged from 0.2 to 8.7 µg/L, with a median of 1.5 µg/L. All detections of MTBE were less than the lower limit of the EPA draft lifetime health advisory (20 µg/L) for drinking water. Eighty-three percent of all detections of MTBE in stormwater were in samples collected from October through March 1991–1995, a timeline that corresponds with the expected seasonal use of oxygenated gasoline in areas where carbon monoxide exceeds established air-quality standards. The median concentration of MTBE and benzene for all samples was statistically different and higher in samples collected during the October–March season than in samples collected during the April–September season. Sixty-six percent of all MTBE detections occurred with BTEX compounds, and a proportionate increase in concentrations was found when these compounds occurred together. The proportionate increase could indicate a common source of MTBE and BTEX for those samples. Toluene and total xylene were the most frequently detected BTEX compounds and the most frequently detected VOCs in these investigations. Detected concentrations of toluene and total xylene ranged from 0.2 to 6.6 µg/L and from 0.2 to 15 µg/L with median concentrations of 0.3 and 0.4 µg/L, respectively.

These data raise questions that remain to be answered because these stormwater investigations were not designed specifically to characterize the occurrence, sources, and behavior of oxygenated gasoline components in stormwater. Questions include

- What are the ranges and seasonal distributions of concentrations of MTBE in stormwater, including municipal separate-storm-sewer systems and combined sewer overflows, in other urban areas of the United States?
- What is the persistence of MTBE in streams or rivers that receive stormwater runoff? Are the concentrations in the receiving stream a cause for concern because of potential effects on aquatic life? Similarly, what effect, if any, does MTBE have on public water supplies from surface-water sources?
- What proportion of MTBE detected in urban stormwater is contributed by precipitation and what proportion is contributed by overland runoff? How much MTBE is contributed to surface water by precipitation that falls directly on larger bodies of water such as reservoirs and lakes?
- Do other oxygenates react similarly to MTBE in the hydrologic cycle and occur in stormwater?
- Is land use an important factor in the occurrence of MTBE or BTEX compounds in urban stormwater?
- Is stormwater recharge or precipitation that contains VOCs an important source of MTBE to groundwater in urban environments?

3.4.1.2. Identification of Research Needs

Many state DOTs have studied highway runoff, so there are several studies available that generally characterize highway runoff quality. The constituents sampled and the concentrations detected do not appear to vary significantly between the studies; therefore, the research topic of general highway runoff characterization does not represent a primary research need. However, there is clearly a need for better highway runoff characterization (including monitoring techniques) of petroleum hydrocarbons, including PAHs, as well as other trace elements not normally included in characterization studies, such as BTEX, MTBE, and PGMs. More advanced highway runoff characterization studies, such as those that investigate first-flush phenomena, the correlation of water quality parameters to independent variables, or the fate and transport of highway runoff pollutants, will be discussed in following subsections.

3.4.1.3. Primary References

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3.4.2. Runoff Characterization with Independent Variable Correlation

This broad category refers to water quality parameters whose presence or magnitudes, or both, are associated with other parameters or external factors. Correlation often is used to account for some of the variability observed in hydrologic and water quality data and to build regression equations for predicting difficult-to-measure parameters. Some of the common research questions posed with regard to runoff water quality correlation include

- How do suspended solids or particle-size distribution relate to constituent concentrations?
- What are the effects of ADT or vehicles during a storm (VDS) on stormwater quality?
- How do hydrological factors such as the antecedent dry period (ADP), rainfall volume, intensity, or duration affect runoff quality?
- Is there a discernable difference in runoff water quality from different land uses?

3.4.2.1. Suspended Solids and Particle-Size Distribution

Several researchers have attempted to correlate various water quality parameters to suspended solids (the residue retained on a 1.2 μm filter, also referred to as filterable residue). Kerri et al. (1985) conducted an intensive runoff monitoring effort at urban highway sites in Redondo Beach, Walnut Creek, and Sacramento, California, as well as from a rural site near Placerville, California, in an effort to develop regression equations for estimating pollutant loads from highways. Rainfall and runoff were monitored continuously. Bubbler flow meters were used with automatic sequential samplers so that stormwater samples could be collected to characterize entire storm events. The constituents that were analyzed were boron, total lead, total zinc, nitrate (nitrogen), ammonia (nitrogen), total Kjeldahl nitrogen (TKN), total phosphorus, dissolved orthophosphate, oil and grease, nonfilterable residue, filterable residue, total cadmium, and chemical oxygen demand (COD). Based on regression analysis, the total residue (TSS) was evaluated and accepted as a satisfactory independent variable for estimating total zinc, nonfilterable residue, and COD in runoff from highways with average daily traffic (ADT) of at least 30,000 vehicles. In another study, Zhao et al. (1999) correlated suspended solids and COD for stormwater runoff from an urban highway in Xi'an, China, indicating that COD is strongly associated with particulate matter.

Sansalone and Buchberger (1997) studied the association of metal elements as a function of particle size for both rainfall runoff and snowmelt. Solids ranged from smaller than 1 μm to greater than 10,000 μm. Flow rate and duration controlled the yield and size of transported solids. Metal element analysis of particle size distribution (PSD) from snow and rainfall indicate that zinc, copper, and lead mass increase with decreasing particle size [i.e., increasing specific surface area (SSA)]. No clear trends, as a function of increasing SSA or between snow and rainfall runoff solids, are apparent for cadmium, which is a very mobile metal and mainly is dissolved in highway runoff. Based on this study, it is apparent that zinc, lead, and copper concentrations on solids may vary significantly from one event to another with the tendency for higher concentrations to be associated with the smaller particle sizes. Cadmium concentrations, however, do not tend to vary with storm events or particle sizes.

Sediment particle size characterization and its relationship with nutrient content (especially phosphorus) is an important element in the treatability evaluation of stormwater runoff. Studies from the Lake Tahoe Basin suggest that movement of total phosphorus in the tributaries to Lake Tahoe correlates with the sediment transport, supporting the contention that erosion and nutrient loading are related. However, there appear to be conflicting observations suggesting that all sediment is not the same with regard to the phosphorus content. A study by Reuter and Miller (2000) indicates that fine-grained sediment (<63 μm, thus finer than sand) correlates better with nutrients than does coarse-grained sediment (≥63 μm), perhaps implying that nutrient transport is more sensitive to the movement of fine-grained materials.

Another study reported by Hydro Science (1999) indicates that 46% of the particulate phosphorus is associated with particles that are the size of sand or larger. Phosphorus, with similar tendencies as heavy metals, also may be bound disproportionately to larger particles (Glen and Sansalone, 2001). Based on this literature review, it is apparent that a broad and clear relationship between particle size and total phosphorus is lacking. Thus, there is a need to characterize suspended sediment loads into fine (clay and silt) versus coarse and to characterize the nutrients associated with them.

3.4.2.2. Average Daily Traffic, Vehicles during a Storm, and Antecedent Traffic Count

Several researchers have attempted to correlate ADT to loads and concentrations in urban runoff with variable success. Driscoll et al. (1990) found that there was no definitive relationship between traffic density and pollutant levels. A strong positive correlation for zinc ($r^2 = 0.7$) and a weak positive correlation for VSS, DOC, and TOC were observed. However, based on the fact that the other metals often associated with highway runoff (e.g., copper and lead) did not appear to be correlated with ADT, the authors concluded that ADT should not be used as a surrogate measure of pollutant levels, and surrounding land use appeared to be more correlated to pollutant levels than to ADT.

In a study conducted by Washington State DOT and summarized by Thomson et al. (1997), the researchers demonstrated that storm event loads of copper, lead, zinc, and TKN could be correlated with ADT and TSS loads. Correlation coefficients were all above 0.8, indicating that greater than 80% of the variability of these constituent loads could be explained by the variation in ADT and TSS loads. However, single variate correlation of ADT alone was not conducted, so it is not possible to statistically assess the amount of variability in constituent loads associated with ADT.

Table 3-7 is matrix of independent variables that affect various constituent concentrations in highway runoff (Thomson et al., 1997).

Kerri et al. (1985) found that the number of VDS was evaluated and accepted as a satisfactory independent variable at the 5% confidence level for estimating the loads of total lead, total zinc, filterable residue (TSS), chemical oxygen demand, and TKN. The authors stress the use of these equations should be limited to highways with ADT of at least 30,000 vehicles. The numbers of antecedent dry days was found not to be a satisfactory independent variable for constituent correlation.

One of the most profound highway runoff correlation studies found in the literature review was conducted by Irish et al. (1995) in Austin, Texas. During this study, 35 storm events

TABLE 3-7 Identification of independent variables affecting constituent concentrations in highway runoff during multiple regression analysis (adapted from Thomson et al., 1997)

	Storm Duration	Storm Volume	Storm Intensity	Vehicles During Storm	Length of Antecedent Dry Period	Antecedent Traffic Count	Previous Storm Duration	Previous Storm Volume	Previous Storm Intensity
Iron		*	*		*				
TSS		*	*		*				*
Zinc	*	*				*	*	*	*
COD	*	*	*		*	*			
Phosphorus	*	*	*			*			
Nitrate		*	*			*			
BOD_5		*	*	*		*			
Lead		*	*	*					*
Copper	*	*		*					
Oil and Grease		*		*					

were simulated using a full-scale rainfall simulator, and 23 natural storm events were sampled at the same location; both events occurred with active traffic. Twenty-one variables were identified for each storm event, and multiple regression analysis was used to determine the relationship of each variable to the quality of the highway runoff. The highway runoff constituents significantly affected by VDS were BOD, lead, copper, and oil and grease. The highway runoff constituents significantly affected by antecedent dry period traffic count (ATC) were COD, BOD, phosphorus, nitrate, and zinc.

3.4.2.3. Hydrological Factors

Some of the common hydrological factors believed to affect the quality of highway runoff are ADP and the runoff volume, intensity, and duration during a storm. As with ADT, researchers have had variable success with the correlation between ADP and stormwater quality. Both Kerri et al. (1985) and Reinertsen (1981) found that the number of antecedent dry days was not a satisfactory independent variable for constituent correlation. Drapper et al. (2000) and Thomson et al. (1997) found that interevent duration can be a statistically significant factor for pollutant concentrations. Thomson et al. (1997) showed that iron, TSS, and COD could be positively correlated to ADP. However, other independent variables such as storm volume and storm intensity were shown to account for a greater amount of the variability in concentrations of these constituents.

With regard to runoff volume, Reinertsen (1981) found that the discharge level alone did not influence the runoff quality as much as might be expected, and in fact no significant correlation was observed between the concentrations and the discharge either within or between rain events. Driscoll et al. (1990), in their analysis of 184 paired data sets representing eight different pollutants at each of 23 highway sites, concluded that pollutant event mean concentrations (EMCs) are independent and unrelated to either rainfall or runoff volume. However, in another study, Colwill (1985) found that the amounts of particulate material and associated contaminant removed from the road surface by individual events are dictated largely by the intensity of rainfall and the total volume discharged. Stenstrom et al. (1982) found a strong correlation between total rainfall and total mass of oil–grease pollution. Therefore, it appears that there is not a significant correlation between runoff volume and concentrations, but there is a significant correlation between runoff volume and loads, as expected. Very few studies were found that investigated the correlation between storm intensity with concentrations or loads. However, it is expected that particulate-bound constituents are influenced greatly by rainfall intensity.

3.4.2.3 Land Use Effects

FHWA and USGS are cooperating on research to determine the various components of impervious surfaces to the overall stormwater runoff issue using existing land use, land cover, and impervious surface data. There are numerous studies on impervious surfaces, but some have differentiated between rooftops and transportation systems and some have identified buildings and roads as the only contributor for all the impervious surfaces. If the components of impervious surfaces are broken down into more detailed components with a watershed, methodologies can be developed and evaluated on how to control and mitigate these impacts. In order to improve understanding of how much each impervious surface is contributing to the total imperviousness for each watershed, this research specifically examines the percentage of transportation infrastructure as well as the percentage of contributions that state transportation agencies maintained highway systems contribute to the total imperviousness of an urban watershed.

The correlation of land use to pollutant loads has been investigated by several other researchers over the last few decades. Probably the largest land use-based runoff characterization study to date is the EPA Nationwide Urban Runoff Program (U.S. EPA, 1983), in which runoff samples were collected from 28 major metropolitan areas across the United States and analyzed over a 5-year period. One of the most significant findings of this research was that runoff concentrations from the various land uses (residential, mixed, commercial, industrial, and open/nonurban) were not statistically significantly different from one another, with the exception of total phosphorus from open/non-urban land use areas. Regardless of these findings, the characterization of runoff according to land use continues to be a topic of interest for many researchers because of the implications for predicting impacts of development.

Since 1994, the County of Los Angeles has been collecting stormwater samples from various land uses throughout the county as part of their Phase I NPDES Permit requirements (Los Angeles County Department of Public Works, 2001). Land uses monitored include retail and commercial, vacant, high-density single-family residential, transportation, light industrial, education, multifamily residential, and mixed residential. Results suggest that there are some distinct differences in the average runoff concentrations of monitored pollutants between land uses; however, the study did not evaluate the statistical significance of those differences. Metals, nutrients, and oil–grease concentrations were highest from transportation and light industrial and commercial sites, although the open space sites had the highest TSS concentrations.

The Oregon Clean Water Agencies published a compilation of land use data collected in Oregon (Willamette Valley) for the Phase I Part II Municipal Stormwater Permit Applications that showed that different urban land uses could be characterized as having different water quality for a number of constituents, including heavy metals (Strecker, 1995). Phosphorus appeared to be more related to surrounding soil types.

In a study conducted by Stenstrom et al. (1982), five field sampling stations were selected in a stormwater basin in Richmond, California, to determine oil–grease pollution by land-use type. Samples were taken from the mouth of the watershed, a parking lot, a commercial street, a residential area, and a light industrial facility. Results of the investigation indicated that land use strongly affects oil–grease in stormwater with the major contributing factor being motor vehicles. Areas with the most auto traffic had the highest concentration of oil–grease in stormwater and the highest hydrocarbon load factor. Mean oil–grease concentration in runoff flow ranged from 4.13 mg/l in an upstream residential area to 15.25 mg/l in a parking lot.

Highways usually are considered an individual land use type but are sometimes further divided according to urban and rural, congested and free-flowing, total area, percent impervious area, the number of lanes, on- and off-ramps, and ADT, which has already been discussed. Only a few studies could be found that discuss differences among some of these more detailed highway land use classification levels.

Based on their analysis, Driscoll et al. (1990) recommended using urban versus nonurban for classifying highway sites rather than ADT. Caltrans (2003) classified highway sites according to congested and free-flowing, but they have yet to statistically analyze their data. However, after briefly perusing the means and standard deviations of the monitored constituents, it appears that there will not be statistically significant differences between the two classification types. Thomson et al. (1997) analyzed runoff quality data from several different highway classification types including the total area, total impervious area, and total number of lanes. The analysis revealed that with the addition of other regression parameters such as TSS, TDS, and TOC, percent impervious area may be useful for predicting COD, and the total number of lanes may be useful for predicting chloride, sodium, and COD on a site-specific basis. Drapper et al. (2000) found that sites incorporating exit lanes have recorded higher concentrations of acid-extractable copper and zinc, supporting the hypothesis that brake pad and tire wear caused by rapid deceleration contributes to the concentrations of these metals in road runoff. However, these data were discussed qualitatively only.

3.4.2.4. Identification of Research Needs

With regard to suspended sediment and particle size distribution, the association of typically observed highway runoff pollutants with suspended sediment seems to be well characterized. However, there still appears to be a need for better characterization of constituents associated with different sized particles in highway runoff, particularly heavy metals, nutrients, and hydrocarbons.

The association of traffic volume with runoff concentrations is well documented in the literature reviewed but still lacks a statistically valid amount of data to support significant conclusions. ADT does not appear to be a consistently good predictor of pollutant concentrations and loads. However, VDS may hold promise for estimating concentrations for some metals and nutrients, as well as TSS, COD, BOD, and oil and grease. Thus, there appears to be a need for more research in the area of runoff characterization with correlation to VDS. Only one study was found that investigated the effects of ATC, so this may also represent a research gap.

The hydrological factors such as runoff volume, rainfall volume, intensity, and duration are independent variables that have been shown by a few researchers to affect runoff constituent levels. Total storm volume affects loads of some water quality parameters such as TSS and oil and grease but does not appear to significantly affect concentrations. Correlations between intensity and duration with constituent levels are sparse in the literature reviewed, indicating this may be a research gap.

Land use appears to affect average stormwater runoff concentrations, yet no studies have been found that show statistically significant differences in concentrations based on land use type alone. Land use classification and separation probably are major factors influencing the variability in land use-based runoff concentrations. Land uses often are mixed (which frequently is considered a net benefit to stormwater quality) making it difficult to classify and to separate stormwater flows. Differences in classification levels also make it difficult to compare studies. Runoff quality characterization according to the various highway classifications, especially urban versus rural, on-ramps and off-ramps, and percent impervious area, appears to be an area needing further research.

Staff at the Center for Watershed Protection, in collaboration with Dr. Robert Pitt, are compiling and summarizing the available national data on urban runoff water quality and are conducting data explorations to ascertain potential explaining factors.

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3.4.3. Atmospheric Deposition

Pollutants in the atmosphere consisting primarily of metals and nitrogen can be returned to the earth through processes of wet and dry atmospheric deposition. Atmospheric pollutants are generated from natural and anthropogenic sources. Natural sources include volcanic activity, windblown dust, forest fires, and vegetation. Anthropogenic sources include smelting of ores, fugitive dust from emission controls, and automobile emissions (Osmond et al., 1995). Wet deposition occurs when rain, snow, or fog bring down gaseous or particulate pollutants into the atmosphere. Dry deposition occurs when atmospheric pollutants find their way to the earth in the absence of precipitation (Nilles, 2000). Mercury, lead, and other metals are controlled at the source as required by the provisions of the Clean Air Act (CAA), and emissions have been reduced significantly; however, pollutants deposited previously and atmospheric nitrogen emitted from various sources—some unregulated by the CAA—still pose a significant threat to the environment (Osmond et al., 1995). Potential knowledge gaps in the area of atmospheric deposition include

- Atmospheric pollutant monitoring and sampling methods and technologies,
- Modeling and estimation of atmospheric deposition and prediction of dispersion patterns,
- Characterization of impacts of atmospheric deposition on receiving water systems and biota, and
- Specific contribution of highways to atmospheric deposition.

Atmospheric deposition can be a significant source of trace metals. Research performed by Atasi et al. (1998 and 2000) attributed cadmium and mercury levels in stormwater runoff to atmospheric deposition. The objective of the 1998 study was to investigate the impact of atmospheric deposition on surface runoff, the combined sewer system, and the publicly owned treatment works. Phase I of the study sought to quantify and characterize atmospheric deposition in relation to stormwater loadings. Pollutants of interest were mercury, cadmium, and polychlorinated biphenyl (PCB). A Phase II follow-on study may determine the effects of atmospheric loadings on the Detroit Waste Water Treatment Plant.

Monitoring and sampling activities were performed using state-of-the-art air and deposition equipment. Sampling was performed at sites located in three distinct geographical areas and land use types. For each of the three sites, researchers monitored precipitation, wind speed and direction, and temperature. The study concluded that almost 100% of the cadmium and 36–90% of the PCBs in runoff could be attributed to deposition. Higher-than-expected mercury and cadmium levels were observed in runoff from one site; this observation was hypothesized to be linked to direct deposition from vehicular traffic. The study showed that atmospheric deposition was the main source of the study pollutants.

The Atasi et al. 2000 study investigated the concentrations of 12 trace metals in the atmosphere, in precipitation, and in runoff. The metals sampled included mercury, cadmium, antimony, aluminum, arsenic, chromium, copper, manganese, nickel, lead, vanadium, and zinc. Researchers used specialized equipment and ultraclean analytical methods to monitor meteorological parameters as well as pollutant concentrations and observed that pollutant concentrations were related to spatial variations and dependent on land use. The conclusions indicated that atmospheric deposition is a significant source for trace metals within an urban watershed.

Other studies also have established atmospheric deposition as a significant source of pollutants. Tsai et al. (2001) investigated the contribution of atmospheric deposition to loadings of selected pollutants in the San Francisco estuary. Pollutants studied included copper, nickel, cadmium, and chromium. Monitoring was performed from August 1999 through August 2000, at three different sites chosen to represent the various segments of the estuary. The study observed dry deposition fluxes of copper, nickel, cadmium, and chromium at concentrations of 1100, 600, 22, and 1300 $\mu g/m^2$/year respectively and at concentrations of 1200, 420, 110, and 230 ng/L respectively in precipitation. Researchers concluded that atmospheric deposition contributed less than 30% of the loadings for copper and nickel in stormwater runoff. Contributions for cadmium and chromium in stormwater runoff approximate contributions from effluent discharges. By combining direct loads to the estuary and indirect loads through stormwater runoff, atmospheric deposition may contribute up to three times as much loading as effluent discharges to the estuary.

Researchers are looking constantly for ways to harness technology for the solution of environmental problems. The use of computer models and the development of new monitoring techniques and equipment is a growing area of atmospheric deposition research. Davies (1976) discusses the application of remote sensing to highway environmental problems. Remote sensing can be used to verify results from computer and mathematical models. It also can reveal the nature and concentrations of pollutant gases and can track the mass flow and transport of pollutants. Davies discusses instrumentation and computer models, such as Cospec and Gaspec, and computer models, including a grid-point model, a fixed-source sulphur dioxide model, and a carbon monoxide model.

The pollutants contained in precipitation are acquired from the atmosphere either through rain-out which occurs within clouds or washout which occurs as precipitation leaves the cloud. Shiba et al. (1999) used numerical simulations and a mathematical model to investigate the origins of atmospheric pollution found in stormwater runoff. Researchers provide chemical and mathematical descriptions for the cloud droplet acidification process, and they conclude that pollutants acquired during cloud formation constitute a significant part of the pollution process.

The MAGICWAND model is used to simulate soil and water acidification attributable to atmospheric deposition. Bobba et al. (2000) successfully applied the MAGICWAND model to the Turkey Lake Watershed in central Ontario, Canada, to evaluate the effects of atmospheric change and deposition. Shivalingaiah and William (1983) discuss the use of a multiregression model ATMDST, NEWBLD, and SWMM3 to model the Chedoke Creek catchment in Hamilton. ATMDST was developed to simulate the dust fall and provide input data for NEWBLD to calculate pollutant accumulation. Researchers compared pollutographs from this approach to pollutographs generated from the unmodified SWMM3 algorithms. Pollutants modeled in this study are suspended sediments, BOD, total nitrogen, and total phosphorous.

Sharma and McBean (2002) developed an atmospheric dispersion model for the transport of PAHs using two independent data sets from Ontario, Canada. The object of the investigation was to simulate PAH transport and accumulation in an urban snow pack. Researchers concluded that dry weather deposition is a dominant process in the urban environment. Estimates of deposition velocities and washout ratios were comparable to values obtained in previous investigations.

Researchers have attempted to link atmospheric deposition to external variables such as land use and surface type. Halverson et al. (1982) observed higher concentrations of metals runoff from highly used areas. Runoff sources used in the study included through-fall and stream flow from an urban tree, a suburban residential roof and street, a moderately used shopping center, and a heavily used highway. The authors found that the shopping center and the highway were the primary sources of metals and sulphates. Cadmium, manganese, and copper were observed in only a few samples at very low concentrations. Garnaud et al. (1999) selected four sites in the Paris metropolitan area to investigate dry and wet weather deposition in an attempt to better understand metal transport and metal distributions between dissolved and particulate fractions. Researchers provide a comparison of both dissolved and particulate atmospheric deposits from four roofs, three yards, six gullies, and one catchment outlet. The authors observed medium-range transport of atmospheric pollutants.

3.4.3.1. Identification of Research Needs

There appears to be a paucity of studies that directly relate highways and transportation systems to atmospheric deposition. Filling this gap would provide a better basis to understand how highway-specific atmospheric deposition and dispersion of highway-related pollutants affect receiving water quality, receiving water biota, and roadside ecosystems.

There is also a need to quantify the contribution of atmospheric deposition to pollutant concentrations found in highway runoff. Stormwater runoff data collected as part of DOT NPDES monitoring programs have revealed that surface runoff from highways and other DOT facilities contains pollutants known to be unrelated to transportation activities (except as spilled during transport). Most of these pollutants are organic and include chemicals with a wide range of volatility. The contribution of organic and inorganic pollutants from atmospheric deposition likely differs between urbanized and nonurbanized areas. The fraction of pollutants contributed by atmospheric deposition is not known for different land uses or classes of contaminants.

Research Objectives. Further research in atmospheric deposition would enable DOTs to

- Work with other dischargers to reduce pollutants on a watershed basis,
- Show that they are not responsible for everything appearing in their surface runoff, and
- Implement the best management practice on a regional basis to better control the organic and inorganic pollutants of concern.

The following areas were ranked relatively low by state DOTs but could be considered potential research tasks on a second tier list of research priorities based on gaps in the literature:

- Create a GIS database of regional atmospheric deposition using existing Air Resources Board ambient monitoring data and published deposition velocities (for dry deposition) and washout ratios (for precipitation inputs) to predict mass inputs to varied watersheds.
- Measure atmospheric deposition (both dry deposition and precipitation inputs) of major pollutants in major regions under various land uses. These measurements will be used to validate and calibrate the estimates produced in task 1.
- Identify the pollutants contributed in significant amounts by atmospheric deposition on a regional- and land-use basis using the results of the first two tasks.
- Identify sources of organic and inorganic pollutants using established "fingerprinting" techniques, including atmospheric tracers and elemental ratios.
- Refine the initial GIS model to predict the atmospheric pollutant contributions and their relative loads on regional and land use bases.

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3.4.4. Highway Construction Materials

The contribution of highway construction materials as a source of runoff pollutants cannot be overlooked. The endless rehabilitation and maintenance of the system of highways and the move to use new materials and recycled products in highway construction has increased significantly the chances of runoff contamination from highway construction materials. Research needs and possible knowledge gaps pertaining to highway materials as a source of runoff materials suggested by Nelson et al. (2001) include

- Expansion of available material data,
- Soil sorption and desorption research,
- Role of aluminum,
- Temperature effects,
- Leaching mechanisms, and
- BMPs for mitigating impacts from leached chemicals from highway construction impacts.

A comprehensive NCHRP study (Project 25-09) presented by Nelson et al. (2001) investigated the potential environmental impacts of highway construction and repair (C&R) materials on surface water runoff and groundwater quality. The study's main objective was to develop and evaluate methodologies for identification of possible surface and groundwater impacts from construction materials. Materials evaluated include asphaltic materials (such as asphalt cement), cementitious materials (such as Portland cement), industrial–manufacturing by-products (such as coal combustion fly ash, aggregate dust palliatives, and wood preservatives), and other miscellaneous materials (such as reflective glass spheres and ground tire rubber—"crumb rubber").

Amendment of most test materials with asphalt or aggregate resulted in a reduction or elimination of aquatic impacts. Soil sorption was identified as the most effective pollutant removal mechanism. The mathematical model IMPACT was developed for performing fate and transport analysis for surface and subsurface pathways. The result of this study was the successful development and evaluation of a complete methodology for screening and evaluation of potential environmental impacts of highway C&R materials.

Toxicity tests using algae and Daphnia were conducted to determine the toxicity level in water elutriates prepared from selected road construction and maintenance materials that emulate stormwater runoff (Eldin, 2002). Many of the tested construction materials proved to be toxic to the test organisms. Heavy metals such as aluminum, arsenic, lead, mercury, and some hydrocarbon compounds present in the test elutriates appeared to be major causes of toxicity. However, measured toxicity was reduced greatly or eliminated when elutriates were allowed to be in contact with selected soils. Under actual field conditions, mechanisms other than soil sorption—such as volatilization, photolysis, and biodegradation—are believed to further reduce the toxicity of stormwater runoff.

There appears to be a significant amount of research on finding either new materials for highway construction or ways to reuse existing materials and by-products. Schroeder (1994) presents a synthesis of information about various new and existing materials that are being used in highway construction. He also cites examples of DOTs and other public organizations that have used and evaluated alternative materials for highway construction or repair. Completed studies related to highway construction and repair materials as sources of pollutants are relatively scarce compared to the number of ongoing studies.

EPA, in conjunction with the Vanderbilt University in Nashville, Tennessee, has an ongoing study to develop testing and interpretation protocols for evaluating leaching from granular alternate aggregate replacement materials. Mathematical models and interpretation protocols will be used to evaluate the environmental impacts of leaching that occurs as a result of intermittent infiltration of precipitation into aggregate.

Other related research includes an FHWA-sponsored study being performed by the National Academy of Sciences; the study is called "Impacts of Significant Waste Materials Utilized in Highway Construction." For more information about this project, see the Transportation Research Board's (TRB's) Research-in-Progress (RIP) website.

An ongoing joint effort between the EPA and New Jersey DOT aims to evaluate the use of recycled materials in highway construction. The goals of this study include evaluation of long-term pavement durability, evaluation of environmental concerns, and cost-effectiveness of using recycled materials. Details of this effort are available on TRB's RIP website.

3.4.4.1. Identification of Research Needs

A literature review on the subject of highway construction and maintenance materials as a source of runoff contaminants reveals a limited number of studies on the subject (NCHRP Project 25-09 is the most comprehensive to date) and a significant amount of research in progress. Currently, potential knowledge gaps include the availability of materials properties data, knowledge of soil leaching and the sorption and desorption processes, a better understanding of the chemistry of aluminum in complex mixtures of chemical leachate and in soils, the effects and impacts of temperature, and a better understanding of the capabilities of existing BMPs to mitigate impacts from highway construction material contamination.

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3.4.5. Fate and Transport

The topic of fate and transport is very broad with whole university courses and several environmental engineering and science textbooks dedicated to the subject. This subsection touches on the surface of this vast topic with regard to highway runoff. The topic areas identified as the most important to highway characterization and assessment are sediment transport, speciation, and sorption processes. Other fate and transport topics such as advection, dispersion, diffusion, and volatilization are considered a lower priority in relation to the research needs of highway stormwater management.

3.4.5.1. Sediment Transport

Very little attention was given to urban sediment problems in the past. However, recent booms in housing development, road construction activities, and other large-scale earth-moving activities have drawn more attention to the urban sediment problems that previously received little attention. Urban sediment studies have now expanded in scope to include sediment quality as well as sediment quantity concerns. Even though much progress has been made, certain areas require more work; Brush (1981) suggested the following knowledge gaps and areas of interest:

- Characterization of particle sizes and settling velocities;
- Sediment transport mechanics such as transport and blockage potential of partly full and full conduits in noncircular cross-sections, local storage of sediment at various inlets and through various types of transitions in drainage systems; and
- Sediment yields in relation to various soils, topography, land use, and different kinds of storm hydrographs.

Sediment yield is the amount of sediment removed from a watershed at a given time. Fusillo et al. (1997) studied sediment yields for a watershed in central New Jersey. The authors discovered that construction sites contributed about 80% of the sediment for the basin, which is almost 50 times as high as yields for other land use areas. They observed that sedimentation basins installed at construction sites may reduce significantly sediment loads to streams.

Several researchers have performed studies and experiments with the aim of extending existing sediment transport computer models or creating new ones. Ziegler et al. (2001) replaced the step function in the KINEROS2 model with an exponential decay function. They observed that the method improved the continuous sediment transport time series estimate but underestimated peak sediment output, just like the original version of the model did. They concluded that peak output estimates may be improved through optimization using rainfall simulation data. They also recommended that the method be validated at the hill slope scale before its usefulness for simulating road erosion can be determined.

The Queen's University Urban Runoff Model evolved from the integration of a sediment transport model into an urban runoff model. The sediment transport model is based on the equivalent solids reservoir concept and requires only simple quantity and quality inputs. The model is capable of simulating sediment transport surfaces, gutters, pipes, and detention ponds. Schroeter and Watt (1983) tested the model with data from a stormwater sampling program in Kingston, Ontario, and the results of an independent study in Burlington, Ontario.

The Hydrologic Simulation Program-Fortran (HSPF) was used to model stream flow and TSS within Contentnea Creek in North Carolina. Input data for the model included land use data from EarthSat and historical meteorological data such as precipitation, pan evaporation, and temperature. The model was calibrated on historical time series of observed flow obtained from USGS. The study concluded that the simulated flows were a good fit to observed flows while TSS concentrations were replicated less accurately. The parameter values used in the study were well within the range of values used in other HSPF studies (Cyterski, 2000).

HYPOCRAS is a French-made model that is used to simulate the transport of solids in sewers. Ashley and Bertrand-Krajewski (1993) present a discussion about their work to extend and test the HYPOCRAS model. Other models in this category include SWMM, MOSQITO, and FLUPOL. The authors used data from a substantial data collection program in Dundee, Scotland, supported by the United Kingdom's Water Research Center for extending and testing the model. Two deterministic suspended solids models, one based on SWMM3 algorithms and the other based on fundamental erosion mechanics and sediment transport processes, were applied to two urban catchments. The models were tested with historical data collected on catchments in Pinetown and Alexandria; 16 events and 12 events were tested, respectively. To assess the performance of the models, Coleman (1993) compared the ratio of predicted load to observed load for each event and compared pollutographs from the models to observed pollutographs using the coefficient of efficiency for each event.

Computer models are useful for processing large quantities of data and solving complex problems; however, in situations in which quick estimates of quantities are needed, equations and formulas suffice. Younkin and Connelly (1981) developed an equation based on regression analysis of data from nine stream gages and five watersheds in Pennsylvania. The equation can be used to estimate the increase in suspended sediment yield in a stream due to highway construction. The equation relates factors such as soil erodibility, rainfall, construction phases, and site proximity to stream as well as increases in quantity of transported sediment. The equation may find applications in highway location studies, highway development impact assessment, and the design of sediment control devices.

Other researchers have investigated the significance of sediment particle size in sediment transport processes. Ota et al. (1999) investigated the effects of particle size on sediment transport in sewers. They tested three uniform materials of varying sizes and observed that test results were very sensitive to particle size. Transport rates were observed to be high for finer sand. Coarse material was harder to transport. The graded material was studied further using two different materials. Modified Meyer-Peter and Muller bed load functions were used to fit sediment transport rate for uniform materials.

3.4.5.2. Speciation of Constituents

Speciation of heavy metals in aquatic systems plays a key role in their transport, chemical reactions, and bioavailability. Physical and chemical forms that may cause significant consequences, known as consequential species, must be identified before the potential environmental impact of the metal can be assessed adequately, since biotoxicity is dependent on the available species and not the total metal concentration.

Yousef et al. (1985) investigated heavy metal speciation in rainfall and highway runoff at two sites in central Florida: at the intersections of Maitland Interchange and I-4 and at US-17-92 and Shingle Creek. Total and dissolved fractions of cadmium, copper, lead, and zinc were determined in the study. The dissolved metals fractions were further divided according to behavioral differences and bioavailability. Dissolved metals were first divided according to labile (reactive) and nonlabile (nonreactive) compounds, then according to organic and inorganic, and finally by soluble and colloidal. As dissolved metals do not exist as labile-organic-soluble, there are a total of seven possible speciation classifications. Results indicate that the labile, organic, and colloidal fractions average 82.0%, 5.3%, and 3.2% for cadmium; 92.9%, 0.3%, and 42.7% for zinc; 60.9%, 22.1%, and 55.6% for lead; and 63.7%, 48.9%, and 69.8% for copper in all water samples tested. Therefore, the authors conclude that zinc and cadmium are more reactive, may exist in ionic forms, and are more readily available to biota in natural environments than copper and lead. Other significant conclusions of the study include the following: (1) acidic rainfall generally is neutralized on contact with paved surfaces, and (2) carbonates and fulvates have a substantial effect on dissolved metal speciation, with the tendency to form complexes that are not as bioavailable.

In another speciation study by Morrison et al. (1984) zinc, cadmium, lead, and copper stormwater samples collected from selected urban catchments in England and Sweden were analyzed. The study found that zinc and cadmium exhibited a preference for the dissolved phase, whereas lead predominated in the suspended solid phase. Copper was distributed equally between both phases. Furthermore, the potentially toxic forms of the metals in the dissolved phase (electrochemically available) and in the particulate phase (exchangeable) accounted for 63% of the total zinc, 77% of the total cadmium, 66% of the total lead, and 32% of the total copper.

The biogeochemical processes affecting metal speciation in a gullypot system and at stormwater outfalls were investigated by Morrison et al. (1989). Ionic lead and copper species released from road sediments by acid rain are scavenged by dissolved organic material and suspended solids as a result of a rise in pH through the road–gullypot system. Cadmium tends to remain in the dissolved phase. Bacterial activity and acid dissolution produce increases in dissolved metal in the gullypot liquor, and it is these metals that contribute to the early storm profile. Metals in basal gullypot sediments are mobilized readily during high-volume, high-intensity storms. The resulting stormwater contains dissolved ionic forms of cadmium and zinc, and lead is adsorbed mainly to suspended solid surfaces. Copper also binds to solids, although approximately 50% is transported by dissolved organic material (molecular weight ~ 1000–5000). For the separation of directly toxic metal species, anodic stripping voltammetry at polymer-coated electrodes is preferred. Lead and copper are present respectively as iron/humic colloids and organic complexes, which are not directly toxic to algae. Cadmium is predominantly ionic and inorganically complexed and therefore directly toxic to algae.

Glenn et al. (2002) examined heavy metal (cadmium, copper, lead, and zinc) partitioning results for a series of rainfall runoff events and found that aqueous chemistry, such as low alkalinity and hardness, and short pavement residence time (less than 30 minutes) can result in a majority of the heavy metal mass remaining in solution at the edge of the pavement. Metals partitioning approaches equilibrium conditions only toward the end of the event as heavy metals partition to entrained solids.

3.4.5.3. Sorption Processes

Sorption refers to the removal of a solute (sorbate) from the solution phase by the solid phase (sorbent). The two basic categories of sorption are adsorption (when the sorbate interacts with the surface of the sorbent) and absorption (when the sorbate penetrates the surface of the sorbent).

As a result of sorption of heavy metals onto particulate matter such as iron and manganese oxyhydroxides or organic matter, the concentrations of metals in natural waters are commonly far lower than would be predicted from simple mineral solubility calculations (Bricker, 1999). As such, sorption processes often are used in stormwater BMP technologies.

One important process responsible for the sorption of cations is ion exchange. The negative charge on soil colloids, clay, and organic matter on soil surfaces makes ion exchange one of the most important reactions influencing transport of cations in soils (Bricker, 1999). Ion exchange involves the sorption of one or more species of ions accompanied by the desorption of the previously sorbed species equivalent in total ionic charge. Soils often have surfaces with a net negative charge because of, for example, isomorphic substitution of ions in a clay lattice structure. An electrostatic double-layer is formed when the negative surface charge is counterbalanced by cations, which accumulate on the surface of the particle forming an electrostatic double-layer. This double-layer provides the ability of the matrix to attract ions and eventually to attenuate them.

Sorption processes usually are thought of as beneficial to stormwater quality due to the tendency for pollutants to adsorb and settle out with sediments. However, Davies and Bavor (2000) found that the adsorption of thermotolerant coliforms to fine clay particles (<2 μm) contributed to their survival in stormwater treatment systems. Other studies identified by Bricker (1999) have found that metals and trace organic chemicals also tend to adsorb to fine particulates, with metal concentrations on particulates tending to increase with decreasing particle size (increasing surface area), and that the suspended particulates in highway runoff contained higher overall metal concentrations than road surface dusts.

3.4.5.4. Identification of Research Gaps and Needs

Uncertainty exists in identifying sediment sources and defining transport rates and residence time of sediment in receiving waters. With respect to sediment transport, there appears to be an abundance of information on sediment transport models. However, there may be a need for more detailed studies of sediment transport mechanics in relation to blockage of full and partly full conduits in various cross-sections. Comprehensive studies on the effects of soils, topography, land use, and various storm hydrographs on sediment yield appear to be limited in number. In addition, the behavior of sediment at inlets, junctions, and transitions in the drainage system may require further study. Good predictive models that consider runoff–storm relationships, particularly storm scour and redeposition, are unavailable.

Research on the speciation of pollutants has been primarily on the common metals found in highway runoff, cadmium, copper, lead, and zinc. It is well documented that the dissolved phase of the metals are more bioavailable and therefore more toxic to aquatic biota than the particulate phase. In fact, in 1993 the EPA's Office of Water revised its policy to use dissolved metals concentrations rather than total recoverable metals concentrations to set and measure compliance with water quality standards. The amended National Toxics Rule now includes dissolved metals aquatic life criteria (40 CFR 131). Using dissolved metals instead of total recoverable metals for the purposes of assessing impacts to aquatic life is a step in the right direction, but using dissolved metals alone still does not appear to be an adequate measure of aquatic toxicity. As discussed in the literature above, the reactive and ionic portions of dissolved metals concentrations are more available to aquatic biota than the nonreactive and nonionic portions. Therefore, there appears to be a need for better characterization of the bioavailable fraction of dissolved metals, as well as trace organics, in highway runoff.

Sorption plays an important role in the speciation and bioavailability of pollutants. However, the factors controlling sorption, such as cation exchange capacity and specific surface area, are not investigated often. Highway agencies could benefit from information on the sorption capacity of roadside soils for the purposes of prioritizing retrofits and installations of treatment control practices. Native soils may have the capacity to retain pollutants, which would circumvent the need for additional treatment controls. Based on this fact, there appears to be a general need for more research on the sorption of pollutants to sediment in highway runoff.

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3.4.6. First Flush Characterization

The tendency for concentrations of stormwater runoff pollutants to increase rapidly at the onset of a storm and then to decline slowly is known as the first flush phenomena. First flush can be caused by the accumulation of surface pollutants during dry weather and the subsequent wash-off of those pollutants during wet weather. Thus, the first storm of the wet season usually results in the highest first flush concentrations due to the length of the preceding dry period. This is not always the case though; in fact, a discernable first flush period is not evident for some watersheds and pollutants. Another issue is that higher flushes of pollutants have been observed later in storm events when rainfall intensities increase or pervious areas start contributing to runoff, or both. Furthermore, there is no clear agreement among stormwater professionals how the first flush should be defined. This leads to the following research questions:

- How can first flush be meaningfully defined?
- What water quality parameters are observed commonly in the first flush of highway runoff?
- How do hydrological factors and watershed characteristics relate to first flush?

Several researchers have provided definitions of the first flush. Barbosa and Hvitved-Jacobsen (1999) noted that a storm event exhibits a first flush if the first 50% of the runoff volume contains greater than 50% of the loads. Deletic (1998) defined the first flush as the pollutant load carried by the first 20% of the runoff volume. Several other definitions used by various researchers were summarized by Ma et al. (2002), such as first flush is when at least 80% of the pollutant load is emitted in the first 30% of the runoff or simply the first 25% of the runoff volume (assuming a mass first flush actually occurs). Another definition is provided, and actually recommended by Ma et al. (2002): first flush is when the slope, or mass first flush ratio, of the normalized cumulative mass emission versus the normalized volume is greater than 1. This is a useful definition, because unlike the other methods it does not depend directly on the size of the storm event or on the total loads discharged. Also, the definition provides metrics for first flush magnitude and timing, which can be used to size structural stormwater BMPs based on the fraction of loads desired to be captured and to determine when to take first flush grab samples. This method does require that storm event samples are analyzed before compositing, so the monitoring costs associated with first flush characterization are significantly greater than for general runoff characterization.

A broad range of the pollutants found in stormwater runoff will exhibit a first flush depending on the drainage hydrology, pollutant mobility, and pollutant supply. With regard to typical highway pollutants, Barbosa and Hvitved-Jacobsen (1999) observed a first flush effect for TSS, zinc, copper, and lead loads. Smith et al. (2000) noted that PAH concentrations were highest usually during the first flush of stormwater runoff and that they tapered off rapidly as time progressed. Lau et al. (2002) reported COD, oil and grease, dissolved organic carbon, and particulate phase PAHs all exhibited a first flush. Wachter and Herrmann (2002) noted that trace organic pollutographs of the particle-bound fraction showed a first flush effect, while Deletic (1998) observed only slight first flush effects for suspended solids and conductivity and no first flush effect for pH or temperature. Therefore, it appears that solid-phase pollutants typically exhibit a first flush effect depending on whether or not the source is continuous or subject to buildup and washoff.

Hydrological factors such as rainfall intensity and spatial variability, and watershed characteristics such as watershed size, slope, stream order, and percent imperviousness are all factors that likely are associated with flush phenomena. Understanding how these factors influence the flush of pollutants may circumvent the need for site-by-site first flush characterization. Lee and Bang (2000) analyzed pollutographs from storm events in nine watersheds in the cities of Taejon and Chongju, Korea, and found that for watersheds less than 100 ha with a total imperviousness of 80%, the peak of pollutant concentration preceded that of the flowrate, but for watersheds greater than 100 ha with a total imperviousness of less than 50%, the peak of pollutant concentration was followed by that of flowrate.

Caltrans has completed several first flush studies and a final report. Preliminary findings or conclusions can be summarized as follows:

1. Preliminary results show the existence of a first flush for some parameters, especially for parameters such as oil and grease and COD. For medium-size storms, there is generally 40% of the total mass load in the first 20% of the runoff volume. In some cases metals show a first flush as well. Some parameters, such as the sulfate ion, show a last flush.
2. Strong correlations exist among many of the water quality parameters and metals. Antecedent dry periods in some cases show trends (greater contaminant concentrations with larger elapsed time between storms), but so far there are insufficient data to show statistically significant correlations.
3. An extensive database incorporating the results from all sites is being developed and analyzed. Various hypotheses are being tested, including correlations among parameters to determine if surrogate parameters are useful.
4. In most instances, a first flush phenomenon also was observed for the gross pollutant and litter concentrations. However, the gross pollutant and litter mass loading rates were not highest during the first flush but generally appeared to correlate with the peak flow rate, which is similar to the water quality data. The total litter volume generated appeared to be related to the relative intensity of the storm event. The litter mass loading rates also did not generally decrease across the storm season.
5. A procedure and notation is developed for quantifying mass first flush ratios. The notation allows mass first flushes to be analyzed statistically.
6. The concentrations of PAHs were low, generally at or below detection limits in the dissolved phase. Particulate phase PAHs are reported and show a first flush, although there were fewer monitored events.
7. The concept of collecting a grab sample at the best time to approximate EMC for oil and grease was investigated.

Caltrans also initiated research on the first flush of the particle size during the 2002–2003 monitoring season. See section 3.5.4, Toxicity and Bioassessment, for further discussion of toxicity studies.

In Portland's stormwater monitoring for the NPDES permit application efforts and beyond, interstorms were sampled to explore within storm variability (Strecker, 2003). Results generally showed that pollutants associated with particulates did show a tendency to wash off earlier in storms. Constituents such as dissolved metals either showed no change or increased during the storm. Consequently, while pollutant loads decreased, toxicity potentially increased. Herricks found similar results in his urban runoff sampling work.

3.4.6.1. Identification of Research Gaps and Needs

Several researchers have identified a first flush effect during runoff characterization studies, but nearly all use a different definition. The mass first flush ratio used to define first flush by Ma et al. (2002) appears to be the most meaningful and does not depend on the time of concentration like other definitions that are based on time from beginning of the storm. There appears to be a need for the adoption of a standardized method for defining and identifying first flush phenomena. Also, some parameters appear to exhibit a first flush, while others do not. Therefore, a comprehensive list of highway runoff pollutants that tend to exhibit a first flush may be useful for evaluating receiving waters impacts and the feasibility of treating only the first flush part of a storm.

First flush toxicity information in conjunction with other first flush characterization data can be used to design BMPs that can treat properly the early portion of runoff and bypass the rest for most small watersheds. The current research effort did not find any studies that specifically investigated how the first flush effect was related to hydrological and watershed characteristics, indicating a potential research gap with regard to first flush characterization and assessment.

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3.4.7. Water Quality Runoff Modeling

Runoff models can be grouped into the following three main categories based on the method of analysis used in the model: regression-based models, simulation-based models, and stochastic models. Regression-based models are relatively simple and are sometimes no more complex than simple equations. Simulation-based models are models that are capable of using historical data to account for temporal variations in the variables of interest. Stochastic models are models that are founded on the principles of statistics and probability. Models also can be grouped by the kinds of processes that they simulate. Geochemical models are specialized models that are used mostly to simulate unit processes. The areas of interest and possible knowledge gaps with respect to runoff water quality modeling are as follows:

- The availability of data, data replacement and updating, and new data requirements;
- Development of hybrid models to benefit from the advantages of each of the categories;
- Extension of models to predict loads of a wider range of pollutants; and
- Simulation of herbicide and pesticide concentrations and transport processes.

The main advantages of regression models are in their relative simplicity. Regression methods also tend to have minimal data requirements; however, these models are less capable of simulating temporal and spatial variations. The advantages of simulation models include the ability to simulate the effects of changes and abatement effects by a simple alteration of parameters and the provision of temporal and spatial distributions. Simulation models tend to have the most substantial data requirements, which can be problematic due to the high cost of data collection. Statistical models offer the ability to produce a distribution instead of the mean concentrations provided by regression-type analysis. Distributions can be used then to estimate the probabilities of exceedance of specified concentrations. However, statistical models are not as capable as simulation models at simulating either the interactions of flow and concentrations or the effect of abatement actions (Barrett et al., 1995).

A review of literature related to runoff water quality modeling shows that there are numerous studies that developed or applied, or both, regression models as tools for runoff characterization. A study to identify the variables that affect highway runoff in Austin, Texas, applied regression analysis techniques for predicting pollutant loads. The results of the study suggested that highway stormwater loading variations during a storm event depend on variables measured during previous events, the antecedent dry period, and the current storm event. TSS loads were found to depend on the build up of pollutants before storms, the characteristics of the storm, and the wash-off processes. Oil and grease were found to depend on current storm conditions such as runoff volume and number of vehicles during the storm event (Irish et al. 1998).

A study presented by Kerri et al. (1985) resulted in the development of pollutant load estimation regression equations for urban highway sites in Redondo Beach, Walnut Creek, and Sacramento in California. The regression equations were based on continuous rainfall monitoring data and sequential water quality sampling data. Contaminants analyzed included boron, total lead, total zinc, nitrate-nitrogen, ammonia-nitrogen, and TKN. The authors cautioned against using the regression equations in situations where ADT is less than 30,000 vehicles.

The Washington State study presented by Chui et al. (1982) resulted in the development of a pollutant load model for Washington State. The model was based on extensive monitoring data consisting of 500 storms at nine locations. The model correlates TSS loads, traffic conditions, runoff coefficients, and land use. Pollutant load estimates for individual storms are determined less accurately by the model, as compared to multiple storms over a period of time.

Examples of simulation models include EPA SWMM, STORM, HSPF, and the FHWA urban Highway Storm Drainage Model (Barrett et al., 1995). DeVries and Hromadka (1993) present a comprehensive discussion of runoff water quality models. Models discussed include SWMM, HPSF, QUAL2E, WASP4, AGNPS, and MIKE 11. For each model, the authors present a general overview that includes a description of the model's origins and the applications for which the model was developed. A description of hardware requirements and directions on how to obtain the model also are included. In some cases, the authors also discuss model components and the kinds of problems for which the model has been applied. Guay and Smith (1988) discussed the application and evaluation of DR3M-II and DR3M-qual. The models were applied to a multiple-dwelling residential catchment and a commercial catchment in Fresno, California. Calibration and verification of errors for dissolved solids, dissolved nitrite plus nitrate, total recoverable lead, and suspended solids ranged from 11% to 54%.

Statistical methods were applied in the analysis of runoff quality in the National Urban Runoff Program (NURP), EPA's comprehensive 5-year runoff characterization study in which runoff samples from 28 metropolitan areas across the United States were collected and analyzed (U.S. EPA, 1983). The results of the study suggested that EMCs can be described by lognormal distributions. The statistical methodology used in the NURP program entailed defining dilution ratios and calculating statistical properties of the resulting instream concentrations from the statistical properties of the flows and concentrations. Frequency of exceedance of any target concentration during wet weather was obtainable either through the use of formulas, standard plots of cumulative probability distributions, or calculations from statistical properties of stream concentrations (Barrett et al., 1995).

An FHWA study presented by Driscoll et al. (1990) also applied statistical methods as the basis for the development of a procedure for predicting highway stormwater runoff pollutant loadings. The study also developed methods for estimating potential impacts on receiving waters, including guidance for evaluating the performance of mitigation measures. A total of 993 individual storm events at 31 highway sites in 11 states were monitored. Barks (1996) discussed the development of statistical methods using site-specific data to adjust values obtained from the use of regional equations so that more accurate values could be acquired. The regional regression equations were developed using data from a national database and are used to estimate runoff pollutant loads. The method consists of a single adjustment procedure: a regression of the observed data against the predicted values, a regression of the observed data against the predicted values and additional local independent variables, and a weighted combination of a local regression with regional prediction.

Geochemical models are useful for evaluating the bioavailability and mobility of pollutants. Definitions of four categories of models provided by Bricker (1999) include the following:

Speciation Models—Models used to calculate the partitioning of an element among different aqueous species and complexes. Examples of speciation models include WATEQF and WATEQ4F.

Mass-Transfer Models—Models used to simulated changes in solution chemistry caused by mass-transfer processes. Examples of mass-transfer models are SOLMNEQ.88, MINEQL+, MINTEQ (4.00), and PHREEQC.

Mass-Balance Models—Models used to simulate the net changes in the masses of reactants and products in waters along a flow path. An example of a mass-balance model is NETPATH.

Geochemical Mass-Transport Models—Models used to simulate hydrodynamic advection and dispersion of dissolved species in porous media as well as to speciate the aqueous solution and determine geochemical mass transfer. Examples of geochemical mass-transport models include CHMTRNS, PHREEQM-2d, and PHREEQC.

The author also includes a discussion of the applications and limitations of each of the above categories.

3.4.7.1. Identification of Research Gaps and Needs

As with BMP Modeling (section 3.2.10.), water quality modeling is heavily dependent on the availability of data. Therefore, there is a general need for accurate and representative data for parameter estimation and model calibration and for stochastic models development. The NURP study resulted in the development of a large database of runoff characterization data; however, even with this large data set, differences in runoff quality among different land use types could not be validated statistically. There is, though, still a need for forward-looking data collection efforts that focus more on modern parameters and less on parameters of diminishing importance in highway runoff such as lead. There also is a need to develop hybrid models that take advantage of both stochastic and deterministic methods in order to produce models that have the benefits of both statistical and simulation-based models. Adaptation of agricultural models for herbicide and pesticide modeling in the context of highway runoff management would provide insights into the transport processes of highway pesticides and herbicides. The most commonly modeled contaminants are heavy metals, nutrients, bacteria, dissolved oxygen, and solids. Existing models need to be extended and enhanced to simulate a wider range of contaminants.

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3.4.8. Highway Construction and Vegetation Maintenance

Twelve state DOTs indicated that they have conducted studies or prepared reports on the design or efficiency of stormwater management measures during construction, although 34 state DOTs have not conducted any studies in this area.

Highway construction and maintenance activities have the potential to impact receiving water systems depending on numerous factors, such as land disturbance area, storm event timing, topographic and geological characteristics, and construction and maintenance BMPs. Construction activities that include grubbing, grading, and excavating may reduce slope stability and increase erosion, thereby increasing sediment loads and concentrations to receiving waters. Erosion and sediment controls were discussed in section 3.2.6, and impacts to receiving waters caused by sedimentation and turbidity are discussed in section 3.5.3. Vegetation maintenance activities such as roadside herbicide application have the potential to cause impacts to receiving streams. Several researchers have investigated conditions and activities that may contribute to poor runoff quality from highway construction and vegetation maintenance sites. Common research questions posed include

- How can suspended-sediment data be used to make erosion control and vegetation maintenance decisions at construction sites?
- How does construction site runoff impact receiving waters?
- How mobile are herbicides applied to highway shoulders?
- How do roadside vegetation maintenance practices impact receiving streams?

NCHRP Synthesis 20-5, Topic 33-04, is synthesizing roadside vegetation practices for erosion control and stormwater management, along with a variety of other purposes. This research will be available in early 2004.

Barrett et al. (1995a) provides a thorough literature review of environmental effects of highway construction that includes more than 30 references of studies conducted in the 1970s and 1980s. A more recent investigation by Barrett et al. (1995b) involved monitoring the impacts to Danz Creek in southwestern Travis County, Texas, during the construction of a new highway. Ten storms were monitored at sites upstream and downstream of the highway crossing. The results indicated that the concentration of suspended solids in Danz Creek increased at least fivefold during and immediately after storm events despite the presence of a system of temporary controls (primarily silt fences) and restrictions on the use of heavy equipment at the creek crossings. The only other monitored parameter that appeared to increase substantially was iron, due to high iron content in the site soils. Copper and zinc were shown to increase by 11% and 85%, respectively.

Fifteen highway construction sites were monitored by Caltrans to assess the water quality of stormwater runoff from the sites (Kayhanian et al., 2001). Results obtained during the 2-year characterization study indicated that

1. Caltrans construction-site runoff constituent concentrations detected during this study were less than typical Caltrans and non-Caltrans highway runoff constituent concentrations, with the exception of total chromium, total nickel, total phosphorus, TSS, and turbidity.
2. The concentrations of TSS and turbidity likely are due to the disturbed soils present at most construction sites.
3. The origin of the high concentrations of total chromium, total nickel, and total phosphorus concentrations is unknown. Concentrations of these constituents varied between sites, so it is possible that site-specific soils and vegetative conditions contributed to the concentrations of these constituents.
4. A correlation (R-squared values greater than 0.5) was observed between TSS runoff concentrations and particulate runoff concentrations of chromium, copper, and zinc, indicating that minimizing particulate matter may reduce total metals concentrations.

In another Caltrans study (Caltrans, 2002), 120 storm events were monitored at 27 construction sites during four rainy seasons beginning in 1998–1999 and ending in 2001–2002. One of the primary purposes of the sampling study was to develop a baseline set of construction site stormwater quality concentrations. Sites were selected to represent a wide range of typical Caltrans construction activities, geographic areas, and hydrometeorologic conditions, as well as other site-specific conditions. The results were reviewed to compare annual means of individual parameters for the four reporting years. Mean concentrations of total lead, nickel, and zinc varied over the 4-year period, while mean concentrations of total copper, cadmium, and arsenic were relatively consistent over the study period. All dissolved metals remained relatively consistent over the study period except for zinc, which had consistently higher concentrations during the later years. With the exception of TKN, nutrient concentrations were relatively consistent over the 4-year monitoring period, excluding one abnormally high total phosphorus concentration in the second year. Measured hardness was relatively consistent over the 4-year monitoring period, while TSS concentrations were much higher during the second monitoring year compared to other monitoring years. Total and dissolved organic carbon concentrations were low compared to dissolved and suspended solids, suggesting that dissolved and suspended solids are composed primarily of inorganic particulate matter.

Statistical comparison tests showed a statistically significant difference in measured runoff concentrations between new construction and modification facilities and existing facilities for dissolved copper, total coliform, dissolved lead, dissolved nickel, and dissolved zinc, with the concentration of each of these constituents being lower at new construction sites. Comparing water quality runoff from northern California versus southern California sites, the statistical comparison test showed a significant difference for dissolved arsenic, dissolved chromium, nitrate, nitrite, ammonia, TKN, dissolved lead, dissolved nickel, total nickel, TSS, TOC, and DOC, with the majority of these constituents showing higher concentrations in southern California. Statistical comparisons between seasons showed a significant difference for dissolved orthophosphate, nitrate, ammonia, oil and grease, diazinon, total coliform, dissolved zinc, TDS, TSS, pH, and specific conductance for one or more seasons compared to other seasons. Still, no consistent pattern was observed. Construction site stormwater runoff data was compared to Caltrans highway runoff data. The statistical comparison showed significantly higher concentrations in highway runoff for total cadmium, dissolved copper, dissolved lead, total zinc, and dissolved zinc. TSS and hardness were significantly higher in construction site runoff than highway runoff, while oil and grease and COD were significantly higher in highway runoff.

With regard to highway vegetation management a few studies were found that investigated herbicide migration from highway rights-of-way. Powell et al. (1996) conducted a study in Glenn County, California, to assess the concentrations of simazine and diuron (herbicides often applied to highway rights-of-way) in runoff from the pavement shoulder at three highway sites during simulated rainfall events and at two sites during natural rainfall events.

At the simulated rainfall sites, soil was sampled to a depth of 3 m at the site where no runoff occurred and to a depth of 1 m at the other sites. Herbicide was not found below a 0.3 m-depth at any of the three sites. Of the total 38 samples taken from the top 0.3 m of soil, 13 contained simazine (maximum concentration 694 μg/kg, found prior to herbicide application) and 17 contained diuron (maximum concentration 874 μg/kg, just after rainfall simulation). At one of the natural storm event sites, concentrations ranged from 29 to 337 μg/L simazine and from 46 to 2849 μg/L diuron. The largest amounts removed in any sampled period were 5.3% of the applied simazine and 8.4% of the diuron in one 28-hr period.

At the other natural storm event site only simazine was applied. Samples were collected from a flume that discharged runoff into a drainage canal. The first runoff sample was taken after a total of 100 mm of rain had fallen, and simazine concentration averaged 105 μg/L in 52–66 m^3 of runoff water collected. The greatest mass discharge in any sampled period was 155–200 m^3 of runoff in 20 hr, with an average concentration of 83 μg/L simazine.

In another study, Huang et al. (2002) investigated the transport of five different pesticides (glyphosate, oryzalin, isoxaben, transline, and diuron) in highway biofiltration strips at two geographically separated sites in northern California. Herbicides were detected in runoff water from both sites after all storm events. The EMC and loading percentage had large ranges among different herbicides at the two sampling locations for the past three years (glyphosate: 0.1–21.5 μg/L, oryzalin: 0.1–42.4 μg/L, isoxaben: 0.1–14.4 μg/L, transline: 0.5–7.1 μg/L, diuron: 0.1–10.2 μg/L). Loadings as a percentage of the amount of pesticide applied also varied greatly (glyphosate: <1%, oryzalin: 0.1–5.4%, isoxaben: 0.1–15.0%, transline: 44%, and diuron: 0.6–4.4%). The high percent loading for transline undoubtedly was due to its relatively high solubility. The results of the study suggest that biofiltration strips along highway roadsides can significantly attenuate herbicides in runoff, particularly those with low solubility.

A study by Wood (2001) investigated the potential of herbicides applied to roadsides in the Willamette Valley near Colton, Oregon, to migrate to nearby surface waters. The study was divided into two phases. During the first phase (spring 1999), 0.3-inch-per-hour rainfall events were simulated and runoff was collected 1 day, 1 week, and 2 weeks after the application of an herbicide compound typical of Oregon DOT application rates and concentrations. The simulated rainfall was applied long enough to collect between 13 and 15 liters of runoff (between 0.5 and 1.9 hours). The EMC in the runoff of each of the herbicides (diuron, glyphosate, bromacil, and sulfometuron-methyl) declined by about 1.5 orders of magnitude between the first day after application and the second week after application. The results of the simulated rainfall experiments suggested that a heavy rainstorm occurring soon after herbicide application could generate concentrations in the runoff leaving the road's shoulder of nearly 1 mg/L glyphosate and diuron and concentrations on the order of a few hundred μg/L of sulfometuron-methyl. Bromacil was not measured in this phase. During the second phase (winter 1999–2000), concentrations were measured in the runoff occurring from natural rain events after a single herbicide application. Five rainfall events were chosen for the sampling. Runoff flowing directly from the shoulder remained in the 1–10 μg/L range for diuron for all events sampled with concentrations decreasing with time.

Based on the studies summarized above, it is clear that herbicides have the potential to migrate to receiving waters. However, what is not clear is whether these herbicides pose a significant threat to receiving water biota. A study conducted by Johnson and Hall (2002) evaluated the impacts of Surflan™ (with the active ingredient oryzalin) on Japanese medaka (*Oryzias latipes*), a standard laboratory organism for testing impacts to fish. Results from three distinct assays support the conclusion that Surflan and oryzalin are endocrine-disrupting compounds. But, this study was conducted at much higher concentrations than those observed by Huang et al. (2002). Since lowest-observed-adverse-effect-levels for reproductive effects of oryzalin and Surflan were not defined in this study, and there appears to be a nonlinear dose-response relationship, this study should be repeated at concentrations more typical of highway runoff concentrations.

3.4.8.1. *Identification of Research Gaps and Needs*

The disturbance of land during highway construction activities significantly increases the potential for sediment transport even with the implementation of erosion control practices. To evaluate the effectiveness of (or need for) erosion control practices, suspended sediment is the primary (and often the only) parameter monitored during highway construction runoff characterization studies. However, it often is not clear in the literature, particularly in abstract summaries, whether TSS or SSC are being reported, as these two terms often are used interchangeably. As discussed by Bent et al. (2001), these two measures of sediment concentration are not transferable because SSC is a measure of the total mass of sediment, while TSS is a measure of a subsample of the water-sediment mixture. Subsampling may inadvertently preclude larger-sized particles, resulting in an underrepresentation of the true sediment concentration. Due to the fact that TSS is reported and used often in the calculation of sediment loads, there appears to be a research gap in this area and a need to make stormwater practitioners aware of this potential issue.

An equally important and related parameter that is not as frequently monitored as sediment concentration is the sediment particle-size distribution. Particle size plays an important role in the transport and aquatic biota impacts of mobilized sediment. Particle size distribution also seems to play an important role in the transport of some metals, nutrients, and trace organics. Monitoring for particle size and these other parameters could increase significantly the costs of a construction project. It would be beneficial to have an initial screening method for assessing the quality of site soils on a grain-size basis to determine the level of monitoring as well as sediment and erosion controls necessary to prevent impacts to receiving waters.

It is apparent from the literature reviewed that additional work is needed in the area of roadside vegetation management. The potential for herbicides to migrate from roadsides to receiving waters is strongly dependent on the type of chemical applied (i.e., depends primarily on solubility and hydrophobicity).

Numerous herbicides are in use by DOTs throughout the country, of which only a small number have been tested for their mobility and potential toxicity to aquatic biota. Most studies have been conducted under highly controlled conditions in a laboratory or by using simulated rainfall. Furthermore, toxicity studies have been conducted at higher concentrations than likely to occur at the rates applied. More herbicide runoff characterization studies during storm conditions are needed in conjunction with toxicity studies at the concentrations found. Furthermore, an analysis of the adsorption of herbicides to various grain sizes would assist in determining the potential for migration. Once more information is available on potential impacts of herbicides, a detailed cost–benefit comparison of using herbicides as opposed to other vegetation control methods, such as manual clearing, should be considered.

3.4.8.2. Primary References

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3.4.9. Drain Inlet and Gross Pollutant Studies

The control of gross pollutants in highway runoff was addressed in section 3.2.2., Gross Pollutant Removal. This section focuses on the characterization of gross pollutants in highway runoff.

Gross pollutants can be grouped loosely into three categories: litter or trash, debris, and coarse sediments. Examples of litter include unwanted anthropogenic waste materials such as paper, metal, glass, and plastic. Examples of debris include organic materials such as grass, leaves, and wood. Coarse sediments consist mainly of inorganic solids such as construction materials and soil particles (England and Rushton, 2003). Gross solids can cause odors, release pollutants, and become an unsightly mess; yet gross solids are monitored infrequently as are other pollutants in many of the studies available (England and Rushton, 2003). Improperly disposed gross solids can be carried by stormwater or wind to water bodies, causing environmental degradation (Sedrak et al., 2001). Factors that determine the mobility and persistence of gross solids include buoyancy, the ability to be blown around by the wind, and degradability (Sedrak et al., 2001). Research questions and areas of interest with respect to gross solids management include

- Sources of gross solids,
- Gross solids monitoring measuring techniques,
- Gross solids impacts to stormwater and receiving water systems, and
- Gross solids modeling and estimation techniques.

Several studies are available that define and characterize gross solids. Armitage and Rooseboom (2000) presented a discussion that defines urban litter, identifies sources of litter, and suggests litter management strategies. Factors identified as contributing to litter problems included antisocial behavior, excessive packaging, inadequate street sweeping services and disposal facilities, and lack of effective law enforcement. The authors noted that the rate of litter production is related to type of development, density of development or land use, income level of the community, types of industry, rainfall patterns, types of vegetation in the catchment, and the level of a community's environmental awareness. The authors conclude by providing a discussion of litter load estimation with equations for evaluating litter quantities for design purposes.

The results of a comprehensive study showed that plastics made up more than 40% (by weight) of the floatable litter found on the streets of New York City. Details of this study are provided by England et al. (2003) in addition to simple methods for measuring and characterizing gross solids removed by various BMPs for both wet and dry weather. A study presented by Sedrak et al. (2001) identified high trash generating areas in Los Angeles and proposed both structural and nonstructural controls to manage trash. This study also found that plastics are the single largest component of trash. Trash enters receiving water bodies mainly by direct disposal by hikers or beachgoers, stormwater, and wind. The authors concluded that commercial, industrial, and residential land use areas produce the most trash. They suggested nonstructural trash control measures including street sweeping, catch basin cleaning, antilittering statutes, abandoned trash hotlines, trash cans, educational programs, and community clean-up programs. Structural trash or litter controls suggested include Continuous Deflective Separation™ units, Netting Trash Trap™, catch basin inserts, and catch basin opening covers.

In a Caltrans study, Lippner et al. (2001) investigated the characteristics of litter in highway stormwater and evaluated the effectiveness of BMPs by conducting a 2-year pilot study in the Los Angeles area. The researchers found that plastic, paper, and Styrofoam constituted about 42% by weight and 57% by volume of total freeway litter. Securing a mesh bag on an outfall with Velcro™ worked well as a monitoring technique, however the suggested monitoring technique is not recommended for outfalls that directly connect to other subgrade drainage systems. Two of the BMPs that the researchers tested increased litter pick-up, and the modified drain inlet substantially reduced litter. Street sweeping, the bicycle grate, and the Litter Inlet Deflector were ineffective in controlling litter.

The importance of the effects of water velocity and depth in the transport of gross solids was investigated by Davies et al. (1998). The authors presented the results of a laboratory study on solids advection with applications in solids transport modeling. Milne et al. (1996) collected and analyzed gross solids in an attempt to estimate the related impacts and interaction with sediment. They sampled wet and dry weather flows and monitored gully discharge.

3.4.9.1. Identification of Research Gaps and Needs

Because of the variety of materials that make up gross pollutants in highway runoff, characterization and assessment is difficult. Areas that appear to be well covered in the literature include the determination of sources of gross solids and the composition, characteristics, and transport of gross solids. Most researchers quantify gross pollutants by either weight or volume, and some segregate according to material type, such as plastic or metals. For the purposes of data transfer, there appears to be a need for the development of standard methods for quantifying gross pollutants. As mentioned in section 3.2.2, a potential research need may be to identify a uniform definition of gross solids (and its components) for purposes of standardizing the reporting of data. There also appears to be a need for more studies on receiving water impacts of gross solids, with a particular need for modeling and estimation techniques for gross solids especially in relation to TMDLs.

Another potential research gap may be the leaching or sorption capacity, or both, of pollutants captured in catch basins. For instance, cigarette butts, which can contribute as much as 10% by dry weight of all street litter (City of Los Angeles, 2001), contain several toxic and carcinogenic compounds that may leach to receiving waters during stormwater runoff events. On the other hand, bulk paper trash may aid in the sorption of oil and grease in stormwater runoff.

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3.4.10. Cold-Weather Studies

Cold-weather highway runoff quality studies primarily characterize snowmelt runoff and evaluate winter maintenance activities such as highway sanding and deicing agent application. This field also encompasses studies that evaluate the effects of frozen soil on runoff and infiltration rates, as well as snowbank pollutant accumulation studies. Finally, a few studies have looked at the functioning of BMPs during cold weather. Compared to stormwater runoff, snow exposed to traffic and winter maintenance practices has a much greater capacity to accumulate and retain heavy metals, fine dusts, and other anthropogenic constituents. Traffic activities and winter storm management practices can have a significant impact on pollutant accretion in urban snow. Urban snowpacks accumulate large quantities of solids and contaminants, which originate from such sources as airborne fallout, vehicular deposition, and applied and ground up grit and salt. Both contaminants and solids may be released quickly during the periods of snowmelt, and consequently melting contaminated snow in urban areas in cold climates has the potential to impact substantially the water quality of receiving waterbodies (Oberts, 2000; Smith et al., 2000). Cristina et al. (2001) and Sansalone and Glenn (2001), in their detailed studies involving physical and chemical characterization of snowmelt runoff, indicated that extended residence times of snow as a roadway snowbank exposed to traffic activities and winter maintenance practices lead to significant pollutant accretion and partitioning in the snow matrix. Several other studies discuss the accumulation of pollutants in the snow and eventual shock loading of pollutants during snowmelt or rain on snow events (Thorolfsson, 1999; Hatch et al., 1999).

In another study, Sansalone and Buchberger (1997) presented the effect of snowbank residence time on PSDs and particulate-bound metal element concentrations for two snow events. Results indicated that for each snow event, increasing residence time of the snowbank did not result in a clear increase in zinc, cadmium, or copper concentrations. Zinc concentrations on solids from rainfall events were significantly higher than for snow events. Snowbank lead concentrations decreased over time for the finer fractions of solids for the first snow event with a similar trend for the second snow event, except for the finest solid class, which showed a slight increase with time. In contrast to zinc, lead concentrations on rainfall runoff solids were generally lower than on snow solids.

In their highway runoff monitoring study in Lake Tahoe, Caltrans (2002) characterized particles removed from the sand traps and filter boxes using the sieve and hydrometer method. Particle sizes ranged from less than 2 μm to more than 9500 μm, with the majority of particles falling in the range from 100 to 2000 μm. These mid-sized suspended particles are relatively large and over a relatively short period settle easily out of suspension because of gravity. Yet, the remaining colloidal (0.001 μm–1 μm) and smaller suspended particles tend to remain suspended in waters because of their low gravitational settling (less than 0.01 cm/sec) which could cause an increase in turbidity. It should be noted that in their study about the effectiveness of double barrel sand traps, removal of more than 90% of the total mass of TSS did not remove total phosphorus to the same degree (i.e., less than 20%). Particles associated with the snow ranged from 5000 μm to less than 25 μm and had a d50 of 1222 μm. Specific gravity ranged from 2.5 to 3.2 and tended to be lower for particles less than 100 μm. Metal analyses of the snow residuals indicated that 50% of the heavy metal mass of lead, copper, cadmium, and zinc was bound to particles greater than 250 μm.

The treatment of snowmelt runoff is confounded by several factors including frozen conduits, ponds, soils and wetlands, biological dormancy, and the addition of chemicals and grit to roadways (Oberts, 2000). Adaptation of commonly used BMPs can be undertaken to accomplish some level of treatment, such as modifying outlet structures on detention ponds and using new subsurface “vault” treatment systems. Other measures include selective use of deicing chemicals (see section 3.5.7 for discussion on deicing impacts to receiving waters) and constructing road snow storage areas. However, there is still significant research needed in this area.

The results of some of the more recent cold weather studies, such as those discussed above, indicate the quality of snowmelt runoff from highways may be highly degraded and may be seriously impacting receiving streams. This realization, combined with the implementation of the NPDES Phase II stormwater regulations, is causing an increasing interest in nonpoint source control of cold climate runoff. In fact, a first-of-its-kind North American 3-day stormwater conference entitled *Stormwater Management in Cold Climates: Planning, Design, and Implementation* was held in Portland, Maine, in November 2003 to focus specifically on the challenge of managing stormwater in cold climates (http://www.cascobay.usm.maine.edu/coldsw.html).

3.4.10.1. Identification of Research Needs

Based on the literature review, there is clearly a need for more monitoring and characterization of snowmelt runoff from highways. The studies reviewed indicate that snowmelt runoff, especially during the first major snowmelt runoff events of the year, often have highly elevated pollutant concentrations. Still, because of the hydrological complexity of snowmelt and freeze phenomena, it is difficult to monitor and characterize snowmelt runoff events. One alternative is to collect snow samples from roadsides, melt them, and then analyze them. This approach, however, is highly subjective and dependent on the age of the snow. It may overrepresent actual snowmelt concentrations, since it is likely that not all of the pollutants present in the roadside snow will become mobilized during melting periods. Based on these difficulties, there is an apparent need for guidance on monitoring roadside snow as well as snowmelt runoff. Developing models that can be used to predict the occurrence of a snowmelt runoff event would be helpful in determining when monitoring should take place. Also, the performance and feasibility of stormwater BMPs during cold weather need to be evaluated. Another issue faced by cold weather stormwater managers is the management of removed snow from urban highways.

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3.5. RECEIVING WATERS IMPACT ASSESSMENT

This category refers to studies conducted in receiving waters, including mixing zones. Thirty-five state transportation agencies have performed some research on impacts on receiving waters. This section presents research that seeks to address the impacts of beneficial uses on receiving waters. According to Pitt et al. (2002) beneficial uses of receiving waters can be summarized as

- Stormwater conveyance,
- Biological uses,
- Noncontact recreation, and
- Contact recreation.

Other beneficial uses include drinking water, domestic animal drinking water, crop irrigation, and fisheries. Urbanization often leads to changes in the physical, chemical, and biological characteristics of receiving waters. These changes often result in habitat that is significantly different from the habitat to which aquatic life is accustomed (May, 1998). Increased impervious area and degradation of water quality are traits that accompany urbanization. These traits can have negative impacts on stream morphology, in-stream habitat, wetlands, and aquatic biota. Transportation development contributes to that increase in impervious area, in addition to contaminants generated from highway construction, maintenance, and usage. Such contaminants include deicers, metals, petroleum-related organic compounds, sediment, and agricultural chemicals (Buckler and Granato, 1999).

Since 1879, USGS has played a vital role in monitoring and assessing surface and ground water. USGS activities, studies, and programs provide support for decision making at all levels of government. According to Gail and Pixie (2002), USGS contributions to receiving waters impact research include

- Monitoring more than 40 watersheds from 1980 to 1996 as part of nutrient transport studies in the Mississippi River Basin,
- Conducting studies in San Francisco Bay for more than 26 years to assess impacts to aquatic biota in the context of environmental and meteorological changes, and
- Pioneering studies on the impacts of MTBEs.

USGS also has pioneered the use of several techniques useful for assessing receiving waters impact, including groundwater age dating, and maintains a large database containing chemical data from more than 335,000 waterbodies (Gail and Pixie, 2002). USGS and the Delaware River Basin Commission, funded by the New Jersey DEP, conducted a study to investigate the impacts of urbanization of five watersheds in New Jersey. The objective of the study was to assess the current state of water quality, habitat, and stream morphology; develop and evaluate watershed assessment methods; and develop goals and objectives for the watersheds. The study, summarized in a report by Albert and Limbeck (2000), reviewed the effects of urban runoff on stream channel stability, water quality, aquatic organism habitat, and macroinvertebrates. The authors observed that percent imperviousness is a good indicator of receiving water impacts and impervious area mitigation using BMPs may be pivotal to successful watershed management strategies. Percent of connected impervious surface is still more precise, when such information is available.

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3.5.2. Stream Crossings

Stream crossings are especially vulnerable to pollution from roads. Contaminants such as sediment have easy access to the underlying streams at stream crossings at every stage in the lifecycle of a road.

Most of the available studies on roadway impacts on stream crossings are related to unpaved roads and forest road impacts and bridge construction and maintenance impacts. Areas of interest cited by Taylor et al. (1999) include

- Short- and long-term impacts of stream crossing installations;
- Data from varying stream sizes, soil types, terrain, and climatological conditions;
- Development of standard measuring methods and continuous automated sampling technologies;
- Evaluation of proportions of contaminant contributions from the stream crossing structure and the road approaches; and
- Stream crossing impacts of stream ecology.

Another potential research area is the effect of scour, sedimentation, and turbidity on aquatic biota. Since this topic is beyond the realm of stream crossings, it is more appropriately addressed in the next section. The discussion here is limited to the potential impacts of roadway runoff at stream crossing on aquatic biota.

Data and analytical methods are available to predict the runoff constituents and concentrations for highway and waterway scenarios. NCHRP Projects 25-13 and 25-13(02) developed guidelines on how to use these data and methods to make comprehensive assessments of the impacts of bridge runoff on receiving waters and a guide to assist practitioners in making decisions on the need for, and the extent of, control of bridge-deck runoff in both new and retrofit applications (Dubois, 2002a and 2002b). These projects integrated known technology applicable to the quality of runoff water, the background quality of the receiving water, and the water quality criteria applicable to the receiving water and addressed reasonable treatments and proper disposal systems if and when warranted.

The guidebook encompassed consideration of runoff constituents (e.g., metals, sediments, and nutrients), types of bridge runoff-management designs, impacts on receiving waters and aquatic biota, and other potential runoff impacts. Also included in the guidebook were a risk assessment for special potential problems, benefit and cost-effectiveness assessments, and other elements of a strong management process to streamline and normalize consideration of runoff concerns within the project development process. Where warranted, the process addressed a range of mitigation alternatives from on-site control of bridge deck runoff to off-site watershed-based mitigation and pollution trade-off opportunities. Where on-site control is proposed, appropriate new bridge design parameters for runoff and opportunities for existing bridge retrofits were considered along with non-structural BMPs.

Both the design and construction of stream crossing structures can impact receiving waters and roadside ecosystems. A study of aquatic communities at three bridge sites in Florida was performed by Birkitt and Dougherty (1984). An analysis of aquatic communities including dominance, diversity, and evenness values revealed adverse impacts to aquatic biota at one bridge site; the authors attributed the adverse impacts to bridge design practices. Adverse impacts at the second bridge site were attributed to construction practices. The third site showed only minimal impacts to aquatic biota. The authors recommended locating bridges at sites that require minimum alteration to river channels or the flood plain, using design principles and construction methods that strive to maintain existing hydrological, sedimentary, and illumination characteristics of the river system and result in minimum site disturbance. A stream relocation and culvert installation project presented by Kober and Kehler (1987) found that incorporating mitigative measures into the project resulted in cost savings. Furthermore, post-construction biological conditions in the two streams used in the study were similar to or better than preconstruction conditions.

Research has shown the presence of heavy metals in bridge runoff. An analysis of runoff from the Skyway Bridge in Ontario, Canada, for five heavy metals (zinc, lead, nickel, copper, and cadmium) found EMCs for zinc, copper, and lead to be 0.337 mg/l, 0.136 mg/l, and 0.072 mg/l, respectively, in whole water samples. Mean PAH EMCs ranged from 0.015 µg/l to 0.5 µg/l. Sediment analysis revealed mean concentrations of zinc, copper, and lead to be 997 µg/g, 314 µg/g, and 402 µg/g. This study by Marsalek et al. (1997) concluded that discharging bridge runoff directly into receiving waters without prior treatment could cause significant impacts to receiving water bodies.

The preservatives used to treat wood bridges (or components) often are slowly released into the environment over time and could potentially end up in receiving waters. An evaluation of six bridges—two bridges treated with creosote, two bridges treated with pentachlorophenol, and another two treated with chromated copper arsenate—was performed by Brooks (2000). Study results indicated an absence of PAHs in water near any of the bridges. However, low levels of PAHs were detected in sediment directly underneath the bridges and immediately downstream. An analysis of aquatic invertebrate communities did not reveal any adverse effects and neither did laboratory bioassays conducted on water and sediment. According to the authors, robust invertebrate communities found in slow-moving streams were not susceptible to PAH levels that would be expected to impact more sensitive organisms in faster-moving streams. Dilution of contaminants in the faster-moving streams was found to attenuate contaminant concentrations to levels that were not biologically significant. The authors recommended that even though timber bridges pose little environmental risk, BMPs should be developed and deployed for all bridge types.

A cooperative effort by Auburn University's Biosystems Engineering Department and the U.S. Department of Agriculture's Forest Service Southern Research Station and its engineering research work unit in Auburn, Alabama, is underway to fill some of the knowledge gaps pertinent to the impacts of stream crossings. The objectives of the project include

- Quantifying and comparing water quality impacts from different types of stream crossings,
- Quantifying the amount of sediment produced by road approaches at stream crossing sites, and
- Documenting lifecycle costs of various types of stream crossings.

Another ongoing research effort by the Kentucky Transportation Cabinet will evaluate potential receiving water impacts from lead and other heavy metal contaminants generated as a result of pressure washing operations. The study also will examine existing paint on the selected bridges to assess the potential risk to receiving waters. The study will culminate in the development of alternative practices for wastewater treatment and disposal. Details of both this study and the Auburn University study are available on the TRB RIP website.

3.5.2.1. Identification of Research Needs

Receiving waters impacts at stream crossings include impacts that are well beyond the topic of highway runoff, such as impacts to stream channel morphology, sonic impacts to aquatic species during pile-driving activities, and impacts to fish passage through culverts. Although further research in these areas may be needed, the focus herein is on highway runoff, and the discussion has been limited to impacts caused directly by stormwater runoff or by runoff generated during maintenance activities such as bridge deck cleaning. Other bridge maintenance activities such as painting, surface treatments, substructure repair, joint repair, drainage structures repair, and pavement repair or repaving also may cause impacts to receiving waters depending on storm event timing, duration, and intensity. With regard to highway runoff, the potential impacts to receiving waters at stream crossings appear to have been assessed by only a limited number of studies. NCHRP Project 25-13 is likely the most extensive assessment to date on this topic.

The recommended research topics suggest (1) examining the water quality effects of maintenance practices through field studies, (2) developing a bridge deck runoff quality constituents database, (3) applying laboratory bioassays appropriate for stormwater discharges and field biosurveys, (4) examining the potential risks associated with hazardous material spills, and (5) identifying mitigation practices for controlling bridge runoff quality. Effects of bridge design and ADT on runoff quality present another research need.

3.5.2.2. Primary References

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3.5.3. Sedimentation and Turbidity

Increases in flow rates to receiving streams caused by increased impervious areas, in turn, increase the potential for streams to scour, particularly near outfalls without sufficient energy dissipation controls. Scour can cause increased downstream turbidity. Poor erosion controls near surface waters, particularly during and shortly after grubbing and grading activities, can cause sedimentation and high turbidity in receiving waters. Methods to reduce erosion and turbidity were discussed in section 3.2.6. This section addresses the impact of sedimentation and turbidity on receiving waters.

Research by Bash et al. (2001) evaluated the effects of sediments and turbidity on salmonids in Washington State. A literature review found that excessive sediment in hatchery water may smother eggs by depriving them of oxygen and by reducing the ability of juveniles to capture prey. The literature review also suggested that gill injuries increase as angularity and particle size of suspended solids increase. The authors concluded that a better understanding of sediment size, shape, and composition, as well as a better understanding of salmonid species and life history stages, cumulative and synergistic stressor effects, and overall habitat complexity and availability in a watershed is required. They also recommend that for short-term construction projects, operators must measure background turbidities on a case-by-case basis to determine if they are exceeding regulations. Turbidity standards developed by several states and provinces in the region attempt to consider natural variability in turbidity by requiring the regulated community to measure "background turbidity" upstream of any proposed activity. Although, since the background turbidity measured in these situations represents a measurement at one point in time, regulating turbidity levels based on this type of measurement may not protect salmonid health.

3.5.3.1. Identification of Research Needs

With regard to sediment and turbidity impacts to fish in general and salmonids in particular, significant research needs identified by Bash et al. (2001) included (1) developing new exposure metrics that account for sublethal effects (as opposed to direct mortality); (2) examining the effect of frequent short-term pulses of suspended sediment; (3) conducting additional research on correlations between particle size, shape, and composition of sediments to fish sensitivity; (4) studying relationships between seasonal timing and effect of sediment load; and (5) determining whether knowledge of survival responses to turbid flows can be used to develop mixing zones, work windows, treatment systems, and buffers that will allow fish to perform their necessary life functions during project construction and operation.

3.5.3.2. Primary Reference

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3.5.4. Toxicity and Bioassessment

Toxicity testing and bioassessments can be used to characterize and assess the cumulative/synergistic impacts of stormwater pollutants on receiving waters and sediments. Bioassessment includes evaluating indicators of receiving water health, such as biomass and species diversity. Toxicity testing requires evaluation of a test species' survivability in a water sample or sediment sample. The testing is included frequently in water quality management studies, because it can provide an indication of the potential impact of discharged contaminants on receiving waters and associated biota.

Regulators are attempting to increase regulatory control of toxic contaminants relative to constituents that have low or zero toxicity. Knowing the potential toxicity of highway runoff is important, because if toxicity is high, one can expect greater regulatory control and the implementation of treatment programs to reduce the toxic pollutants. Alternatively, if runoff is demonstrated to be nontoxic, controls subsequently will be reduced. Potential research questions include

- What is the applicability and limitation of the various toxicity testing methods with regard to the assessment of receiving water impacts?
- How can biomass and species diversity be used to evaluate the health of receiving waters?

As mentioned in section 3.2.12, information describing toxicity specific to road runoff in the open literature is scarce. Few toxicity studies have been conducted where the runoff was predominantly or exclusively from roadways or highways. One multiyear toxicity study was conducted in the Santa Clara Valley, California; samples were collected predominantly from freeway runoff. These samples showed high incidences of toxicity to *C. dubia* (freshwater crustacean), but the toxic response was quantitatively different from that seen in samples deriving from other land use categories (BASMAA, 1996). The cause of toxicity for highway runoff in the BASMAA study was found to be nonpolar organics and metallo-organics. Two other highway runoff toxicity studies reached similar conclusions on measuring a higher level of toxicity in highway runoff compared to the other land uses [Pitt et al. (1991) and Marsalek et al. (1999)]. The high level of toxicity in these runoff samples may have been due, in part, to the presence of deicing chemicals or to higher concentrations of bioavailable heavy metals.

In addition to water toxicity testing, some researchers have evaluated the toxicity of sediments near urban stormwater outfalls to assess the effects of these discharges. Rochfort et al. (2000) assessed relationships among three separate aspects of the benthic environment: sediment chemistry (metals, PAHs, and nutrients) and particle size, sediment toxicity (ten endpoints with four benthic taxa), and benthic invertebrate community structure. Researchers found that while contaminant (metals and PAHs) concentrations were relatively high in sediments, biological effects were not evident (i.e., toxicity of sediments was low, benthic communities appeared unaltered, and neither toxicity endpoints nor benthic community descriptors could be related to sediment contaminant levels).

In a similar investigation, the chemical characteristics of urban stormwater sediments in the rapidly growing Phoenix metropolitan area of Maricopa County, Arizona, were analyzed (Parker et al., 2000). Results showed that the inorganic component of the sediments generally reflected geologic background values, but some metals concentrations (e.g., cadmium, copper, lead, and zinc) were above background values, indicating an anthropogenic contribution of these elements. Organochlorine compounds and PCBs were ubiquitous in the sediment samples, even though many of these compounds have been banned from general use for as long as three decades. Sediment toxicity results seem to suggest that surficial sediments from stormwater-control basins, city streets, vacant lots, and unpaved parking areas are a significant environmental problem, but the temporal and spatial variability in the test results makes such a conclusion tentative.

With respect to bioassays for the evaluation of potential toxic effects of highway runoff, Dubois (2002) noted that the toxicity test methods should be modified to account for the episodic nature of runoff; hence, test organisms for bioassays should be exposed to runoff for a length of time equal to the storm event length. Limitations of traditional toxicity testing methods also are discussed by Burton et al. (2000). Such time-variable bioassays were performed in the study for runoff from two distinct bridges. The I-85 bridge in North Carolina, which crosses a small stream, had a medium-level of ADT—74,000 vehicles at the time of the study. The San Francisco–Oakland Bay Bridge, which crosses the San Francisco Bay, had a high ADT of 274,000 vehicles at the time of the study. No toxicity was found in time-variable bioassays for I-85 runoff. Some toxicity was found in traditional chronic 7-day bioassays with 100% runoff (did not reflect runoff event duration). This demonstrates the importance of using the time-variable technique (described in this report) to assess accurately potential toxicity. There was some toxicity with 100% runoff from the San Francisco–Oakland Bay Bridge using the time-variable technique. There was significant toxicity with 100% runoff using the traditional 7-day chronic test (did not reflect runoff event length).

Recently, Caltrans initiated a comprehensive toxicity study of runoff from their various facilities, including 24 highway sites on a statewide basis (Caltrans, 2002). The goal of this Statewide Toxicity Testing Research Project was to assess the toxicity associated with discharges from its storm drain system, determine the cause of the toxicity, and provide some understanding of the sources of these discharges. In most cases, a single discrete sample was obtained from various facilities and tested for toxicity based on the EPA's standard three species test. These single discrete samples were collected at different points of the hydrograph with the majority being collected at the beginning of the storm events. Stormwater was captured by grab samples and shipped to the Aquatic Toxicology Laboratory at the University of California, Davis. The results obtained for the past two monitoring seasons (2000–2001 and 2001–2002) are summarized below (Caltrans, 2002).

- *Pimephales*—Of the 98 tests performed, 82 (83.7%) indicated significant toxicity for either survival or growth. Significant reductions in biomass were found in 52 samples, and significant mortality was found in 28 samples, indicating that most often, reductions in biomass were common, and acute toxicity was less common. No pattern in toxicity with respect to date of sampling was apparent, as significant toxicity was found at all dates from October to May.
- *Ceriodaphnia*—Of the 98 tests performed, 72 (73.5%) indicated significant toxicity. These results included all tests for which acute toxicity occurred and chronic tests were not possible to perform. As with the *Pimephales*' toxicity test results, there appeared to be no pattern with respect to date of sampling, as significant toxicity was found throughout the entire period of sampling.
- *Selenastrum*—Of the 98 tests performed, 46 (46.9%) indicated significant toxicity. The *Selenastrum* test was never the sole positive test result for any site at any sample date. Again, no patterns were evident in the positive results.
- Toxicity Identification Evaluations (TIEs)—Thirty TIEs were performed on samples in which acute toxicity was observed. The TIEs indicated that no single source of toxicity was common among sites. However, nonpolar organic compounds were suggested as the putative source of toxicity in 5 of the TIEs, metals were suggested as the putative source in 11 TIEs, and surfactants were suggested as the putative cause in 7 cases. In one case, a metabolically active pesticide was implicated. The remainder had no discernable cause.

Overall, more than two-thirds of the discrete samples collected were found to be toxic. This method of sample collection and toxicity testing may produce misleading results, as the single sample is not representative of the entire event. More importantly, the relative toxicity of samples from the beginning of the event (first flush) compared with the rest of the event will not be known. Toxicity measurement on a hydrographic scale is more appropriate as it would provide information describing the variability of toxicity on a time and flow scale.

An investigation of the relationship of toxicity to flow and time was initiated as part of the Caltrans first flush study during the 2002–2003 monitoring season (Caltrans, 2003). Only three storm events were monitored during the 2002–2003 wet season. The results indicate the presence of a toxic first flush at some sites, which maybe useful for BMP selection. However, results are insufficient to make conclusions regarding the cause of toxicity and the influence of site-specific or storm-specific factors. Caltrans would like to continue the first flush toxicity study for two more seasons to address hydrographic toxicity of highway runoff for BMP selection, but the availability of future funding is unsure.

Náb̆elková et al. (2002) studied two tributaries of the Vltava River in Prague in an effort to evaluate the ecological risk of pollutants. They analyzed potential impacts of individual pollutants to aquatic organisms with the aid of mathematical simulations. For each pollutant they developed an ecological risk description in toxicological units. The researchers found that heavy metals did not pose an ecological risk in surface water, but chronic heavy metal loads were found in bottom sediment, which did pose an ecological risk.

Environmental indicators developed by the Center for Watershed Protection (CWP) can indicate the extent of impacts to receiving water and the effectiveness of stormwater management programs. The Santa Clara Valley Urban Runoff Pollution Prevention Program implemented and tested 20 of the CWP's 26 Environmental Indicators to Assess Stormwater Programs and Practices (Cloak and Bicknell, 2001). The researchers found that the CWP indicators were useful for tracking and enhancing pollution prevention efforts and also for holistic evaluations of stream function for the purposes of watershed management and planning.

Bioindicators have been used in studies to demonstrate impacts to the environment. Lemly and King (2000) used the occurrence of bacterial growth on aquatic insects as an indicator of nutrient impacts on wetlands. During field investigations, nitrate and phosphate levels were linked to the growth of filamentous bacteria on insects. The authors concluded that the use of the insect bacteria bioindicator is a reliable metric for evaluating nutrients impacts on wetlands where Wetland Bioassessment Protocols were applicable. Biological assessment methods can be used to assess wetland condition, evaluate the performance of wetland protection and restoration activities, and track water quality conditions in wetlands (Danielson, 1998).

3.5.4.1. Identification of Research Needs

As mentioned above in section 3.2.12, the top two research needs identified by GKY and Associates in the original NCHRP Project 25-20 report were (1) to identify and develop regional aquatic biological indicators to assess impacts of highway runoff and (2) to conduct research methods for assessing the toxicity of highway runoff. This recent literature review effort supports the claim that there do not appear to be adequate bioassessment methods for assessing impacts of highway runoff on receiving water systems, particularly at the time-scales typical of stormwater-runoff events. Also, there are a wide variety of assessment methods currently used by the few highway water quality researchers conducting toxicity and bioassessment studies, so it is difficult to quantitatively compare existing data or to make any general assessment of the impacts of highway runoff on receiving water biota. In addition, more within-storm toxicity testing needs to be conducted to ascertain what parts of storm events are most toxic. A comparison of drainage systems (e.g., vegetated versus piped conveyance) with regard to toxicity is also a potential research gap.

3.5.4.2. Primary References

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Rochfort, Q., Grapentine, L., Marsalek, J., Brownlee, B., Reynoldson, T., Thompson, S., Milani, D., and C. Logan. Using Benthic Assessment Techniques to Determine Combined Sewer Overflow and Stormwater Impacts in the Aquatic Ecosystem. *Water Quality Research Journal of Canada*, Vol. 35, No. 3 (2000) pp. 365–397.

3.5.5. Modeling of Water Quality Impacts

Modeling has become an important part of stormwater management. Nonetheless, modeling development efforts have focused mostly on surface runoff models, and little attention has been devoted to developing sophisticated groundwater models. James and Ulan (1997) present discussions about the utilization of shallow ground routing routines in SWMM4.3 and HSPF to model infiltration BMPs. Beckers and Frind (2000) developed a model adapted to simulate situations where groundwater recharge may be impacted significantly by heterogeneity above the water table. The model accepts precipitation and evapo-transpiration as direct inputs.

Hvitved-Jacobsen et al. (1996) simulated oxygen depletion from 35 years of rain events using a modified oxygen sag theory. Balmforth et al. (2002) discuss the Leeds Urban Pollution Management Study, which modeled an area with more than 500,000 people and 130 inadequate combined sewer overflow (CSO) systems. The model was used to generate BOD, ammonia, and suspended solids loads, which then were compared to water quality standards to determine the contribution of individual discharges to the failure of standards. The researchers observed that modeling and data collection costs can be reduced through careful management and through the application of the bespoke model. Also, a detailed model allows simulation of vital processes such as first flush. Temperature is a significant water quality parameter for cold-water aquatic habitats.

Haq and James (2002) present a thermal enrichment model for Portage Creek, a cold-water habitat for fish located in Portage, Michigan. Using 1½ years' of continuous temperature data, they created a model to simulate the heat budget for pavement runoff. The researchers concluded that pavement runoff impacts stream temperature.

Temperature change associated with runoff from paved areas has been documented, as has the effect of detention basins on receiving water temperature conditions. However, temperature often is overlooked as a physical characteristic of receiving waters. It is possible to model temperature effects of urban runoff, but when temperature is related to chemical or biological processes in receiving waters a number of issues are unresolved; available models are often site-specific or limited in scope (e.g., addressing only summer season issues). Nevertheless half of state DOTs ranked this as a low-priority research area. Only 10% of the DOTs ranked it as a high priority; in most of these cases, impacts on cold-water fish species are a driving factor.

Bioavailability of metals in sediments is linked directly to pore-water metal activity, which is influenced by physical, chemical, and biological processes. Wood and Shelly (1999) developed a system dynamics model to represent these processes and the major influences affecting pore water metal activity in a treatment wetland receiving stormwater influent. The model structure and behavior were tested and validated using several system dynamics validation techniques. The model was run using metal specific parameter values typical of metals commonly found in stormwater runoff. Simulation results demonstrated that chemical processes of acid volatile sulfide and organic carbon in binding metal in reduced sediments are the greatest influences in controlling metal bioavailability. As represented in the model, the effect of bioturbation was negligible. The amount of organic carbon in the sediment plays the most substantial role in controlling metal bioavailability in the long run.

Using 5 years' of highway runoff characterization data, including 500 storms at nine locations in Washington State, Horner and Mar (1983) developed a model that relates highway segment length to cumulative pollutant loadings. The model incorporates the effects of high traffic density and the mitigative effects of draining highways through roadside swales. The model can perform three levels of analysis ranging from detailed analysis to a simple screening method.

3.5.5.1. Identification of Research Needs

The area of water quality modeling shares a few of the research gaps identified under the BMP Modeling section (section 3.2.10) of this effort. These research gaps include the availability of data for accurate and representative parameter estimation, the ability to accurately measure and analyze unit processes, model calibration, and the need for an expert system for model evaluation and selection. Other potential knowledge gaps pertinent to water quality modeling include guidance on modeling temperature change impacts from pavement runoff, further development and enhancement of stochastic water quality models, evaluation of the limitations imposed by snow on water quality modeling methodologies, and the development of solutions for more accurate simulation of the effects of snow in water quality models.

3.5.5.2. Primary References

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3.5.6. Water Quality Impacts of Combined Sewer Overflows

CSOs are drainage systems that discharge excess untreated sewage and stormwater directly into marine waters, lakes, rivers, and other water bodies when the system capacity is reached. In most cases CSOs are legacy systems built in the past and left unchanged as a result of cost constraints. In the old days, CSO systems were not considered as a major source of pollutants; it was assumed that by the time sewage systems overflowed, the majority of the contaminants would have been flushed already. Also, the increased volume of the receiving water body was assumed to provide adequate dilution. These assumptions are hard to verify (Villeneuve and Lavallee, 1985).

Since the advent of wastewater treatment plants in the 1950s, CSO impacts to stormwater have been subject to increasing scrutiny. In some municipalities, interceptor pipes have been built to convey all wastewater, including discharges from CSOs, to wastewater treatment plants. However, in many older cities, CSOs still remain an issue. According to Seidl et al. (1996), the main impacts of CSOs include bacteria loads and increased consumption of oxygen due to organic matter. The water quality impacts of CSOs need to be better understood in order to facilitate development of appropriate regulations for the protection of receiving waters. According to Kaunelis and Johnson (2000), areas of interest and research questions concerning CSOs include

- Is CSO discharge sufficiently clean to meet water quality standards?
- What impacts should be measured?
- How can CSO impacts be isolated and measured independently of other impacts to receiving waters?
- How much data is needed to support CSO decision making?

A number of research projects have investigated the impact of CSOs on receiving waters. Many more monitoring projects are still in progress. Kaunelis and Johnson (2000) discuss an ongoing evaluation of nine facilities built by the Rouge River National Wet Weather Demonstration Project to store and treat CSO effluent in metropolitan Detroit. The results of this effort will determine if more capital investment is needed to mitigate CSO impacts. An investigation by Hvitved-Jacobsen and Harremoes (1981) found that CSO impacts on dissolved oxygen occur in two phases. The immediate phase is oxygen depletion attributed to the soluble fraction of organic matter in the discharge. The delayed phase is potentially more serious and attributed to "adsorption of soluble, colloidal and fine particulate fractions." Widera and Podraza (1996) describe chemical analyses as "spot checks" that show water quality at a definite time while stream biota analyses reveal long-term effects.

Several studies provide insight into CSO effluent composition. The Rouge River National Wet Weather Demonstration Project monitored CSOs for 2 years. Kaunelis and Johnson (2000) summarized the methodology and the results of this study. Monitored pollutants included carbonaceous biological oxygen demand (CBOD), TSS, ammonia, and total phosphorus. EMCs for four basins were as follows: CBOD, 4.5–43.2 mg/l; TSS, 24–82.7 mg/l; ammonia, 0.14–4.47 mg/l; and total phosphorus, 0.58–1.26 mg/l. The study concluded that the impacts of CSOs can be isolated from other sources of pollution to quantify the effectiveness of CSO mitigation measures. Two years' of monitoring data and/or 10 overflow events can provide adequate data to support CSO-related decision making. Data from a 5-year study of the Cumberland River in Nashville, Tennessee, showed that dissolved oxygen depletion was not an issue with the CSO system. This study by Thackston and Murr (1999) also ruled out the CSO system as the source of the fecal coliform bacteria problem in the river. Data from the study saved $106,000,000 in planned redundant improvements to the drainage system.

Seidl et al. (1996) presented a discussion on monitoring data collected as input to run the model Prose and monitored six rainfall events and parameters including conductivity, turbidity, TSS, COD, ammonia, DOC, BOD5, and bacteria. Researchers found similar ratios between the parameters under various conditions and concluded that high DOC may originate from urban surface deposits or resuspension of sewer deposits. They observed a decrease of DOC for the big rainfall events; they attributed the decrease to dilution. Fluctuations in bacterial levels made observed bacteria biomass level results less conclusive and harder to correlate to other parameters.

A number of studies focus on creating new CSO pollutant models or modifying existing models. Hvitved-Jacobsen and Schaarup-Jensen (1990) discussed the application of a dissolved oxygen stream simulation model. O'Connor et al. (1993) presented a discussion of the use of EPA's SWMM to model pollutants in a CSO abatement study of Newton Creek in New York. Villeneuve and Lavallee (1985) presented methodologies to characterize CSO wastewater and to define lateral and longitudinal diffusion of wastewater. The paper also discussed mitigation of intermittent CSO discharges. Michelbach et al. (1999) presented a method for estimating nutrient loads to Lake Constance in Europe from CSOs. The authors developed new functions to calculate nutrient loads from average nutrient concentrations, annual overflow rate, and solids transport in sewers.

3.5.6.1. Identification of Research Needs

CSO systems are widely variable, and water quality impacts depend on a host of site-specific parameters. Measurement of impacts is based mostly on computer simulations. There is a need for better monitoring of CSO effluent quality in relation to meteorological factors. What prevailing conditions or factors increase or decrease CSO impacts? What methods can be used to mitigate impacts (structural and nonstructural)?

3.5.6.2. Primary References

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3.5.7. Deicing Agent Impacts

Deicing agents were discussed briefly under the context of Highway Runoff Characterization and Assessment. This section evaluates the impacts of deicing agents on stormwater runoff. Potential research questions include

- How do deicing agents impact receiving waters, and what are the least toxic alternatives?
- What factors influence or compound receiving waters impacts, and how can these factors be minimized?

A comprehensive study performed by Michigan DOT investigated the environmental and economic impacts of deicing agents. The study includes an analysis of various deicing materials: sodium chloride, calcium magnesium acetate (CMA), Motech, calcium chloride, and proprietary products such as CMS-B, CG-90 Surface Saver, and Verglimit. Deicers containing chloride salts were found to have similar impacts, which in turn appear different from impacts from deicers containing CMA. The Michigan DOT study and pre-existing research concur that only in rare situations can road salts cause significant direct impacts. Results from the model developed for the Michigan DOT study suggest that chloride concentrations in the Great Lakes will not reach toxic levels even in the worst-case scenario; however, chlorides can cause density stratification in smaller water bodies and CMA decomposition can lead to depletion of dissolved oxygen levels. The authors suggest diversion of runoff to less sensitive areas to attenuate impacts on receiving waters (Public Sector Consultants, 1993).

Other research has been done to investigate the impacts of deicing agents in correlation to external variables such as meteorological and climatological factors. In a study near Jamesville, New York, Champagne (1977) found that precipitation and temperature have an effect on the release of salts into receiving waters. Researchers also found that road salts can infiltrate into soils and can impact chloride levels in the receiving water long after road salt application.

Research on modeling and simulation of the impacts of road salts has been performed in a number of studies. Halm (1997) discussed the development of a finite difference model and its application to airport deicing activities. Lewis (1999) conducted an evaluation of the environmental effects of the deicer magnesium chloride, widely used by Colorado DOT during winter highway maintenance activities. The literature review preceding the investigation indicated that magnesium chloride deicers are unlikely to produce adverse environmental effects. However, magnesium chloride may contain other chemicals such as rust inhibitors, which may consist of organic compounds that increase the oxygen demand. These chemicals have not been studied adequately. Results of the Lewis study found that no significant increases in BOD could be detected as a result of the addition of 0.3% deicer solution. Biotoxicity testing was conducted on boreal toad tadpoles, juvenile rainbow trout, *Ceriodaphnia* (aquatic invertebrate), and *Selenastrum* (algae). Tadpoles and juvenile rainbow trout showed no mortality over 96-hour intervals at deicer concentrations of 0.1%, which is close to the expected median deicer concentration within short distances from the roadway. *Ceriodaphnia* had a 48-hour threshold of mortality at 0.1%, and *Selenastrum* showed significant suppression of division rate for algal cells at deicer concentrations slightly in excess of 0.1%. The overall conclusion of the study is that application of magnesium chloride deicer having a chemical composition and application rate similar to those typically used by Colorado DOT is highly unlikely to cause or contribute toward environmental damage at distances greater than 20 yards from the roadway. Even very close to the roadway, the potential of magnesium chloride deicer to cause environmental damage is probably much smaller than that of other factors related to road use and maintenance, including pollution of highway surfaces by vehicles and use of salt and sand mixtures to promote traction in winter. Magnesium chloride deicer may offer net environmental benefits if its use leads to a reduction in the quantity of salt and sand applied to roadways.

A study on the effects of runoff from Chautauqua Lake Bridge, in western New York, on sunfish further illustrates this toxicity (Adams-Kszos et al., 1990). NaCl appeared to be the major contributor to the toxicity of runoff from the Chautauqua Lake Bridge in laboratory bioassays. However, concentrations of zinc and cadmium present in the 50% winter runoff were in the range reported to be toxic to fish and may have been additive or synergistic with the NaCl toxicity in the laboratory bioassays. Because runoff from the Chautauqua Lake Bridge is diluted greatly when it enters the lake, it is unlikely that bridge runoff will be toxic. However, if runoff comparable to that entering Chautauqua Lake during the winter were to enter a much smaller body of water, the metals and NaCl would probably cause significant harm to freshwater organisms.

The effects of the highway deicing activities on the Peshastin Creek watershed in Washington were studied over a 6-month period from December 1999 to May 2000. Steelhead (*Oncorhynchus tshawytscha*), Chinook salmon (*Oncorhynchus mykiss*), and bull trout (*Salvelinus confluentus*), three threatened/endangered species, inhabit the stream, and therefore a study of the effects of deicing activities was warranted. Five reaches along Peshastin Creek and its tributaries were selected for the collection of weekly grab samples and three of these reaches were outfitted with continuous monitoring equipment. Water quality tests, Microtox® toxicity tests, benthic macro invertebrate enumeration, and streambed substrate sieve analyses were used to evaluate the influence of deicing activities (application of traction sand and IceBAN, a liquid deicer) on Peshastin Creek. Chloride exhibited signs of preferential elution and was found to be significantly higher in concentration in areas adjacent to the US Highway 97. The maximum recorded chloride concentration in Peshastin Creek was 3.3 mg/L and 2.7 mg/L at reach 2 and reach 4, respectively. The nonimpacted reaches of Peshastin yielded an average chloride concentration of 0.62 mg/L. Heavy metals concentrations (soluble and total) were much lower than EPA's recommended limits. The benthic macro invertebrate study, although qualitative in nature, suggested that the deicing activities did not adversely impact the three fish food organisms that were quantified. Streambed substrate analyses indicated that the traction sand used in deicing activities had no measurable negative impact on known spawning locations. The physical, chemical, and biological parameters evaluated in this study indicate that deicing activities along SR 97 had no measurable negative impact on Peshastin Creek.

3.5.7.1. Identification of Research Needs

With regard to the receiving water impacts associated with deicing agents, it appears there is a need for a database containing an evaluation of the human health and receiving water impacts along with toxicity test results for all existing deicing agents to aid in the selection of deicing agents. Other potential research needs include the evaluation of the persistence and implications of various deicing agents in roadside soils, evaluation of the factors that influence or compound receiving water impacts, and the development of strategies to minimize impacts. Recommendations suggested by Fischel (2001) include the development and implementation of deicing strategies that reduce the amount of chemicals required and the development of decision support systems based on weather conditions to optimize deicing operations. Minimizing the amount of deicing chemicals used in deicing operations results in a corresponding reduction of the impacts to receiving waters.

3.5.7.2. Primary References

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3.5.8. Groundwater Quality Analysis and Impacts

Increase in impervious area due to urbanization interferes with groundwater recharge. Developed areas that allow some form of infiltration are likely to inject contaminants carried in surface runoff into groundwater. New sources of groundwater recharge that have resulted from urbanization include domestic septic tanks, industrial waste injection wells, agricultural and residential irrigation, and infiltration BMPs (Pitt et al., 1994). All of these new sources of groundwater recharge have the potential to cause negative groundwater impacts. After development, if most runoff is infiltrated, it is likely that overall infiltration volumes will be higher than before redevelopment, as the water loss from evapotranspiration is reduced. Therefore, the potential for increased loadings as well as increased concentrations is created.

Widespread adoption and acceptance of infiltration BMPs as stormwater runoff treatment and control methods have spawned questions as to whether contaminants are treated adequately before runoff mixes with groundwater. Natural organic matter (NOM) present in stormwater reacts with heavy metals to form complexes that have shorter transport times. To investigate the implications of this phenomenon on groundwater impacts, Hathhorn and Yonge (1995) performed a two-phase study to investigate heavy metal–NOM transport mechanics. They found that dissolved organic matter enhanced the transport of lead through NOM-metal complexation. To minimize groundwater impacts, they recommended that in siting an infiltration facility, the organic content of the soil and the background metal content should be determined. Also, the distance to groundwater should be increased from 3 feet to approximately 10 feet.

A study by Barraud et al. (1999) investigated the potential impacts to groundwater from two soakaway (i.e., underground injection control) facilities receiving urban runoff. One facility was 2 years old and one facility was more than 30 years old. Groundwater was monitored during storm events 1 m and 1.5 m down-gradient from the newer and older facilities, respectively. Soil quality also was measured. The results for the newer facility indicated that metal and hydrocarbon concentrations were high near the injection surface but decreased rapidly a few decimeters down. However, the older facility indicated that heavy metals and mineral oils can contaminate the soil over a radius of at least 1 meter around the infiltration facility. Impacts to groundwater were low, but there were measurable increases in copper, lead, and zinc concentrations as compared to background groundwater concentrations. The authors noted that since the data were highly variable and few data points were monitored, it was difficult to draw any definite conclusion from the study.

In a study to assess impacts of an exfiltration pipe, a detention pond, a retention pond, and two swales in Florida, Schiffer (1989) found the concentrations of chromium, copper, and lead in groundwater to be below detection limits. Groundwater near the ponds had the highest TKN levels, while the highest levels for nitrate nitrogen and phosphorus were observed near the swales and the exfiltration pipe. Contaminant concentrations were monitored from 1984 through 1986. The results of this Florida DOT study showed an attenuation of inorganic contaminants; yet, the researchers concluded that organic compounds in the retention pond sediments may eventually impact groundwater quality.

Sela (1994) presented graphical methods that were applied to identify areas of high groundwater sensitivity in a 14-mile-long highway widening project in New Jersey. This information could find potential applications in BMP siting and design.

Little research has been done on DOT impacts to groundwater. The most notable DOT groundwater impacts historically have arisen from maintenance yard contamination to wells, in which case the DOT has sometimes bought wells, homes, or even larger developments. In Pennsylvania DOT's case, such expensive impacts ultimately led to the agency's development of ISO14001-certified environmental management systems in maintenance districts. In cases of special danger where spills contaminate water recharge areas, DOTs have been known to develop agreements and "double ditch" a facility separating water that came underneath the road from water that was coming off the highway to prevent any type of highway spills from affecting the groundwater and endangered species.

There have been numerous studies on MTBE. MTBE is an oxygenate used to increase oxygen levels in gas, thereby enhancing combustion and decreasing carbon monoxide emissions (Delzer et al., 1996). In a study to investigate the extent of MTBE contamination, USGS collected 592 stormwater samples in 16 cities and metropolitan areas from 1991 through 1995. The results of this study as summarized by Delzer et al. (1996) detected MTBE in 7% of the samples analyzed. Another study presented by Squillace et al. (1996) found MTBE to be detected most frequently in shallow groundwater; MTBE was detected in 27% of the 210 shallow groundwater wells sampled in eight areas versus 1% of 412 deep groundwater wells sampled in nine areas. A significant number of shallow wells in urban areas were contaminated as compared to shallow wells in agricultural areas. The majority of the studies on MTBE encountered in this effort appear to be centered on groundwater. However, the Metropolitan Water District of Southern California surveyed six reservoirs, which serve as sources of drinking water in Southern California, to determine the level of MTBE impacts. This study by Dale et al. (2000) found that motorized watercraft can be a significant source of MTBE.

Infiltration systems usually are not designed with any concern for pollution retention. However, it is sometimes proposed that polluted stormwater should pass through a humic layer at the soil surface to effectively screen off any present well-absorbable or degradable pollutants, whereas clean stormwater should be allowed to infiltrate directly into the underground. The implications of such procedures have not yet been investigated thoroughly, and it is rarely realized that they may lead to an unacceptable contamination of surface soils.

In order to investigate the potential impacts to soil and groundwater that have received runoff water from highly trafficked roads for several decades, a field study of a surface infiltration system and a subsurface infiltration system was conducted (Mikkelsen et al., 1996). The results of the investigation found that the infiltration systems served as effective pollutant traps for copper, zinc, cadmium, lead, PAHs, and adsorbed organically bound halogens, and the potential for groundwater contamination caused by leaching of heavy metals was of low concern. The authors noted that soluble constituents such as many pesticides and deicing salts may pass directly through infiltration systems with little or no retention in the soil matrix and should be investigated further. Differences between the ability of surface and subsurface infiltration systems to retain pollutants were not found to be significant, but it was indicated that retention capacity was largely a function of neutral to weakly alkaline pH conditions, and a similar observation may not occur in other types of geology.

3.5.8.1. Identification of Research Needs

Based on the review of literature pertaining to potential impacts to groundwater caused by infiltration of stormwater runoff, there appears to be a need for more research. The methods used to assess impacts are difficult to implement, and the results are difficult to assess. State DOTs need a procedure to estimate the potential extent and magnitude of groundwater quality degradation from transportation BMPs, particularly those that rely on infiltration at their primary treatment mechanism. This guidance would include procedures for identifying and evaluating current and potential uses of groundwater and water quality requirements that could be affected by transportation BMPs. The direction of flow movement in groundwater aquifers needs to be identified. Any pollutant plumes in aquifers must be evaluated, including direction of flow and concentrations. Treated stormwater quality from transportation BMPs that could infiltrate groundwater should be identified in terms of flows, constituents, and concentrations. The role of geology in pollutant retention appears to be a research gap that needs to be filled. The distance between BMP invert and the maximum groundwater elevation must be determined, as must the rate of flow downward to the groundwater.

With regard to the persistence of MTBE in groundwater, potential research questions and areas of interest outlined by Delzer et al. (1996) include the following:

- How persistent is MTBE in streams, what is the rate of degradation, and what are the potential impacts on aquatic life?
- What proportions of MTBE are contributions from precipitation versus runoff contributions?
- Do other oxygenates behave in a similar manner?
- How do factors such as land use relate to MTBE occurrence?
- What are the proportions of contributions from stormwater recharge and precipitation to MTBE in groundwater?

In summary, the fate and transport of stormwater constituents from BMPs as the constituents move through the soil mantle and ultimately move through groundwater must be determined. Past guidance for siting infiltration BMPs has focused on minimum depth to groundwater; however, the filtering and sorption capacity of the soils the water passes through are more important considerations.

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3.5.9. Wetland Impacts

Wetlands provide numerous benefits that include flood and erosion control and water quality improvement. Wetlands are home to one-third of all federally listed endangered species. Unfortunately, the number of wetlands has been reduced drastically because of urbanization. Twenty-two states have lost approximately one-half of their wetlands, while California, Iowa, and Ohio have lost about 90%. The bulk of wetland losses have occurred as a result of agricultural conversion, natural erosion, and urbanization—not as a result of highway construction. According to a study by Apogee Research Inc. (1997), between 310,000 and 570,000 acres of wetlands have been lost as a result of FAHP construction activities between 1955 and 1980. Replacement costs of such wetlands start between $153 million and $6 billion. A review of the literature pertinent to wetland impacts reveals that much research has been done on this subject. However, the discussion herein is limited to wetland impacts caused specifically by highway stormwater runoff. The most pertinent research questions with regard to highway runoff are

- To what highway runoff pollutants are natural wetlands most sensitive?
- Can constructed or mitigated wetlands successfully be used to treat highway runoff without impacting local biota?

The impacts of highway construction and operation on wetlands have been the subject of a number of studies. Harris et al. (1984) discuss a wetland monitoring program developed by the Arkansas Highway and Transportation Department to document impacts to a wetland during the construction of US-67 in White County Arkansas. Yu et al. (1998) evaluate two mitigated wetlands constructed by Virginia DOT. Highway runoff provided the primary source of water for both wetlands. The researchers found that the habitat and biota remained healthy and diverse for both wetlands.

Highway operation and maintenance practices that may potentially impact groundwater are likely to impact nearby wetlands, too. A hydrogeologic investigation (Panno et al., 1999) indicated the migration of contaminants into two wetlands via groundwater. The investigation consisted of a 15-month-long hydrogeologic evaluation of a fen-wetland complex in northeastern Illinois. The origin of the high concentrations of Na^+ and Cl^- ions in groundwater plumes were linked to a private septic tank and road salt operations. Observed impacts to fen vegetation included succession by salt-loving plant species. Large concentrations of sulphate in the second wetland were linked to oxidation of pyrite within underlying soils. There were no discernable impacts on fen vegetation from the high sulphate concentrations. The study demonstrated how easily septic systems and deicing operations could negatively impact wetland vegetation.

A comprehensive synthesis of federal programs that impact wetlands is presented in a two-volume report by the U.S. Department of Interior (U.S. Department of the Interior, 1988 and 1994). Wetland impacts resulting from federal programs such as agricultural programs; water development and management programs; infrastructure; local development and housing programs; and federal programs to promote resource use, extraction, and development are presented in the context of regional variability of impacts. The regions studied in the report include the Mississippi Delta Region; the Prairie Pothole Region; southeastern Alaska; the Central Valley in California; the Everglades in Florida; Maryland's Eastern Shore; Coastal Michigan; Northern Michigan; the Pocosins in North Carolina; New Jersey; the Puerto Rican Mangroves; the Texas Coast; and riparian areas in Idaho, Nevada, and New Mexico.

The literature has established that highway runoff can have a negative impact on wetlands; however, the provision of some form of detention as pretreatment prior to the wetland has been shown to significantly alleviate impacts. An evaluation by Schiffer (1989) of the effects of highway runoff on two wetlands in central Florida showed that the concentration of automobile-related contaminants and sediment can be reduced by detaining runoff before it is released into wetlands. Spatial variations of pollutants within the freshwater marsh indicated that for most contaminants, concentrations decrease with increasing distance from the inlet. Color, total organic carbon, and chromium concentrations behaved in the opposite manner. The behavior of chromium may be due to the fact that chromium remains dissolved longer than some of the other metals and could also be linked to atmospheric deposition. The study concluded that detention structures larger than the 12′-by-25′ trash retainer used at the freshwater marsh may provide significant sorption and settling of contaminants, thereby minimizing impacts to wetlands.

Mitigated wetlands formed as a result of highway construction projects or for economic incentives or wildlife habitat creation can provide significant water quality benefits. A study (Yu et al., 1998) examined the feasibility of using mitigated wetlands as stormwater BMPs. Two mitigated wetlands were evaluated and monitored during storm events. Wetland vegetation density and wildlife diversity were used as metrics of highway runoff impacts. Peak flow reduction for both sites was observed to be in excess of 40%. Removal rates for TSS, COD, total phosphorous, orthophosphate, and zinc were as high as 90%, 65%, 70%, 70%, and 50%, respectively. Vegetation and wildlife at the two sites were observed to be healthy and diverse. According to Knight et al. (1998), the Greens Bayou Wetland Mitigation Bank, implemented in cooperation with Texas DOT, also was intended to provide stormwater quality mitigation benefits. Approximately 220 acres of wetlands are included in the project. An intricate train of treatment was included as part of the design to provide multiple benefits such as highway runoff water quality improvement, flood flow retention, and the creation of wildlife habitat. This project will provide treatment for a significant portion of the additional flows resulting from the expansion of Beltway 8.

Larson and Neill (1987) examined three main biophysical elements of wetlands (hydrology, soils, and vegetation) in relation to artificial wetlands constructed in fulfillment of mitigation requirements. The importance of each of these elements to basic wetlands function was evaluated, and the data requirements for assessing the significance of each of the elements were defined. Hunt et al. (1999) discussed the use of an in-stream wetland for nitrogen removal in a contaminated stream. The authors concluded that in-stream wetlands are good landscape features that can be used to mitigate excess nitrogen and are a good complement to other BMPs.

3.5.9.1. Identification of Research Needs

Based on the review of literature, the potential highway runoff impacts on natural and mitigated wetlands appear to be well documented. The tendency for many highway runoff pollutants to accumulate in wetland sediments and vegetation raises some concern with regard to long-term impacts on wetland biota. Current regulatory requirements for monitoring and assessing impacts to existing wetlands ensure that water quality and sediment quality, as well as toxicity data, are and will continue to become available for analysis. However, as discussed in section 3.5.4, there is a general lack of applicable bioindicators for evaluating impacts associated with the episodic nature of stormwater runoff. A potential research need may be to develop indicators for assessing impacts to wetlands from highway runoff by conducting a detailed analysis of currently available data on wetlands receiving runoff from highway facilities.

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CHAPTER 4

SUMMARY OF IDENTIFIED RESEARCH GAPS AND NEEDS

The survey of state departments of transportation (DOTs) water quality practitioners and the review of available research and ongoing studies revealed several potential research gaps with regard to highway runoff water quality management and receiving waters impacts. Research categories were identified within the five main topic categories: Brief Review of Major Recent Syntheses of Highway Runoff/Urban Stormwater Quality Research, Evaluation of Stormwater Control Facilities and Programs, Watershed-Based Approaches, Highway Runoff Characterization and Assessment, and Receiving Waters Impact Assessment. Many of these research categories span two or more of the main topic categories, so they were combined for a total of 33 individual research categories in the final presentation of itemized research needs statements shown in Table 4-1.

The individual research categories have been ranked and sorted (on a scale from 1 to 5) according to DOT research preferences, results from the literature review, and opinions of professional investigators. The itemized research needs statements beneath each individual research category have been organized, in some cases according to the logical progression of research activities and in other cases according to the perceived priority of the research team. Based on the top-ranking research topic areas, 14 research project statements—including necessary tasks, timeline, and approximate budget—have been prepared and included in this report's Summary section.

TABLE 4-1 Ranked and sorted listing of identified gaps and needs in highway runoff water quality research

Itemized Research Needs	Ranking		
	DOT Ranking	Based on Literature Review	Research Team's Ranking
NCHRP Panel Recommended Research Needs	n/a		
Evaluation of the impacts and implication of TMDLs on DOTs			
BMP Maintenance and Longevity	5	5	5
Development of contract administration of BMP requirements and contractual methods to improve BMP implementation			
Compilation of BMP maintenance and lifetime effectiveness information			
Cost-benefit analysis of BMP maintenance practices			
Guidance for estimating life-cycle costs of BMPs that account for maintenance required for continually functioning and efficient BMPs			
Development of nationally applicable BMP operations and maintenance guidance (maintenance frequencies, logistics and personnel requirements, estimates based on influent characteristics and site conditions)			
Development of methods for increasing longevity and minimizing maintenance requirements of infiltration BMPs			
Evaluation of sediment toxicity as a function of maintenance frequency			
Evaluation of issues and methods of disposing or reusing BMP maintenance-generated wastes			
Evaluation of designs and maintenance of BMPs to reduce conflicts with endangered and threatened species			
Information Sharing and Technology Exchange Systems	4	5	5
Compilation of major syntheses of stormwater runoff research and guidance into a master bibliographic database			
Development of a stormwater runoff and BMP performance and design database specific to highways			
Development of an information sharing system for highway runoff research documents and monitoring data			
Identification and guidance of practical and accepted monitoring methods for highway runoff			
Watershed Planning	4	5	4
Development and evaluation of techniques to integrate transportation-related runoff analysis into overall watershed management			
Development of standard methods, models, and data for establishing critical needs within a watershed to prioritize areas for retrofit and BMP implementation			
Development of geomorphologic models for estimating watershed development impacts on receiving streams			
Quantification and development, or both, of indices and indicators of the contribution of state highway infrastructure relative to total impervious surface area in a watershed			
Evaluation of the ability of watershed or regionally based enhancements of wet weather storage capacity to improve baseline (high and low flow) hydrology and ecological productivity downstream			
Characterization on a watershed basis and the availability and prioritization of sites for constructed wetlands and wet ponds			
Demonstration of the costs and benefits of alternative/offsite/watershed-based stormwater mitigation			
Economic Analysis and Assessment of BMPs	5	4	5
Guidance on quantifying BMP lifecycle costs and benefits associated with receiving waters protection			
Evaluation of potential reductions in costs of stormwater treatment through alternative siting within the watershed			
Evaluation of the BMP benefits and constraints in highly urbanized corridors			
Cost comparisons of BMP treatment trains, distributed BMPs, and regional BMP systems			
Development of BMP cost estimation tools that account for land value, site constraints, construction, operations, and maintenance, as well as receiving waters protection, aesthetics, and infrastructure savings on conventional drainage structures			
Cost estimates for nonstructural BMPs			
General BMP Evaluation and Selection	4	4	4
Development of standard performance measures for BMP efficiency			
Development of an expert system for BMP selection and design			
Assessment of and design guidance for ultra-urban BMPs			

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TABLE 4-1 (Continued)

Itemized Research Needs	Ranking: DOT Ranking	Ranking: Based on Literature Review	Ranking: Research Team's Ranking
Low Impact Development (LID)/Distributed BMPs	4	4	4
Development of LID design strategies, performance standards, and specifications			
Documentation of LID's applicability, efficacy, and long-term economic sustainability for transportation systems			
Evaluation of the type of hydrologic losses that can be achieved under various climatic, soil, slope, and vegetation conditions			
LID modeling and design guidance for accurately sizing end-of-pipe control systems			
Development of methods and technologies to promote the reuse of stormwater			
Design Variables Affecting BMP Performance	3	5	4
Evaluation of design variables that are related to biochemical and geochemical treatment mechanisms			
Conduct of pilot-scale experiments that evaluate the relation of various design variables on BMP performance			
BMP Modeling	3	5	4
Evaluation of modeling approaches and guidance on model selection and application			
Pilot experiments to collect data needed for parameter estimation and model calibration			
Development of unit treatment models that incorporate sorption, biodegradation and uptake, photolysis, and volatilization			
Development of models for simulation of BMP treatment trains			
Development of BMP treatment models that account for treatment efficiency losses over time			
Development or evaluation of models that can be used for modeling pollution plumes in BMPs			
Hydraulic Assessment of BMPs	3	4	4
Evaluation of the characteristics and effects of short-circuiting, bypass, and overflow			
Evaluation of the nature of correlation between hydraulic residence time and performance			
Development of methods or models for estimating the true hydraulic residence in stormwater ponds			
Development of methods to optimize detention basin design to maximize treatment			
Methods to Improve Pollutant Removal in Existing Stormwater Systems	3	4	4
Cost–benefit analysis of alternative flood control retrofits with consideration of overall feasibility and potential impacts to flood control			
Risk assessment of alternative, less conservative flood control methods through the use of continuous runoff simulation modeling			
Development of detailed design guidance for flood control retrofits			
Evaluation of the effectiveness of BMP retrofits			
Development of recommendations for soil amendments for use in BMPs to passively improve performance			
Development of methods for improving and maintaining hydraulic conductivity of infiltration-based stormwater control facilities			
Evaluation of the effectiveness of combination of sedimentation, filtration, and chemical addition for stormwater BMP construction projects			
Evaluation of the potential impacts of coagulants to receiving waters			
Detailed guidance for areas that require coagulant use to meet water quality objectives			
Development of new technologies and improvements on existing designs to increase the removal of high-priority pollutants			
Sedimentation and Turbidity Impacts	3	4	4
Development of new exposure metrics that account for sublethal effects (as opposed to direct mortality)			
Examination of the effects of frequent short-term pulses of suspended sediment			
Need for additional research on correlations between particle size, shape, and composition of sediments to fish sensitivity			
Evaluation of the relationships between seasonal timing and effect of sediment load			
Evaluation of the applicability of the knowledge of fish survival responses to turbid flows to the development of mixing zones, work windows, treatment systems, and buffers that will allow fish to perform their necessary life functions during project construction and operation			
Identification of practical means of controlling turbidity			
Development of hydromodification measures (estimated downstream hydrological changes) and then measures for assessing potential downstream channel and bank instability.			

TABLE 4-1 (Continued)

Itemized Research Needs	Ranking: DOT Ranking	Ranking: Based on Literature Review	Ranking: Research Team's Ranking
Erosion and Sediment Control	4	3	3
Evaluation of the effectiveness of erosion controls at removing fine particulates			
Evaluation of the effectiveness of using polyacrylamides or other flocculants in conjunction with other sedimentation and erosion control practices			
Development of techniques to increase germination, soil coverage, and survival rates of native vegetation			
Evaluation and comparison of the different types of vegetation for riprap planting			
Research on the necessary "top elevation" for conventional riprap as a function of velocity, turbulence, and flow duration			
Comparison of terraced versus sloping riprap in terms of hydraulic performance and planted vegetation success			
Evaluation of alternative bank stabilization techniques that have a lesser effect on riparian and aquatic habitat than riprap			
Detailed inspection of riprap where vegetation is now growing or has grown, to better understand its impacts on bank stability			
Guidance for seed mixes and effective establishment and maintenance of erosion control vegetation for short-term first growth and long-term establishment			
Evaluation of potential water quality impacts of soil stabilizers used in erosion control			
Development of standard, approved postconstruction erosion control inspection and enforcement programs			
Evaluation of slope and soil conditions necessary for vegetation establishment			
Evaluation of new and innovative erosion control technologies			
Evaluation of erosion control methods for arid regions			
Evaluation of the performance of nonvegetative permanent soil stabilizers for reducing erosion and potential water quality impacts			
Development and evaluation of temporary nonvegetative soil stabilization techniques			
General Constituent Characterization of Highway Runoff	3	3	3
Characterization of chemical constituents not monitored generally, but believed to be present frequently in highway runoff			
Evaluation of representative methods for monitoring and analyzing oil and grease and total petroleum hydrocarbons			
Atmospheric Deposition	3	3	3
Studies that directly relate highways and transportation systems to atmospheric deposition			
Development of methods to evaluate the contribution of atmospheric deposition to highway runoff pollution			
Evaluation of the fractions of pollutants contributed by atmospheric deposition for different land uses and classes of contaminants			
First Flush Characterization	3	3	3
Adoption of a standardized method for defining and identifying first flush phenomena			
Development of a list of highway runoff pollutants that tend to exhibit a first flush			
Evaluation of toxicity of road surface runoff from different phases of a runoff event			
Correlation of toxicity with respect to pollutographs and hydrographs			
Evaluation of the effects of watershed characteristics on first flush phenomena			
Evaluation of BMPs designed to capture the first flush			
Impacts of Highway Construction and Vegetation Maintenance Activities	3	3	3
Standardization of suspended-sediment measurement and reporting methods			
Development of screening methods for assessing the quality of site soils on a grain-size basis as to determine the level of monitoring as well as sediment and erosion controls necessary to prevent impacts to receiving waters			
Herbicide runoff characterization and toxicity assessments			
Guidance on maintenance facility BMP design			
Development of guidance for fertilizer utilization for seeding and turf establishment near sensitive water bodies (nutrient runoff prevention)			
Equipment testing methods and performance assessment of mechanical and mechanical/vacuum sweepers			
Stream Crossings	3	3	3
Examination of the water quality effects of maintenance practices through field studies			
Development of bridge deck runoff quality constituents database			
Examination of the potential risks associated with hazardous materials spills			
Evaluation of how bridge design and average daily traffic affects runoff quality			
Assessment of potential receiving water temperature changes and mitigation			
Development and evaluation of BMPs and standards for abating receiving water temperature impacts			

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TABLE 4-1 (Continued)

Itemized Research Needs	Ranking: DOT Ranking	Ranking: Based on Literature Review	Ranking: Research Team's Ranking
Unit Treatment Processes	2	4	3
Characterization and evaluation of the fundamental treatment processes within different BMP types			
Pilot-scale experiments for the collection of data on unit treatment processes for various BMP types			
Compilation and assessment of available unit treatment processes data			
Research to obtain within storm data on BMP effectiveness to assess short-term pollutant issues and collect unit treatment processes information			
Evaluation of metals fractionation under anaerobic and anoxic conditions			
Development of the ability to accurately measure and analyze unit treatment processes			
Evaluation of BMP design and performance with respect to particle size distribution in stormwater runoff and associated metals			
Evaluation of the physical, chemical, and biological treatment processes of BMPs			
Toxicity and Bioassessment	2	4	3
Development of standardized toxicity and bioassessment methods for assessing impacts of highway runoff on receiving water systems			
Evaluation of the parts of storm events that are most toxic to receiving waters			
Assessment of BMP performance in terms of toxicity reduction or other biological impact indicator			
Guidance on BMP selection based on toxicity			
Evaluation of chemical, physical, and toxicity impacts to aquatic biota of stormwater discharges			
Evaluation of viral pathogen indicators and development of treatment options			
Fate and Transport of Highway Runoff Constituents	2	4	3
Identification of sediment sources and evaluation of transport rates and residence time of sediment in highway runoff, treatment facilities, and receiving waters			
Evaluation of sediment transport mechanics and blockage at inlets, junctions, and transitions in full and partly full conduits			
Comprehensive studies on the effects of soils, topography, land use, and various storm hydrographs on sediment yield			
Evaluation of nutrient leaching and the sorption and desorption processes of roadside soils			
Development of predictive models that consider runoff/storm relationships, particularly storm scour and redeposition			
Characterization of the bioavailable fraction of dissolved metals and trace organics in highway runoff			
Market-Driven Approaches: BMP Asset Management and Pollutant Trading	2	4	3
Research into the practicality of pollutant trading as a viable approach to highway runoff management			
Enhancement of maintenance management systems to facilitate asset management of BMPs			
Gross Pollutant Removal/Drain Inlet Studies	2	4	3
Evaluation of the effectiveness and limitations of source controls at reducing gross solids in highway runoff (e.g., public education, catch basin cleaning, and street sweeping)			
Development of a standard method for measuring and reporting gross solids and its components			
Development of modeling and estimation techniques for gross solids			
Evaluation of the impacts of gross solids in highway runoff			
Evaluation of leaching or sorption, or both, capacity of pollutants captured in catch basins			
Guidance on gross solid removal device design and performance			
Pollutant Retention in BMPs	2	3	3
Investigation of the potential for leaching or resuspension of previously captured pollutants			
Investigation of how changes in pH, oxidation-reduction potential, hardness, and organic content may affect desorption or dissolution, or both, of captured pollutants			
Assessment of the long-term ability of BMPs to keep pollutants sequestered			
Bioavailability of pollutants in the sediments of wet ponds and wetlands used for highway stormwater treatment			

TABLE 4-1 (Continued)

Itemized Research Needs	Ranking		
	DOT Ranking	Based on Literature Review	Research Team's Ranking
Water Quality Runoff Modeling	2	3	3
Forward-looking data collection efforts that focus more on new parameters that may be required by models of the future			
Development of hybrid models that take advantage of both stochastic and deterministic methods in order to produce models that have the benefits of both statistical and simulation-based models			
Adaptation of agricultural models for herbicide and pesticide modeling			
Extension and enhancement of existing models to simulate a wider range of contaminants			
Evaluation of the validity of build-up and washoff as a method of estimating pollutant loads			
Cold-Weather Studies	2	3	3
Guidance on monitoring roadside snow as well as snowmelt runoff			
Development of modeling methods for estimating snowmelt runoff events			
Evaluation of the performance and feasibility as well as maintenance issues of stormwater BMPs during cold weather			
Assessment of deicing agent and traction sand impacts on receiving water bodies			
Guidance on the management and storage of snow removed from urban highways to minimize impacts of snow storage area runoff			
Development of deicing agent selection criteria based on cost, effectiveness, and potential environmental impact			
Guidance and methods for applying the minimum amount of deicing chemicals and traction sand necessary to maintain safe road conditions			
Modeling of Water Quality Impacts to Receiving Waters	2	3	3
Need for research and data to support model parameter estimation			
Guidance on water quality model selection			
Development of stochastic water quality models			
Development of models that predict pollutant bioavailability and toxicity			
BMPs Vector Control	2	3	3
Evaluation of public health impacts of various stormwater management alternatives			
Evaluation of maintenance and design methods for controlling mosquitoes and other vectors in highway BMPs			
Runoff Characterization with Independent Variable Correlation	3	2	3
Better characterization of constituents associated with different-sized particles in highway runoff, particularly heavy metals, nutrients, and hydrocarbons			
Evaluation of statistically valid traffic volume-related studies			
Development of correlations between storm event intensity and duration with constituent levels			
Identification of statistically significant differences in concentrations in relation land use type alone			
Runoff quality characterization according to the various highway classifications (e.g., urban, rural, on-ramps, off-ramps, and total impervious area)			
Establishment of traffic thresholds beneath which certain pollutants in highway runoff can be considered negligible or irreducible			
Wetlands Impacts	3	2	3
Compilation and analysis of available water quality, sediment quality, and bioassessment data for wetlands receiving runoff from highway facilities			
Development of indicators for assessing impacts to wetlands from highway runoff by conducting a detailed analysis of currently available data on wetlands receiving runoff from highway facilities			
Public Perception/Aesthetics of BMPs	1	3	2
Conduct of public opinion surveys to assess the public's perception of stormwater management, in general, and BMPs, in particular			
Guidance on how to improve public perception of various types of BMPs			
Quantification of BMP impacts to property values and evaluation of methods to improve aesthetics and multiuse functionality			
Impacts of Highway Construction and Repair Materials	1	3	2
Compilation of properties data for highway construction and repairs materials			
Evaluation of the speciation, bioavailability, and toxicity of metals in highway construction material leachate			
Evaluation of the effects and influence of temperature on the leachings of pollutants from construction materials			
Evaluation of the capabilities of existing BMPs to mitigate impacts from highway construction material contamination			

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TABLE 4-1 (Continued)

Itemized Research Needs	Ranking: DOT Ranking	Ranking: Based on Literature Review	Ranking: Research Team's Ranking
Groundwater Quality Analysis and Impacts	2	2	2
Development of a standardized procedure for monitoring and assessing soil and groundwater impacts caused by infiltration facilities	2	2	2
Evaluation of the pollutant retention capacities of different soil types and geological conditions	2	2	2
Evaluation of the potential groundwater impacts of soluble highway runoff pollutants such as herbicides, nutrients, deicing agents, petroleum hydrocarbons (e.g., BTEX), and gasoline oxygenates	2	2	2
Determination of the sources of MTBE in groundwater	2	2	2
Development of approaches to addressing groundwater contaminants introduced to surface waters from dewatering operations	2	2	2
Development of infiltration guidance to prevent groundwater contamination	2	2	2
Water Quality Impacts of Combined Sewer Overflows (CSOs)	1	1	1
Hydraulic assessment of highway runoff contributions to CSOs impacts to receiving waters.	1	1	1
Better monitoring of CSOs effluent quality in relation to meteorological factors	1	1	1
Evaluation of the prevailing conditions or factors that increase or decrease CSOs impacts	1	1	1
Development and evaluation of practices (structural and nonstructural) to mitigate CSOs impacts	1	1	1

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APPENDIX A

STATE DEPARTMENT OF TRANSPORTATION SURVEY AND RANKING OF RESEARCH PREFERENCES

DEPARTMENT OF TRANSPORTATION WATER QUALITY MANAGEMENT, RESEARCH, AND RESEARCH NEEDS SURVEY

This survey, conducted by phone and online, combined two state-initiated efforts in process at the time and NCHRP 25-20(02) on water quality research and research needs. Department of Transportation (DOT) Research Directors contacted separately were asked to send water quality research performed or funded by their state DOT and to provide electronic copies or online links if available.

Venner Consulting combined the existing data, assisted the Virginia Transportation Research Center (VTRC) in completing their survey effort, and focused on reaching all 50 state DOTs for participation in Sections 2 through 8. These sections provide information most directly pertinent to NCHRP 25-20(02). At the same time, information was presented on the current state of knowledge about practice in each individual state to update and further complete this information. A large number of states contributed information in these other sections, facilitating related research efforts at VTRC and providing a basis for further research and information sharing pertaining to water quality best practices.

Manuals and Design Guidelines for Stormwater Management at DOT Facilities

(1.1) Do you have a Highway Runoff Manual?
(1.2) If so, please provide the web link or contact information for obtaining copies the Manual.
(1.3) Year updated: 1990–2003
(1.4) Has your DOT developed a set of design guidelines or protocols for stormwater management at non-highway DOT facilities?
(1.5) If so, please provide the web link or contact information for obtaining copies of such studies and/or reports.
(1.6) Year updated: 1990–2003
(1.7) Has your DOT developed a set of design guidelines or protocols for stormwater management during construction?
(1.8) If so, please provide the web link or contact information for obtaining copies of such studies and reports.
(1.9) Year updated: 1990–2003

Design Criteria

(1.10) What are your currently unaddressed needs in this area?
(1.11) If your agency has not developed such guidelines, who or what agency decides the design criteria to be used?
(1.12) Does your agency have any other manuals or resources that could be shared with other state DOTs?
(1.13) Comments

Research on Stormwater Impacts on Receiving Waters

(2.1) Has your agency performed any research on stormwater impacts on receiving waters?
(2.2) If so, please provide the web link or contact information for obtaining copies of such studies and reports.
(2.3) What are your most important unaddressed research needs in this area that would increase your ability to improve water quality?

Please express the priority your DOT would place on research in assessing stormwater impacts on receiving waters, and resultant decision-making related to stormwater management from 1 (low interest or priority) to 3 (high priority).

(2.4) Chemical, toxicity (level and causes), and physical (habitat) impacts to aquatic biota of stormwater discharges
(2.5) Role of total suspended solids and dissolved organic carbon in controlling concentrations of dissolved metals in stormwater runoff
(2.6) Herbicide runoff characterization (concentrations, transport and fate, impacts to aquatic biota)
(2.7) Water quality problems due to urbanization and heavy metal concentrations in relation to or projected from Total Connected Impervious Area in the watershed
(2.8) Threshold traffic densities below which certain pollutants in highway runoff can be considered negligible or irreducible and can be dispersed on roadsides
(2.9) Methodologies to determine where flow controls on runoff volumes and high flow durations are

appropriate to prevent streambank erosion in ultra-urban areas

(2.10) Ability of watershed or regionally based enhancements of wet weather storage capacity to improve baseline (high and low flow) hydrology and ecological productivity downstream
(2.11) Characterization on a watershed basis: availability or prioritization, or both, of sites for constructed wetlands
(2.12) Contribution of highway runoff to watershed loadings
(2.13) Receiving water temperature change reduction
(2.14) Other
(2.15) Suggested research needs related to impacts on receiving waters

Research on Stormwater Management Effectiveness

(3.1) Has your DOT conducted any studies or prepared reports that evaluate the effectiveness, efficiency, or performance of source control or treatment control stormwater management measures at DOT facilities?
(3.2) If so, please provide the web link or contact information for obtaining copies of such studies and/or reports.
(3.3) What are your most important unaddressed research needs in this area that would increase your ability to improve water quality?

Research on Stormwater Management Maintenance

(4.1) Has your DOT conducted any studies or prepared reports on the maintenance aspects of stormwater management measures at DOT facilities?
(4.2) If so, please provide the web link or contact information for obtaining copies of such studies and reports.
(4.3) What are your most important unaddressed research needs in this area that would increase your ability to improve water quality?

Research on Stormwater Management Retrofitting

(5.1) Has your DOT conducted any studies or prepared reports on the retrofitting of existing stormwater management measures at DOT facilities?
(5.2) If so, please provide the web link or contact information for obtaining copies of such studies and reports.
(5.3) What are your most important unaddressed research needs in this area that would increase your ability to improve water quality?

Research on Stormwater Efficiency during Construction

(6.1) Has your DOT conducted any studies or prepared reports on the design or efficiency of stormwater management measures during construction?
(6.2) If so, please provide the web link or contact information for obtaining copies of such studies and reports.
(6.3) What are your most important unaddressed research needs in this area that would increase your ability to improve water quality?

Research on Stormwater Maintenance during Construction

(7.1) Has your DOT conducted any studies or prepared reports on the maintenance aspects of stormwater management measures during construction?
(7.2) If so, please provide the web link or contact information for obtaining copies of such studies and reports.
(7.3) What are your most important unaddressed research needs in this area, which would increase your ability to improve water quality?

Please express the priority your DOT would place on research in the following areas from 1 (low interest or priority) to 3 (high priority).

(8.1) Technical feasibility of BMPs
(8.2) Construction costs of BMPs
(8.3) Construction BMP efficiencies
(8.4) Operations and maintenance costs of BMPs
(8.5) Valid monitoring methods
(8.6) Compliance with numeric water quality standards
(8.7) Methodology to quantify BMP benefits and costs
(8.8) Development of small footprint BMPs
(8.9) Performance of BMP retrofits/effectiveness (removing constituents of concern, hydraulic performance, export of elements to receiving waters)
(8.10) Effectiveness of combinations of sedimentation, filtration, and chemical addition for stormwater BMP construction and retrofit projects
(8.11) Selection of treatment BMPs and documentation of process
(8.12) Design and maintenance of BMPs to reduce mosquito and other vermin populations

(8.13) Design and maintenance of BMPs to reduce conflicts with endangered and threatened species.
(8.14) Viral pathogen indicators and treatment
(8.15) Detention basin design optimization
(8.16) Bypass detention basin design and effectiveness
(8.17) Gross solid removal device design and performance
(8.18) Physics and chemistry of BMP design
(8.19) Practical and effective ways to improve dissolved metal removal in current treatment systems
(8.20) Infiltration guidance to prevent groundwater contamination
(8.21) Toxicity controls
(8.22) BMP benefits and constraints in highly urbanized corridors
(8.23) Best methods for improving stream ecology through water quality BMPs, alternatives to regulating runoff in urban areas
(8.24) Demonstrating the costs and benefits of alternative/offsite/watershed-based stormwater mitigation
(8.25) Applicability and effectiveness of particular Low Impact Design (LID) methods in linear corridors/for transportation
(8.26) LID modeling and design so that end-of-pipe control systems can be accurately sized
(8.27) New erosion control technology evaluation
(8.28) Temporary non-vegetative soil stabilization evaluation
(8.29) Performance of non-vegetative permanent soil stabilizers for reducing erosion and potential impacts of products on stormwater quality
(8.30) Vegetation establishment
(8.31) Guidance for seed mixes and effective establishment and maintenance of erosion control vegetation for short-term first growth and long-term establishment.
(8.32) Arid region erosion control
(8.33) Soil evaluation process for slope vegetation
(8.34) Deicing agent selection criteria
(8.35) Traction sand removal BMPs for snow areas
(8.36) Other

Innovative Stormwater Management Practices

Does your DOT employ innovative stormwater management techniques and technologies at DOT facilities? Please check all that apply:

(9.1) Water Quality Inlets
(9.2) Constructed Wetlands
(9.3) Grassed/Vegetated Swales and Buffer Strips
(9.4) Wet Ponds
(9.5) Dry Ponds
(9.6) Wet Vaults/Tanks
(9.7) Dry Vaults/Tanks
(9.8) Porous/Permeable Pavement Designs
(9.9) Oil and Water Separators
(9.10) Silt Fences
(9.11) Infiltration Basin/Trench
(9.12) Sand Filter
(9.13) Low Impact Design (LID)
(9.14) Hydrodynamic Ultra-Urban BMPs
(9.15) Filtration Ultra-Urban BMPs (e.g., StormFilter Compost/Peat Filter; Storm Treat System; Austin, Texas, System)
(9.16) Natural Stream Channel Design and Stabilization (Including Bioengineering)
(9.17) Herbicide Alternatives for Roadside Vegetation Maintenance
(9.18) Trash
(9.19) Dry Weather Diversion
(9.20) Flocculating Agents
(9.21) Other

Stormwater Management Regulatory Compliance

(10.1) Is there a state stormwater management regulation in effect in your state which affects DOT projects?
(10.2) If so, please provide the web link or contact information for obtaining copies of the regulation.

What stormwater permitting requirements apply?

(10.3) NPDES: What stormwater permitting requirements apply?
(10.4) Construction: What stormwater permitting requirements apply?
(10.5) UIC: What stormwater permitting requirements apply?
(10.6) What other stormwater permitting requirements apply?
(10.7) Does your DOT assist municipalities in developing permits and complying with Phase II stormwater permits?
(10.8) If so, in what way?

Has your state completed an outfall inventory?

(11.1) In Phase I MS4 regulated areas?
(11.2) In Phase II MS4 regulated areas?
(11.3) MS4 areas plus other priority areas (e.g. near impaired/TMDL waters)?
(11.4) Statewide
(11.5) Comment

Stormwater quality practices that you use:

(12.1) Temporary Erosion Soil Control (TESC)
 (12.2) Describe
(12.3) Permanent stormwater facility
 (12.4) Describe
(12.5) Stormwater retrofit
(12.6) Stormwater monitoring
(12.7) Water quality BMPs in operations and maintenance

Alternative Mitigation

(13.1) Have you developed research or resources in the area of programmatic or other alternatives to project-specific mitigation, including means for establishing critical needs and priority mitigation projects on a watershed scale?
(13.2) If so, please provide the web link or contact information for obtaining copies of such studies and reports.
(13.3) What are your most important unaddressed research needs in this area that would increase your ability to improve water quality?

Alternative Mitigation/Stormwater Management Flexibility

(14.1) Onsite mitigation
(14.2) Offsite (within sub-basin)
(14.3) Offsite (within larger watershed)
(14.4) Alternative mitigation
(14.5) Stormwater banking
(14.6) Cross-category trading

Water Control Requirements

(15.1) Is your agency subject to water quality control requirements such as inches retained, detention times, buffer zones, etc?
(15.2) If yes, please describe these requirements.
(15.3) Is your agency subject to water quality requirements on additional flow beyond those in the previous question (such as additional requirements for treatment after detaining the first inch of runoff)?
(15.4) If yes, please provide details.
(15.5) What agency or permit dictates this requirement?
(15.6) Other comments or issues related to control requirements.

Rapid Aquatic Toxicity or Ecologic Impact Assessment

(16.1) Have you developed or are you using rapid aquatic toxicity or ecologic impact assessment of untreated highway runoff (hot spots) by using highway/receiving water/land use characteristics rather than through direct testing?
(16.2) If yes, please describe.

Are there any other issues or comments that you would like to include? If so, please include them below.

(17.1) Notes.

TABLE A-1 Research areas ranked according to priority by state DOTs

Research Areas Ranked in Priority by State DOTs					
RANK	Research Area	High Priority (3)	Mid-level Priority (2)	Low Priority (1)	SCORE
	WEIGHT	4	2	-1	
1	Operations and maintenance costs of BMPs	36	10	4	160
2	Construction BMP efficiencies	37	8	5	159
3	Technical feasibility of BMPs	30	14	6	142
4	Methodology to quantify BMP benefits and costs	27	17	6	136
5	Construction costs of BMPs	29	12	9	131
6	New erosion control technology evaluation	28	13	9	129
7	Threshold traffic densities below which certain pollutants in highway runoff can be considered negligible or irreducible and can be dispersed on roadsides	26	15	8	126
8	Contribution of highway runoff to watershed loadings	26	12	11	117
9	Development of small footprint BMPs	22	18	10	114
10	Performance of nonvegetative permanent soil stabilizers for reducing erosion and potential impacts of products on stormwater quality	23	15	11	111
11	Applicability and effectiveness of particular low impact development (LID) design methods in linear corridors/for transportation	19	19	9	105
12	Temporary nonvegetation soil stabilization evaluation	23	13	14	104
13	Valid monitoring methods	23	12	14	102
14	Demonstrating the costs and benefits of alternative/offsite/watershed-based stormwater mitigation	17	21	9	101
15	Performance of BMP retrofits/effectiveness (removing constituents of concerns, hydraulic performance, export of elements to receiving waters)	21	14	15	97
16	Best methods for improving stream ecology through water quality BMPs---alternatives to regulating runoff in urban areas	18	18	12	96
17	Vegetation establishment	20	15	15	95
18	BMP benefits and constraints in highly urbanized corridors	17	19	12	94
19	Selection of treatment BMPs and documentation of process	18	18	14	94
20	Detention basin design optimization	16	20	14	90
21	Effectiveness of combination of sedimentation, filtration, and chemical addition for stormwater BMP construction and retrofit projects	17	18	15	89
22	Guidance for seed mixes and effective establishment and maintenance of erosion control vegetation for short-term first growth and long-term establishment	20	13	17	89
23	Infiltration guidance to prevent groundwater contamination	18	15	16	86

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TABLE A-1 (Continued)

Research Areas Ranked in Priority by State DOTs					
RANK	Research Area	High Priority (3)	Mid-level Priority (2)	Low Priority (1)	SCORE
	WEIGHT	4	2	-1	
24	Methodologies to determine where flow control of runoff volumes and high flow durations are appropriate to prevent stream bank erosion in ultra-urban areas	14	21	12	86
25	Design and maintenance of BMPs to reduce conflicts with endangered and threatened species	17	15	18	80
26	Characterization on a watershed basis and the availability/prioritization of sites for constructed wetlands	14	19	14	80
27	Chemical, toxicity and physical impacts to aquatic biota of stormwater discharges	16	16	17	79
28	Role of total suspended solids and dissolved organic carbon in controlling dissolved metal concentration	14	15	11	75
29	Soil evaluation process for slope vegetation	13	20	17	75
30	Bypass detention basin design and effectiveness	13	19	17	73
31	LID modeling and design so that end-of-pipe control systems can be accurately sized	13	18	16	72
32	The ability of watershed or regionally based enhancements of wet weather storage capacity to improve baseline (high and low flow) hydrology and ecological productivity	13	18	18	70
33	Compliance with numerical water quality standards	14	15	21	65
34	Design and maintenance of BMPs to reduce mosquito and other vermin populations	15	12	23	61
35	Deicing agent selection criteria	14	13	23	59
36	Gross solid removal device design and performance	12	15	23	55
37	Water quality problems due to urbanization and heavy metal concentration in relation to or projected from total connected impervious area in the watershed	8	21	20	54
38	Practical and effective ways to improve dissolved metal removal in current treatment systems	9	19	22	52
39	Traction and removal BMPs for snow areas	12	12	26	46
40	Toxicity controls	7	20	22	46
41	Receiving water temperature change reduction	5	19	25	33
42	Herbicide runoff characterization	5	17	27	27
43	Physics and chemistry of BMP design	5	15	29	21
44	Arid region erosion control	10	5	34	16
45	Viral pathogen indicators and treatment	4	10	34	2

TABLE A-2 Potential pooled-fund research opportunities—states ranking each research area as a high or moderate-level priority

POTENTIAL POOLED-FUND RESEARCH OPPORTUNITIES		
RESEARCH AREA	**STATE DOTs with HIGH INTEREST**	**STATE DOTs with MODERATE INTEREST**
Chemical, toxicity (level and causes), and physical (habitat) impacts to aquatic biota of stormwater discharges	AK, AZ, CO, CT, DE, FL, HI, IN, MI, MO, NY, OH, OR, SD, TN, UT	AL, AR, CA, GA, IA, KY, MD, NC, NH, NV, OK, RI, SC, VA, VT, WA, WY
Role of total suspended solids and dissolved organic carbon in controlling concentrations of dissolved metals in stormwater runoff	AK, CO, CT, DE, FL, HI, IN, ME, NY, OH, RI, SC, UT, VT, WI	AL, CA, ID, KS, MA, MO, MI, NM, MT, NH, NV, OK, TX, VA, WA, WV
Water quality problems due to urbanization and heavy metal concentrations in relation to/projected from total connected impervious area in the watershed	FL, ID, KY, SC, UT, VA, WA	AK, AL, AR, CA, CO, CT, GA, HI, IL, LA, MI, MN, MO, MT, NC, NV, NY, OH, OK, OR, TN, WI
Threshold traffic densities below which certain pollutants in highway runoff can be considered negligible or irreducible and can be dispersed on roadsides	DE, FL, GA, HI, IL, IN, KY, ME, MI, MN, MO, MS, MT, NC, NJ, NV, NY, OH, OR, SC, SD, TN, TX, UT, VA, WA, WY	AL, CA, IA, KS, LA, MA, MD, NE, NH, OK, PA, RI, WI, WV
Methodologies to determine where flow controls on runoff volumes and high flow durations are appropriate to prevent streambank erosion in ultra-urban areas	AR, AZ, FL, KS, ME, MO, MS, NC, NY, OH, SC, TN, VA, VT	AK, AL, CA, CO, DE, HI, ID, IL, IN, KY, MI, MT, NJ, NM, NV, OK, OR, RI, TX, UT, WI
Ability of watershed or regionally based enhancements of wet weather storage capacity to improve baseline (high and low flow) hydrology and ecological productivity downstream	FL, ID, IN, KY, MD, ME, MO, MS, NV, NY, SC, VT, WI	AL, AR, AZ, CA, CO, DE, IA, LA, MT, ND, NJ, OH, OK, OR, TN, TX, VA, WV
Characterization on a watershed basis: availability/prioritization of sites for constructed wetlands	CO, FL, IA, ID, LA, MO, MS, MT, NV, NY, SC, VA, WV	AK, CA, GA, IN, KS, KY, MD, ME, MI, NC, NE, NH, NJ, NM, OH, OK, TX, UT, WA, WI
Contribution of highway runoff to watershed loadings	CA, CO, DE, FL, HI, ID, IN, KY, LA, ME, MI, MO, MT, NC, NH, NJ, OH, SC, SD, TN, TX, UT, VA, VT	AK, AL, IA, IL, MA, MD, ND, OK, OR, RI, WA, WI
Reduction in receiving water temperature change	ID, MD, ME, SC, VA	CA, FL, IN, KY, LA, MI, MN, MO, MT, NC, NJ, NY, OH, OK, OR, RI, TN, VT, WV
Technical feasibility of BMPs	AK, AZ, CA, CO, DE, FL, HI, ID, IN, LA, ME, MI, MS, MT, ND, NE, NH, NJ, NV, NY, OH, OK, OR, RI, SC, TN, TX, VA, WA, WY	AL, AR, GA, IL, KS, KY, MA, MN, MO, NC, NM, SD, UT, WI
Construction costs of BMPs	AL, CA, CO, FL, GA, HI, IN, KS, LA, MI, MN, MO, MS, MT, NC, ND, NE, NJ, NM, NV, NY, OH, OK, RI, SC, TX, VA, WA, WY	AK, AZ, IA, ID, IL, KY, NH, SD, TN, UT, VT, WI
Construction BMPs efficiencies	AK, AL, AZ, CA, CO, DE, FL, GA, HI, ID, IN, KS, KY, LA, MD, ME, MI, MN, MO, MS, MT, NC, NE, NH, NJ, NM, NV, NY, OH, OK, SC, SD, TN, UT, VA, VT, WY	IA, IL, MA, MI, ND, RI, TX, WA, WI

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TABLE A-2 (Continued)

POTENTIAL POOLED-FUND RESEARCH OPPORTUNITIES		
RESEARCH AREA	**STATE DOTs with HIGH INTEREST**	**STATE DOTs with MODERATE INTEREST**
Operations and maintenance costs of BMPs	AL, AZ, CA, CO, DE, FL, GA, HI, IN, KS, KY, LA, MD, MI, MN, MO, MS, MT, NC, ND, NE, NH, NJ, NM, NY, OH, OK, RI, SC, TX, UT, VA, VT, WA	AK, IA, ID, IL, MA, ME, OR, SD, TN, WI, WY
Valid monitoring methods	AL, CA, CT, DE, FL, HI, ID, KY, LA, ME, MN, MO, MS, ND, NE, NV, NY, OR, RI, TN, VA, WA	AL, CA, CT, FL, GA, HI, ID, LA, MN, MO, NV, NY, TN, UT, CO, DE, IN, KS, MD, ME, MI, MT, NC, ND, OH, OR, SD
Compliance with numeric water quality standards	AL, CA, CT, FL, GA, HI, ID, LA, MN, MO, NV, NY, TN, UT	CO, DE, IN, KS, MD, ME, MI, MT, NC, ND, OH, OR, SD
Methodology to quantify BMPs benefits and costs	AL, CA, DE, FL, ID, IL, IN, KY, MA, MD, ME, MI, MN, MS, MT, NC, ND, NV, NY, OH, SC, SD, TN, VA, VT, WI	AK, AR, AZ, CO, GA, HI, KS, LA, MO, NE, NH, NJ, OK, OR, TX, UT, WA
Development of small footprint BMPs	AL, CA, CO, FL, IL, IN, LA, MD, ME, MI, MN, NC, NJ, NY, OH, OR, SC, TN, TX, VA, WA	AR, GA, HI, ID, KS, KY, MA, MO, MS, MT, ND, NE, NH, NY, OK, SD, UT, VT
Performance of BMPs retrofits/effectiveness (removing constituents of concern, hydraulic performance, export of elements to receiving waters)	AL, CA, DE, FL, ID, IN, LA, MD, MN, MO, NC, NH, NY, OH, RI, SD, TN, UT, VA, WA	AK, CO, HI, KS, KY, MA, MI, MS, MT, ND, NE, NJ, OK, SC
Effectiveness of combinations of sedimentation, filtration, and chemical addition for stormwater BMPs construction and retrofit projects	AL, CA, FL, HI, ID, IN, LA, MN, MO, ND, NE, NH, NY, OK, TN, VA	AK, AR, CA, CO, DE, GA, KS, KY, ME, MT, NC, NJ, OH, SC, SD, UT, VT, WA, WI
Selection of treatment BMPs and documentation of process	AK, CA, CO, FL, ID, IN, LA, ME, MI, MN, MS, NC, NJ, NY, OH, RI, TN, VA	AL, DE, GA, HI, IL, KY, MA, MO, ND, NE, NH, NV, OK, SC, SD, UT, VT, WI
Design and maintenance of BMPs to reduce mosquito and other vermin populations	AL, FL, LA, MN, MO, NE, NJ, NV, NY, OR, RI, SD, TN, VA	AR, CA, CO, DE, IN, MA, MD, MI, NC, ND, OH, WA
Design and maintenance of BMPs to reduce conflicts with endangered and threatened species	FL, GA, ID, LA, MN, MO, MS, NE, NJ, NY, RI, SC, SD, TN, VA, WA	AK, AL, CA, CO, IN, KS, KY, MD, MI, ND, NV, OK, OR, UT, WI, WY
Viral pathogen indicators and treatment	CA, LA, SC, VA	AL, KS, MI, NC, NJ, TN, UT, WY
Detention basin design optimization	AZ, CA, FL, GA, ID, IN, KY, MN, MO, NE, NY, OK, SC, TN, TX, VA	AK, AL, CO, IA, KS, LA, NC, ND, NH, NJ, NM, NV, OH, RI, SD, UT, WA, WI, WV
Bypass detention basin design and effectiveness	CA, FL, ID, IN, KY, MN, NE, NY, OK, SC, TN, TX, VA	AK, AL, AR, CO, GA, KS, LA, MO, NC, ND, NJ, NM, NV, OH, SD, UT, WA, WV
Gross solid removal device design and performance	CA, CO, CT, DE, FL, MI, MO, ND, NV, NY, UT, VA	AK, AL, HI, KS, KY, MA, MN, NE, NA, NJ, OH, SC, WA, WI

TABLE A-2 (Continued)

POTENTIAL POOLED-FUND RESEARCH OPPORTUNITIES		
RESEARCH AREA	**STATE DOTs with HIGH INTEREST**	**STATE DOTs with MODERATE INTEREST**
Physics and chemistry of BMPs design	CA, FL, KY, MO, VA	AK, AL, ID, IN, MI, NC, NE, NH, NJ, NV, NY, OR, SD, TN
Practical and effective ways to improve dissolved metal removal in current treatment systems	CA, DE, MN, MO, NH, NV, NY, VA, WA	AK, AR, AZ, CA, CO, FL, ID, IN, KS, LA, NC, ND, OH, OK, RI, SC, TN, UT, WV
Infiltration guidance to prevent groundwater contamination	AK, AR, AZ, CA, FL, HI, ME, MI, MN, NJ, NV, NY, OH, OR, RI, TN, VA, WA	AL, CO, IN, KS, MA, MO, ND, NH, OK, SC, SD, UT, WI, WV
Toxicity controls	CA, MO, NY, TN, UT, VA	AK, AR, CO, DE, HI, IN, KS, LA, MI, MN, ND, NH, NV, OH, OR, SC, TX, WA, WI, WV
BMPs benefits and constraints in highly urbanized corridors	CO, FL, HI, MD, MI, MN, NJ, NY, OH, OK, RI, SC, TX, UT, VA, WA	AL, AR, AZ, CA, CT, DE, FL, GA, IA, ID, IL, IN, KS, KY, LA, ME, MO, NC, VT, WI
Best methods for improving stream ecology through water quality BMPs—alternatives to regulating runoff in urban areas	AK, DE, FL, GA, KY, LA, ME, MI, MO, NY, RI, SC, SD, TX, VA, WA, WV	AZ, CO, HI, IL, IN, KS, MD, MN, MS, NC, ND, NH, NJ, NV, OH, OK, VT, WI
Demonstrating the costs and benefits of alternative/off-site/watershed-based stormwater mitigation	AK, AR, AZ, CO, GA, KY, MD, MN, MS, NH, NJ, NY, OH, SC, SD, VA, VT, WA	AL, FL, HI, ID, IN, KS, LA, ME, MO, NC, ND, NE, NV, OK, RI, TN, TX, UT, WI, WV
Applicability and effectiveness of particular low impact development design (LID) methods in linear corridors/for transportation	AK, AR, AZ, CO, CT, FL, HI, IN, MD, ME, MO, NJ, NY, OH, SC, TN, TX, VA, WA	AL, DE, GA, ID, KS, KY, LA, MN, NC, ND, NE, NH, OK, SD, UT, VT, WV, WY
LID modeling and design so that end-of-pipe control systems can be sized accurately	AK, CO, CT, HI, IN, MD, NE, NJ, NY, OH, SC, VA, WA	AL, DE, FL, GA, ID, KS, KY, LA, ME, MN, MO, NC, ND, OR, TN, TX, VT
New erosion control technology evaluation	AK, CA, CO, DE, FL, GA, HI, IA, ID, LA, MI, MN, MO, MS, MT, ND, NE, NH, NJ, NV, NY, OK, SC, TN, TX, VA, WY	AL, IL, IN, KS, KY, MA, ME, NM, OR, RI, UT, WA
Temporary nonvegetative soil stabilization evaluation	AK, CA, CO, DE, FL, GA, HI, ID, IN, LA, MN, MT, NC, ND, NH, NV, NY, OK, SC, TN, TX, VA	AZ, FL, IA, KY, ME, MI, MO, NE, NJ, NM, OR, RI, SD, UT, WY
Performance of nonvegetative permanent soil stabilizers for reducing erosion and potential impacts of products on stormwater quality	AK, AZ, CA, CO, FL, HI, ID, LA, MN, MO, MT, NC, ND, NJ, NV, OK, OR, SC, SD, TN, TX, VA	AL, AR, DE, FL, GA, IA, IN, KY, ME, MI, NE, NH, RI, UT, WV, WY
Vegetation establishment	AK, CA, CO, FL, HI, ID, IN, KY, LA, ND, NE, NV, NY, OK, RI, SC, SD, UT, VA	AL, AZ, DE, GA, IA, IL, KS, MT, NM, OH, OR, TN, TX, VT, WI
Guidance for seed mixes and effective establishment and maintenance of erosion control vegetation for short-term first growth and long-term establishment.	AK, CA, FL, GA, IA, ID, IN, KY, LA, ND, NV, NY, OK, OR, RI, SC, SD, TN, VA	AZ, CA, CO, DE, HI, IL, KS, MO, NE, NM, OH, TX, UT, VT

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TABLE A-2 (Continued)

POTENTIAL POOLED-FUND RESEARCH OPPORTUNITIES		
RESEARCH AREA	**STATE DOTs with HIGH INTEREST**	**STATE DOTs with MODERATE INTEREST**
Arid region erosion control	AK, AZ, CA, ID, MT, NV, OK, OR, SD, UT, WY	CO, HI, NE, NM, WA
Soil evaluation process for slope vegetation	AK, AZ, CA, FL, GA, IK, KY, MN, MT, NY, SC, SD, VA, WY	CO, HI, IA, IN, KS, LA, MI, MO, ND, NH, NM, NV, OH, OK, OR, TN, UT, WI, WV
Deicing agent selection criteria	AK, CA, CO, CT, ID, IN, ME, MO, NH, NY, OH, SD, UT, VA, WY	AZ, DE, HI, IA, IL, KY, MI, NV, OR, RI, TN, WI
Traction sand removal BMPs for snow areas	AK, CA, CO, CT, ID, IN, NV, NY, SD, UT, VA, WY	AZ, DE, IA, IL, MA, MI, MT, NH, OR, RI, TN WI

APPENDIX B

BRIEF LISTING OF GUIDELINES AND PROTOCOLS FOR HIGHWAY RUNOFF CHARACTERIZATION AND MANAGEMENT

This appendix describes manuals that provide guidance on monitoring highway runoff, designing stormwater control facilities or programs, evaluating BMP performance, or general stormwater management. This is not an attempt to include all available guidance manuals relevant to highway runoff characterization and management, but rather to provide a list of some of the more recent and comprehensive documents that can be used by highway stormwater professionals. Note that some documents span multiple subject areas and therefore may be listed more than once.

B.1 GENERAL STORMWATER MANAGEMENT AND REGULATORY POLICIES GUIDANCE

Water Quality Standards Inventory Database

The database consists of water quality objectives (numeric or narrative limits) and beneficial uses that have been established by each Regional Board for California surface waters. http://endeavor.des.ucdavis.edu/wqsid

Screening Quick Reference Tables

NOAA has developed a set of Screening Quick Reference Tables (SQuiRTs) that present screening concentrations for inorganic and organic contaminants in various environmental media. The SQuiRTs also include guidelines for preserving samples and analytical technique options. http://response.restoration.noaa.gov/cpr/sediment/squirt/squirt.html

National Environmental Methods Index (NEMI)

The tool is a free web-based online clearinghouse of environmental monitoring methods. The NEMI database contains chemical, microbiological and radiochemical method summaries of lab and field protocols for regulatory and non-regulatory water quality analyses. It is searchable over the World Wide Web, providing up-to-date methods information through a standard Internet connection and browser. By visiting http://www.nemi.gov users can access directly current methods information. In the future, NEMI will be expanded to meet the needs of the monitoring community. For example, biological methods will be added to NEMI, along with additional field and laboratory methods of importance to the monitoring community.

Sediment Toxicity Testing Methods and Data Interpretation Bibliography

This resource lists select literature dealing with sediment: (1) toxicity testing, (2) bioaccumulation, (3) sediment quality triad, and (4) sediment quality guidelines. It was prepared for a presentation on "Sediment toxicity testing methods, and data interpretation," National Environmental Contaminants meeting of the U.S. Fish and Wildlife Service, Big Cedar Lodge, Missouri, Monday, April 12, 1999; Chris Ingersoll, Columbia Environmental Research Center, USGS, Columbia, MO, chris_ingersoll@usgs.gov; Don MacDonald, MacDonald Environmental Sciences, Ltd., Ladysmith, British Columbia, sff-mesl@island.net. http://www.cerc.cr.usgs.gov/pubs/sedtox/sedbib.htm

B.2 HIGHWAY RUNOFF MONITORING

USGS. (2003). "National Highway Runoff Water-Quality Data and Methodology Synthesis, Volume I—Technical Issues for Monitoring Highway Runoff." Final Report to the Federal Highway Administration, Granato, G. E., Zenone, C. and Cazenas, P. A., eds., FHWA-EP-03-054, 479 pp.

Strecker, E., Mayo, L., Quigley, M., and Howell, J. (2001). "Guidance Manual for Monitoring Highway Runoff Water Quality." Final Report to the Federal Highway Administration. FHWA-EP-01-022.

Granato, G. E., Driskell, T. R., and Nunes, C. (2000). "CHEMICAL HELP—A Computer Help Application for Classification and Identification of Stormwater Constituents." U.S. Geological Survey Open-File Report 00-468, 10 p. http://ma.water.usgs.gov/FHWA/products/ofr00468.pdf

Granato, G. E., and Tessler, S. (2000). "Data Model and Relational Database Design for Highway Runoff Water-Quality Metadata." U.S. Geological Survey Open-File Report 00-480, 15 pp.

Caltrans. (2000). "Guidance Manual: Stormwater Monitoring Protocols." CSTRW-RT-00-005. http://www.dot.ca.gov/hq/env/stormwater/special/index.htm

U.S. EPA. (1992). "NPDES Storm Water Sampling Guidance." EPA 833-B-92-001. http://www.epa.gov/npdes/pubs/owm0093.pdf

B.3 STORMWATER CONTROL FACILITIES AND PROGRAMS: DESIGN, OPERATIONS, MAINTENANCE, AND MONITORING

Federally Sponsored Stormwater BMP Manuals

FHWA. (2000). Stormwater Best Management Practices in an Ultra-Urban Setting: Selection and Monitoring. FHWA-EP-00-002.

Schueler, T. (1987). Controlling Urban Runoff—A Practical Manual for Planning and Designing Urban Best Management Practices. Metropolitan Washington Council of Governments. Washington, D.C., 240 pp.

ASCE/EPA. (2002). Urban Stormwater BMP Performance Monitoring: A Guidance Manual for Meeting the National Stormwater BMP Database Requirements. EPA 821-C-02-005.

Caraco, D. and Claytor, R. (1997). Stormwater BMP Design Supplement for Cold Climates. Prepared by the Center for Watershed Protection for the U.S. EPA. http://www.cwp.org/cold-climates.htm

FHWA. (2002). Roadside Use of Native Plants. http://www.fhwa.dot.gov/environment/rdsduse/index.htm

State-Sponsored Stormwater BMP Manuals

The U.S. EPA Region 10: The Pacific Northwest provides web links to stormwater BMP manuals from various state agencies:

http://yosemite.epa.gov/R10/WATER.NSF/0/17090627a929f2a488256bdc007d8dee?OpenDocument

The documents below are a few of the most comprehensive and highway-relevant state BMP manuals.

California
California Stormwater Quality Association Stormwater BMP Handbooks
http://www.cabmphandbooks.com

Los Angeles Stormwater Program (click "Publications")
http://www.lastormwater.org

California Department of Transportation (Caltrans) Stormwater Quality Handbooks
http://www.dot.ca.gov/hq/construc/stormwater.html

Stormwater Quality Handbook—Project Planning and Design Guide
http://www.dot.ca.gov/hq/oppd/stormwtr/index.htm

Georgia
Georgia Stormwater Management Manual
http://www.georgiastormwater.com

Maine
Environmental Office Erosion and Sedimentation BMP Manual
http://www.state.me.us/mdot/contractor-consultant-information/pdf/bmprevision90602.pdf

Maryland
Maryland Stormwater Design Manual, Volumes I and II
http://www.mde.state.md.us/Programs/WaterPrograms/SedimentandStormwater/stormwater_design/index.asp

Massachusetts
Massachusetts Department of Environmental Protection Stormwater Handbooks
http://www.state.ma.us/dep/brp/stormwtr/stormpub.htm

Michigan
DEQ Index of BMPs/Individual BMPs
http://www.michigan.gov/deq/1,1607,7-135-3313_3682_3714-13186—,00.html

Minnesota
Protecting Water Quality in Urban Areas: A Manual
http://www.pca.state.mn.us/water/pubs/sw-bmpmanual.html

Urban Small Sites Best Management Practice Manual
http://www.metrocouncil.org/environment/watershed/bmp/manual.htm

Missouri
Protecting Water Quality: A Construction Site Water Quality Field Guide
http://www.dnr.state.mo.us/wpscd/wpcp/wpcp-guide.htm

Montana
Montana Department of Water Quality—Stormwater Program—BMPs and Erosion Control Plans
http://www.deq.state.mt.us/pcd/wpb/erosion.htm

New Hampshire
Innovative Stormwater Treatment Technologies Best Management Practices Manual
http://www.des.state.nh.us/wmb/was/manual

New Jersey
Revised Manual for New Jersey: BMPs for Control of Nonpoint Source Pollution from Stormwater
http://www.state.nj.us/dep/watershedmgt/bmpmanual.htm

New York
New York State Stormwater Management Design Manual
http://www.dec.state.ny.us/website/dow/swmanual/swmanual.html

North Carolina
http://h2o.enr.state.nc.us/su/Manuals_Factsheets.htm

North Carolina Dept. of Environment and Natural Resources
http://h2o.enr.state.nc.us/su/Manuals_Factsheets.htm

Ohio
http://www.epa.state.oh.us/dsw/storm

Oregon
http://www.deq.state.or.us/wq/wqpermit/wqpermit.htm

Pennsylvania
Pennsylvania Department of Environmental Protection
http://www.dep.state.pa.us/dep/deputate/watermgt/WC/subjects/StormwaterManagement/JustReleased.htm

South Carolina
http://www.scdhec.net/water/html/swnpdes.html
http://www.scdhec.net/water/html/erfmain.html

Tennessee
http://www.state.tn.us/environment/wpc
http://www.ci.knoxville.tn.us/engineering/bmp_manual

Texas
http://www.txnpsbook.org/SiteMap.htm

Utah
http://www.deq.state.ut.us/EQWQ/updes/stormwater.htm
http://www.ci.west-valley.ut.us/pworks/storm%20water%20utility/bmp3.htm

Virginia
Northern Virginia Regional Commission
http://www.novaregion.org/es_pubs.htm#bmp

Virginia Department of Conservation and Recreation
http://www.dcr.state.va.us/sw/e&s-ftp.htm

Washington
http://www.ecy.wa.gov/programs/wq/stormwater/manual.html#copies
http://www.wsdot.wa.gov/fasc/engineeringpublications/library.htm#H
http://dnr.metrokc.gov/wlr/Dss/Spcm.htm

Wyoming
http://deq.state.wy.us/wqd/watershed/92171.pdf State Storm Water BMP Manuals

B.4 WATERSHED PLANNING

Water Quality Trading Assessment Handbook
http://yosemite.epa.gov/R10/OI.NSF/Effluent+Trading/ET

U.S. EPA National Water Quality Trading Website
http://www.epa.gov/OWOW/watershed/trading.htm

A Watershed Approach to Urban Runoff: Handbook for Decisionmakers Guide
http://www.ctic.purdue.edu/CTIC/Catalog/WatershedManagement.html

B.5 ASSESSMENT OF RECEIVING WATER IMPACTS AND RESTORATION

Stormwater Effects Handbook: A Toolbox for Watershed Managers, Scientists, and Engineers
http://www.epa.gov/ednnrmrl/publish/book/handbook

Restoration of Urban Streams: Practical Evaluation of Options for 319(h) Funded Projects Urban Stream Restoration Field Manual
http://www.state.nj.us/dep/watershedmgt/DOCS/Restoration%20of%20Urban%20Streams.pdf

Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation