TR NEWS

July–August 2020 NUMBER 328

Stormwater

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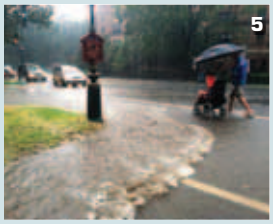

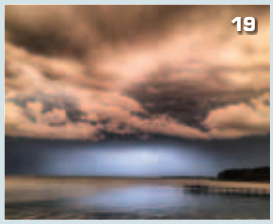

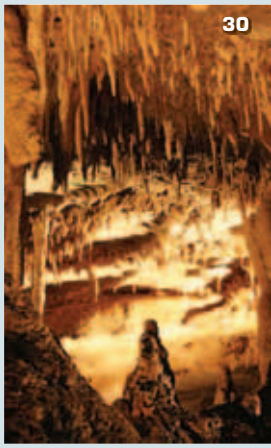

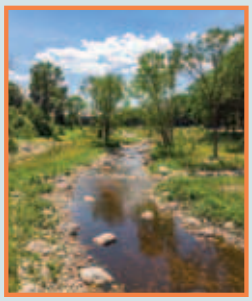

COVER More than 4,000 linear feet of concrete once lined Underwood Creek in Wauwatosa, Wisconsin. But, when the gray infrastructure failed to control flooding, the Milwaukee Metropolitan Sewerage District naturalized the creek using vegetation and bioengineering. Today, flood risk is reduced, biodiversity—including enhanced aquatic habitat—is improved, and Underwood Creek is reconnected to its flood plain. (Photo: Milwaukee Metropolitan Sewerage District)

TRB COVID-19 Resources

Agencies and organizations can use TRB publications and online resources for useful and timely information to help address issues related to the novel coronavirus pandemic. To read about TRB's current research and activities, and for a list of relevant publications, visit www.nationalacademies.org/trb/blog/transportation-in-the-face-of-communicable-disease.

Coming Next Issue

The September–October 2020 issue of *TR News*, "Embracing the Future," celebrates TRB's centennial with articles forecasting the future of transportation. Authors present outlooks that are multimodal, creative, diverse, inclusive, and thought-provoking, offering a pause point for transportation researchers, policy makers, and practitioners as they contemplate new directions for transportation.

TR NEWS

features articles on innovative and timely research and development activities in all modes of transportation. Brief news items of interest to the transportation community are also included, along with profiles of transportation professionals, meeting announcements, summaries of new publications, and news of Transportation Research Board activities.

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Stormwater

Photo: Jim Ecklund, National Park Service

SCOTT TAYLOR AND WENDY TERLIZZI

Taylor is Vice President, Michael Baker, Carlsbad, California; past chair, TRB Standing Committee on Stormwater; and cochair, TRB Standing Committee on Hydrology, Hydraulics and Stormwater. Terlizzi is Environmental Services Manager, Idaho Transportation Department, Boise, and member, TRB Standing Committee on Hydrology, Hydraulics, and Stormwater.

Above: Moss-covered boulders flank the flow of a small cascade on Alberta Falls Trail in the Colorado section of Rocky Mountain National Park. Water quality is relatively high in the Rockies compared with much of the United States, but excess aerial nitrogen deposits to lakes and streams threaten the ability of water to run clean and clear.

The importance of water cannot be overstated. Over the next several decades, how we use and reuse water will change dramatically—enabled through technology and required by necessity. This special issue of *TR News* is dedicated to water and to the role of state departments of transportation (DOTs) in the stewardship of this resource. It explores the evolution of stormwater regulation; how state DOTs manage water in planning, design, construction, and operations; total maximum daily load requirements for state DOTs; and more.

Less than 1% of water on Earth is fresh and easily accessible. Here are some other facts about water, compiled by the Pacific Institute (*1*):

- The amount of anthropogenic wastewater produced annually is approximately six times greater than the amount of water that exists in all the world's rivers.
- Poor countries with access to clean water and sanitation services have experienced faster economic growth than those without.
- Sanitation and drinking water investments have high rates of return: for every $1 invested, there is a projected $3–$34 return in economic development.
- Nitrate, an agricultural fertilizer, is the most common chemical contaminant in the world's groundwater aquifers.

> Thousands have lived without love,
> not one without water.
>
> W. H. Auden

Photo: Washington State DOT

Crews from the Washington State DOT confer on a stormwater detention vault installation at the intersection of 1st Avenue South and South Atlantic Street in Seattle. The underground structure manages excess runoff from developed areas.

Photo: hasan-cilingir, Pixabay

Stormwater picks up contaminants in urban areas. Traffic adds dirt, exhaust particulates, motor oil, and heavy metals to runoff, an urban broth that then flows into drainage systems on its way to receiving waters—often with no treatment.

State DOTs must ensure that pollutants do not come in contact with stormwater in the right-of-way; manage stormwater runoff volume and peak flow; and protect coastal, riverine, and lake waters and habitats, all to the maximum extent practical. On an average annual basis, state DOTs discharge an estimated 8 million acre-feet of runoff from their rights-of-way—worth about $11 billion, using California wholesale water rates. Historically, nutrients have been among the most important pollutants in surface waters, but emerging contaminants such as microplastics (tire wear), per- and polyfluoroalkyl substances, and pesticides are ubiquitous and will be difficult to manage for the foreseeable future.

Water is a valuable resource that merits our protection. Read on to understand how state DOTs are protecting and preserving water. Actions to protect water quality within a state DOT and working with other stakeholders in each state are vital to the promotion of sustainable water resources.

REFERENCE

1. World Water Quality Facts and Statistics. Pacific Institute, March 22, 2010.

The *TR News* Editorial Board thanks Nelson Gibson, Transportation Research Board, for his work assembling and developing this issue.

CENTENNIAL QUOTE

"As an African-American woman, my 30-plus years of experience in the transportation industry enable me to make a difference in the lives of those who are transit dependent and who reside in minority communities, marginal communities, or both. When I sit on TRB panels or speak on various transportation organization panels, I am often the only voice who can address issues of the transit-dependent community. Given that reality, my contributions—as they relate to decision making—impact and shape how our industry plans and moves with the new mobility agenda for transportation in the future.

—MARION JANE COLSTON
Senior Director, Strategic and Organizational Planning,
Los Angeles County Transportation Authority,
Los Angeles, California

HISTORY OF REGULATION OF STORMWATER RUNOFF FROM TRANSPORTATION

Photo: Lynette Batt

BRIAN K. CURRIER

The author is Research Engineer, Office of Water Programs, California State University, Sacramento.

Above: Rushing stormwater forces pedestrians to take to the street in a Washington, D.C., neighborhood. Two-thirds of the District is served by separate systems consisting of two independent piping systems: one for stormwater and the other for household and business sewage. The remaining one-third of the District is served by a combined sewer system developed before 1900.

Regulation of stormwater runoff dates back to the 1970s, but even earlier environmental regulations affected transportation projects as well (Figure 1). The Rivers and Harbors Act of 1899 established federal protection of navigable waters, but its impacts were limited mostly to projects that could directly impede navigation in coastal areas. Some noteworthy attempts at controlling pollution from industrial processes and sanitary sewage were attempted in the 1940s, 1950s, and 1960s, but it was the passage of the 1972 amendments to the 1948 Federal Water Pollution Control Act—commonly known as the Clean Water Act (CWA)—that prompted dramatic improvements in water quality.

CWA established the basic structure for regulating pollutant discharges into waters of the United States and established the National Pollutant Discharge Elimination System (NPDES), which required permits

Photo: James Thomas

Black smoke roils skyward as Cleveland's Cuyahoga River blazed in 1952—and not for the first time. Such fires—fueled by factory waste and agricultural field runoff—helped shape future environmental protection policies in the United States.

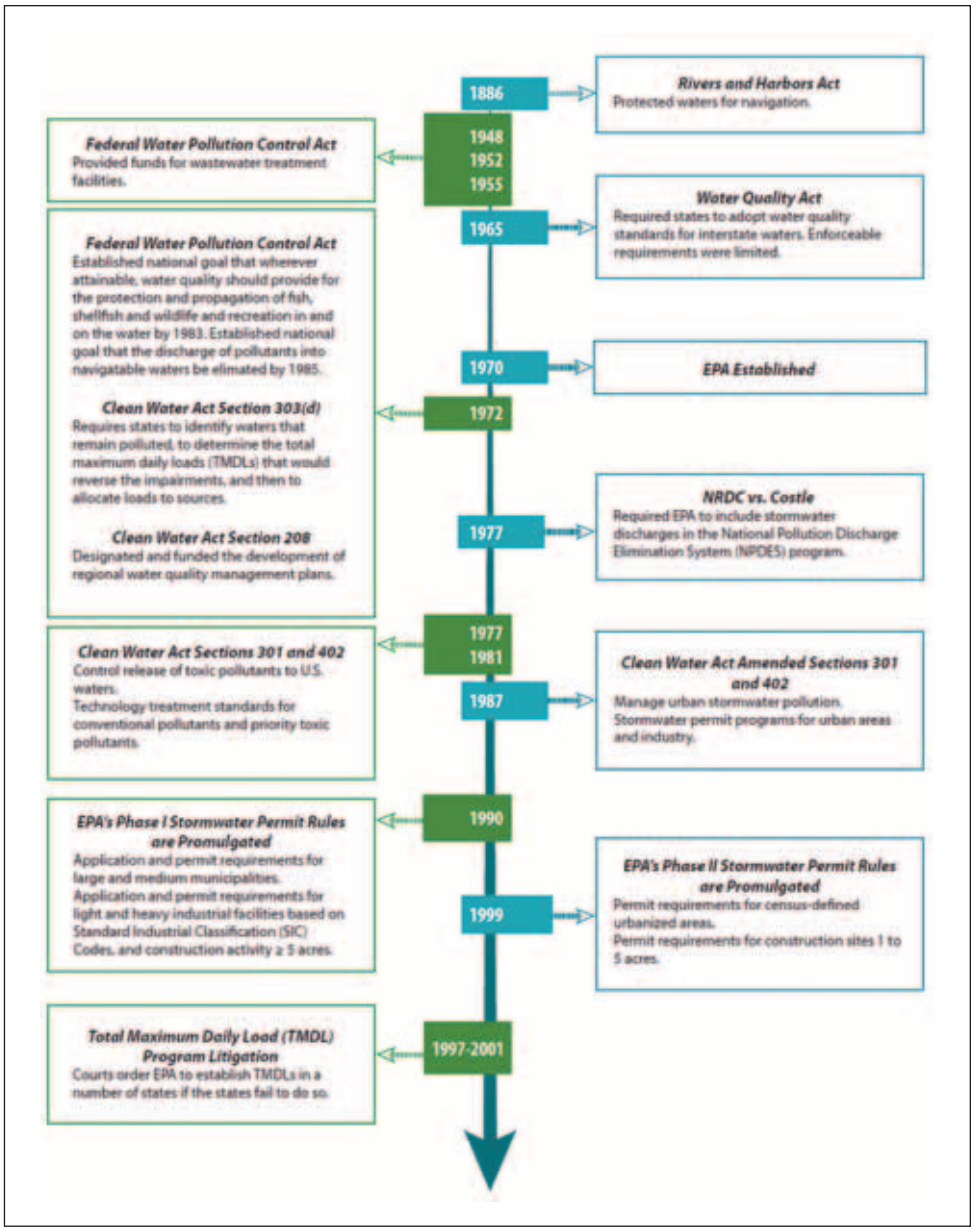

FIGURE 1 Timeline of water protection legislation since 1886.

for discharges of pollutants from point sources into navigable waters. In addition to requiring treatment of sanitary and industrial waste streams before discharge, this landmark legislation made permit requirements federally enforceable, added stricter requirements and timelines, and allowed third-party lawsuits.

The U.S. Environmental Protection Agency (EPA) categorically excluded stormwater from NPDES regulation; however, a 1977 U.S. Court of Appeals D.C. Circuit ruling in *National Resources Defense Council v. Costle* held that stormwater could not be categorically exempted from regulation (*1*).

From 1978 through 1983, EPA completed the National Urban Runoff Program (NURP), which was the first comprehensive assessment of the impacts of urban runoff and the identification of best management practices for minimizing pollutant discharge. In 1987, informed by the recently completed NURP study, Congress modified CWA via the Water Pollution Control Act to expand the NPDES program in two distinct phases to require permits for several categories of stormwater discharges.

As a result, in 1990 EPA promulgated stormwater regulations, commonly referred to as the "Phase I" stormwater rule, for large- and medium-sized municipal separate stormwater sewer systems (MS4s)—serving populations of 100,000 and more—and industrial activities. After completing a required Report to Congress on the remaining sources of stormwater pollution, EPA added permitting regulations in 1999 for small MS4s [operating in U.S. Census–defined "urbanized areas," including nontraditional MS4s such as departments of transportation (DOTs)] and small construction sites; this was commonly referred to as the "Phase II" rule.

Regulating State Departments of Transportation

For the Phase I MS4 regulations, state DOTs first were regulated as co-permittees with municipalities, but many permit requirements for municipal operators were not written with the unique characteristics of state DOTs in mind. More recently, some state DOTs received individual permits while other state DOTs were regulated as small, nontraditional MS4s under the 1999 Phase II stormwater rules. And at least one state holds both Phase I and Phase II permits (*2*).

These federal permits are not always issued by federal agencies because many states have received authorization to issue NPDES permits (Figure 2). NPDES permit requirements are implemented and enforced by those states, but EPA and the U.S. Army Corps of Engineers retain oversight authority. Individual states also have the authority to include more stringent NPDES requirements than federal requirements.

A 2009 survey explored the resulting mix of permitting authorities and permit types across the country, resulting in several recommendations on common approaches to tailoring stormwater programs to the unique characteristics of state DOTs (*3*). In 2019, EPA developed a compendium of

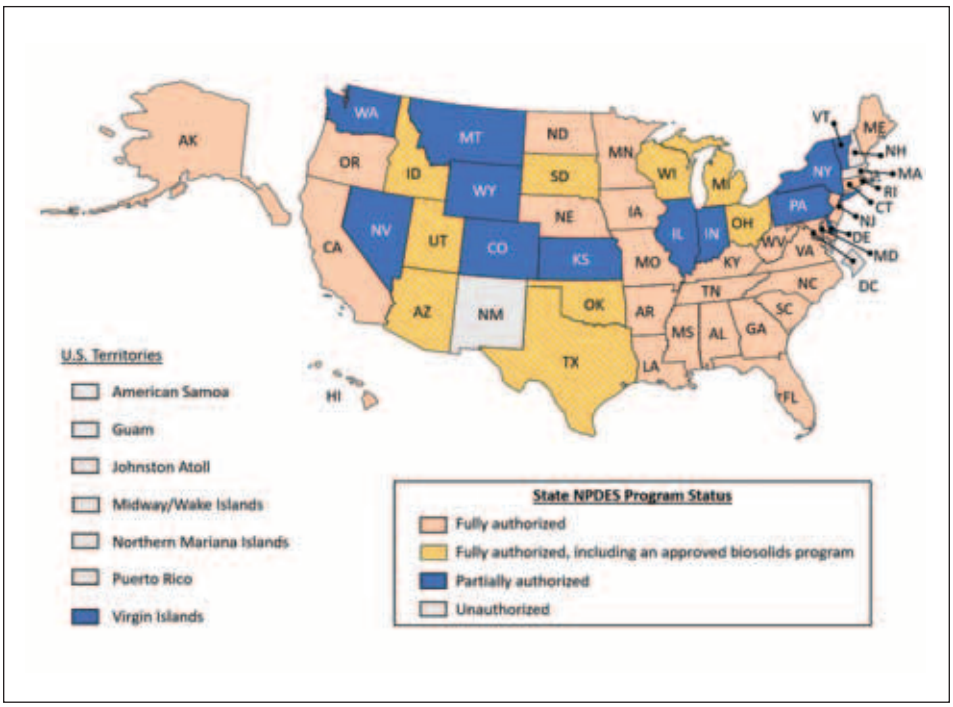

FIGURE 2 Many states are authorized to issue NPDES permits.

permitting approaches to assist writers of state DOT permits (*4*). Updates to the compendium are expected and, to that end, EPA has invited comments from state DOTs.

Beyond the MS4 Permit

Other aspects of the CWA affect transportation facilities and activities. The other primary types of regulation affecting transportation include permits for dredge fill operations (CWA Section 404) and related water quality certifications for permitted projects (CWA Section 401) and NPDES stormwater permits for industrial activities and construction sites.

CLEAN WATER ACT SECTIONS 404/401: DREDGE AND FILL AND THE WATER QUALITY CERTIFICATION

Administered by the U.S. Army Corps of Engineers, CWA Section 404 requires permits for the removal or deposit of sediment within waters of the United States; for example, as when constructing a bridge over water. Unless issued by a state with authority to issue Section 404 permits, each Section 404 permit requires a water quality certification, per CWA Section 401.

Section 401 prohibits a federal agency from issuing a permit for any activity that may result in any discharge to a water of the United States unless the state or authorized tribe from where the discharge originates has issued a CWA Section 401 water quality certification verifying compliance with existing water quality requirements—or waives the certification requirement.

CLEAN WATER ACT SECTION 402: CONSTRUCTION AND INDUSTRIAL DISCHARGE PERMITS

Construction activities that disturb 1 or more acres of land—or that include sites that disturb less than 1 acre but that are part of a common plan of development that disturb 1 or more acres—must obtain permit coverage for their stormwater discharges, unless a state specifies a lower-size threshold that would touch nearly every state DOT construction project (*5*). An ongoing issue for state DOTs and permitting authorities is how to work together on establishing permit conditions that best address some of the unique challenges related to road construction, including limited rights-of-way and phased project schedules.

NPDES industrial permits are based on the Standard Industrial Classification (SIC) for the primary activity at a site (*6*).

Photo: U.S. Army Corps of Engineers

Clearing the way for commerce, the U.S. Army Corps of Engineers (Savannah, Georgia, District) maintains dredging of the harbors at the Savannah and Brunswick rivers. Their work ensures that the authorized depth is safe for cargo ships to import and export their goods.

Airports, rail, and ports all must obtain permit coverage to discharge stormwater runoff.[1] Generally, industrial stormwater dischargers must reduce or eliminate pollutants in stormwater runoff (or do both) to the extent achievable using control measures that are technologically available and economically practicable and achievable in light of best industry practices.

[1] The SIC classifications for airports are SIC 4512–4581; for rail, SIC 4011 and 4013; and for ports, SIC 4412–4499.

In addressing many of these requirements, the articles in this special issue of *TR News* focus on requirements for runoff from construction sites and from existing state DOT rights-of-way that are regulated as MS4s.

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6. National Pollutant Discharge Elimination System (NPDES) Multi-Sector General Permit for Stormwater Discharges Associated with Industrial Activity (MSGP). U.S. EPA, 2015. www.epa.gov/sites/production/files/2015-10/documents/msgp2015_finalpermit.pdf. Accessed January 23, 2020.

EPA and FHWA Resources

The U.S. Environmental Protection Agency (EPA) offers many technical resources, nationally and locally via 10 regional offices. Key studies and resources for transportation agencies are available online at www.epa.gov/npdes/stormwater-discharges-transportation-sources. The Federal Highway Administration Environmental Toolkit, available at www.environment.fhwa.dot.gov/env_topics/water/stormwater.aspx, also offers help for stormwater management.

EPA National Transportation Liaison

The Federal Highway Administration (FHWA) funds transportation liaison positions at several resource agencies, including the U.S. Environmental Protection Agency (EPA). National Transportation Liaisons help facilitate the environmental and permitting review process for transportation projects by providing technical assistance and coordinating the response of resource and regulatory agencies to state departments of transportation (DOTs).

Heather Goss

National Transportation Liaisons serve as FHWA's connection to federal resource and regulatory agencies. Liaisons help improve communication and coordination among state DOTs and resource and regulatory agencies, facilitate environmental protection while streamlining review processes, and increase access to environmental and regulatory expertise for state DOTs.

In 2020, Heather Goss became EPA's National Transportation Liaison. Goss has worked with the agency since 2006, and her experience includes water quality standards, particularly in water quality criteria and antidegradation, as well as standards issues in National Pollutant Discharge Elimination System permits.

Goss has a master's degree in earth sciences from the University of Maine and a bachelor's degree in geology from Haverford College.

Integrating Stormwater Infrastructure into State Department of Transportation Processes

Photo: Jonathan Cutrer

SCOTT ROGERS, ADRIENNE BOER, AND SCOTT CRAFTON

Rogers is Environmental Coordination Engineer, Alabama Department of Transportation Design Bureau, Montgomery. Boer is Environmental Program Manager, Texas Department of Transportation Environmental Affairs Division, Austin. Crafton is MS4 Program Manager, Virginia Department of Transportation Central Office Maintenance Division, Richmond.

Above: Bluebonnets splashed with Indian paintbrush carpet the more than 80,000 centerline miles of Texas roadways in spring. Well-maintained vegetated rights-of-way—such as this swath of bright blossoms—are Texas DOT's most prolific and successful stormwater quality control measure.

Functional stormwater infrastructure is necessary on a roadway, as properly managed stormwater reduces the likelihood of water-related hazards that motorists may encounter and helps to safeguard the quality of natural waters. Stormwater infrastructure must be considered in the design of a roadway, during the construction of the roadway, and in maintenance activities conducted throughout the life of the roadway. For a state department of transportation (DOT) responsible for maintaining, improving, and adding to a large network of roadways, integrating activities related to stormwater infrastructure into established, complex state DOT processes can be especially challenging.

This article describes the experiences of three state DOTs that have performed such integration. Alabama DOT incorporated postconstruction stormwater management (PCSWM) design into the overall roadway design process. Texas DOT developed the approval process for products used in the construction of a roadway to promote vegetation. And Virginia DOT improved the management of data associated with stormwater infrastructure best management practices (BMPs) to effectively focus maintenance efforts.

Postconstruction Stormwater Management Design at Alabama DOT

Roadway design at a state DOT requires meeting multiple, conflicting goals and coordination among various state DOT parties. Many factors—such as traffic capacity, motorist safety, subgrade integrity, and historic site preservation—are considered during the roadway design process. Hydrologic and environmental impacts are also important factors addressed in the process and can serve as formidable constraints on roadway design. With all of these factors in play, a state DOT aims to establish and then maintain a calibrated, effective roadway design process. When a major change in the process is needed, some discomfort and disorientation

Photo: Alabama DOT

Stormwater collects in a Birmingham, Alabama, detention pond under construction in 2014.

among state DOT personnel may occur. Alabama DOT had to undergo such a change in its roadway design process and navigate the subsequent challenges when it formally implemented PCSWM.

PCSWM is now an established municipal separate storm sewer system (MS4) permit requirement for Alabama DOT and many other regulated public entities. The broad objective of PCSWM is the management of stormwater runoff from developed land such that it does not adversely affect the water body into which it drains. PCSWM methods include traditional practices—such as detention ponds—focused more on regulating the discharge rate of channelized runoff, as well as low-impact development–green infrastructure (LID/GI) practices designed to mimic the infiltration of rainwater into subsurface soil and the evapotranspiration of rainwater captured by vegetation that occurs on undeveloped land.

Employing PCSWM practices is contrary to the decades-old approach governing roadway stormwater design, which promotes the removal of runoff from the roadway as quickly as possible. Alabama DOT designers had to adjust to the different stormwater design approach.

Adding to the initial disorientation, the nuances of PCSWM requirements (e.g., type of development eligible for PCSWM regulation and threshold of land disturbance triggering PCSWM requirements) were not intuitive for designers. There were (and still are) only a few studies in literature and limited technical guidance concerning the selection and design of PCSWM practices.

Even with more orientation, Alabama DOT designers encountered implementation challenges unique to state DOTs. PCSWM regulations and guidance are typically developed with municipalities and similar entities in mind, but the linear nature of roadways and the small amount of roadside space available limit the feasible options for the selection and sizing of PCSWM BMPs. Maintenance demands must also be considered in BMP selection, as finite maintenance resources are spread over an entire state. Additional discussion about state DOT–specific challenges can be found in a white paper summarizing the outcomes of the 2012 AASHTO National Stormwater Practitioners Meeting (*1*).

To lay the groundwork for success in meeting PCSWM challenges, Alabama DOT relied heavily on its Office of Environmental Coordination and other mechanisms to coordinate internally during the implementation of the PCSWM program. This effort allowed Alabama DOT design, construction, and maintenance personnel to understand the intricacies of PCSWM concepts and requirements, express any general concerns, and explain any conditions that would make BMP implementation especially difficult or infeasible.

With functional coordination in place, Alabama DOT established an official, agencywide PCSWM policy. This policy concisely mandates accounting for hydrologic changes resulting from the development of Alabama DOT facilities, encourages LID/GI practices, and outlines the key definitions and applicability criteria for PCSWM. The policy was approved by the Alabama DOT chief engineer and the Alabama DOT director, thereby giving the policy proper authoritative support.

Specific and straightforward PCSWM guidance was developed for the designer. The guidance is a step-by-step procedure to determine the net increases in total runoff volume and peak runoff flow rate due to development using a design precipitation depth, which is based on the amount of precipitation resulting from a 95th-percentile storm event. To aid the designer in determining the design depth at a particular location, a map of Alabama with zones of particular precipitation depths was generated (Figure 1). Alabama DOT's roadway design process now includes steps for conducting this hydrologic analysis and coordinating with Alabama DOT's offices involved in stormwater management early in the process so that PCSWM feasibility issues and unique

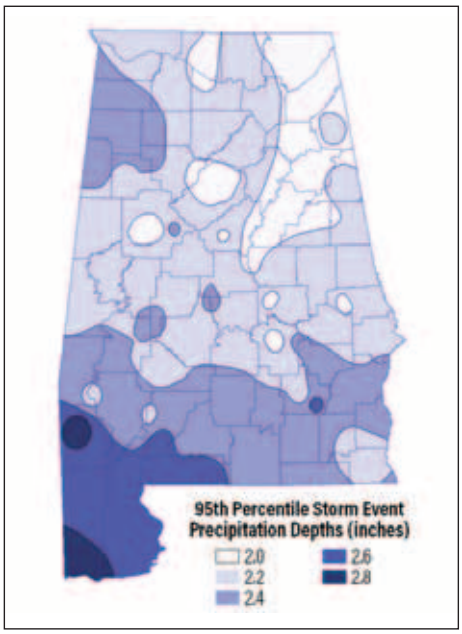

FIGURE 1 Alabama precipitation depths for the 95th-percentile storm event.

site conditions can be explored thoroughly before right-of-way acquisition and major design deadlines.

PCSWM BMP selection is less straightforward for the designer. Knowledge is increasing about the performance of BMPs that are appropriate for placement alongside roadways, but it is still lacking overall. The first Alabama LID handbook was published in 2014, and the guidance it provides is somewhat general (*2*). In addition, a National Cooperative Highway Research Program guidance manual focused on roadway stormwater infiltration was only published in 2019 (*3*). Even with more knowledge, BMP design must be tailored specifically to project site characteristics. Therefore, Alabama DOT currently instructs designers to collaborate with Alabama DOT stormwater professionals during the BMP selection process.

Alabama DOT initially relied on the detention pond (see photo, page 10) as its primary PCSWM BMP. The agency now prefers LID/GI BMPs where site conditions allow for reasonable implementation. Over several years of trial and error, Alabama DOT developed its infiltration swale, a variant of the vegetated swale—as defined by the U.S. Environmental Protection Agency (*4*)—and is currently employing the infiltration swale as its primary LID/GI BMP.

Put simply, the infiltration swale looks like a standard grassed roadside ditch, but it has a designed subsurface soil matrix that promotes infiltration at a rate intended to approximate predevelopment conditions (see photo). By adapting the standard roadside ditch slightly (see left photo, page 12), Alabama DOT has developed a PCSWM BMP that feels familiar to the agency's design, construction, and maintenance personnel and has contributed to the agency's overall buy-in. Preliminary performance evaluations of the infiltration swale have shown promise (see right photo, page 12), though further study is needed to optimize design.

Alabama DOT has established a viable PCSWM program and successfully integrated it into its overall roadway design process. The agency accomplished this goal by understanding and acknowledging its specific challenges and by adapting to those challenges with functional internal coordination.

Photo: Alabama DOT

The inner workings of a Huntsville, Alabama, infiltration swale—under construction in 2017—set it apart from traditional grassed roadside ditches. Alabama DOT designed the soil matrix to allow stormwater infiltration at a rate comparable to that of the area before development.

Product Approval to Promote Vegetation at Texas DOT

Texas DOT maintains more than 80,000 centerline miles (128,000 kilometers) of roadway throughout the multiple ecoregions of Texas. By sheer quantity, Texas DOT's most prolific and successful stormwater quality control is a well-maintained, vegetated right-of-way. Vegetation characteristics, soil composition, and precipitation amounts vary greatly across the large state, and that variability creates specific challenges to vegetation maintenance on the Texas DOT right-of-way.

For vegetation to establish properly on a constructed roadway and maintain adequate integrity after construction, products that provide reasonable assurance of performance must be employed. To that end, starting with the 1993 edition of the Texas DOT's *Standard Specifications for Construction of Highways, Streets and Bridges*, the agency shifted from a material-based specification to one requiring the use of products on an approved product list (APL).[1]

To be placed on the Texas DOT APL, a product must meet or exceed all adopted minimum performance standards for the application. Failure to meet any of the adopted minimum performance standards entails an automatic rejection of the product. The APL is regularly updated as products improve and become more effective. Products are added to the APL and then continue to be listed for up to 3 years. After 3 years, recertification of the product is required. Texas DOT bases minimum performance standards on statistical analysis of performance data collected in controlled performance tests.

Performance tests are conducted at the Texas A&M Transportation Institute Sediment and Erosion Control Laboratory (SEC Lab), which is supported by funding from Texas DOT. The SEC Lab is a 19-acre (7.7-hectare), full-scale, indoor–outdoor facility that recently underwent an expansion to meet industry research needs. The SEC Lab houses indoor rain simulators, runoff beds, testing flumes and channels, soil embankments at varying slopes, and a climate-controlled greenhouse for growing vegetation year-round. The SEC Lab's testing capabilities are amply robust for comprehensively evaluating product performance.

Generally, the minimum performance standards align with the following critical performance factors adopted by Texas DOT:

[1] The current APL can be found online at https://www.txdot.gov/business/resources/erosion-control.html.

Photo: Alabama DOT

A covering of sod completes the Huntsville infiltration swale. Yellow lines outline the approximate swale boundaries.

Photo: Alabama DOT

The Huntsville infiltration swale impounds stormwater runoff before the water slowly drains into the underlying soil matrix. Yellow lines indicate approximate swale boundaries.

- The protection the product provides for an embankment seedbed or a drainage channel from sediment loss during simulated rainfall or channel flow events and
- The degree to which the product promotes warm-season, perennial vegetation establishment.

Texas DOT considers two categories of erosion control and revegetation products: rolled and spray-on products, which include soil retention blankets, and standard hydraulic mulches, which include cellulose fiber mulches. The minimum performance standards recognize that rolled and spray-on products are classified for use by the industry in one of the two following ways:

- Products designed for overland flows associated with typical slope or embankment protection applications (termed "Class 1" applications in Texas DOT Standard Specification Item 169) and
- Products designed for concentrated water flows associated with typical highway drainage channels (termed "Class 2" applications in Texas DOT Standard Specification Item 169).

Texas DOT's current specifications for soil retention blankets and cellulose fiber mulches do not include any of the typical ASTM material requirements, such as mass per unit area, water holding capacity, tensile strength, elongation, and pH. The agency believes performance evaluation under Texas DOT–applicable conditions is more reliable than evaluation according to generalized ASTM parameters. Hence, the agency instead bases approval of soil retention blanket and cellulose fiber mulch products on the formal evaluation conducted at the SEC Lab.

Texas DOT recognizes that the performance of a product may vary if the product is installed under less-than-ideal conditions or is not installed in complete accordance with manufacturer specifications. To supplement the robust product evaluation conducted by the SEC Lab, the agency will soon begin capturing the in-field, real-world experiences of product implementation from users on construction sites. Comments received from onsite users will be used to generate scores for products employed. The APL format will be updated to provide user recommendation ratings and other user performance evaluation information for products on the list.

The key advantage of the updated APL format will be the ability for a user to compare product performance ratings to determine the appropriate products for a real-world construction site. The updated APL format is scheduled to be released in late 2020.

For more than 25 years, the Texas DOT APL has promoted quality assurance in the products used to establish and ensure the integrity of the vast amounts of vegetation that flank agency roadways and that quality assurance should increase as Texas DOT continues to seek improvement in the product evaluation process. As a mark of validation, the Texas DOT APL is not only used and appreciated by the agency; it has been used in more than 25 states throughout the country.

Stormwater Infrastructure BMP Data Management at Virginia DOT

Virginia DOT is in the process of updating its information technology tools to better monitor the inspection and maintenance of various assets at the enterprise scale. This effort will improve the agency's understanding of asset life-cycle costs, which will inform decisions about the cost-effectiveness of materials and practices that may be used in future roadway and facility designs. Asset management associated with stormwater management BMPs is particularly important, as Virginia DOT currently has more than 2,400 BMPs in its inventory to manage stormwater runoff in compliance with applicable regulations and permits.

Virginia DOT recently updated its BMP inspection application for mobile devices to improve the data collected during BMP inspections and to more precisely identify

specific maintenance needs. The application is built on ESRI ArcGIS Enterprise and Survey 1-2-3 software. The application can be employed in the field. As soon as data from a field inspection is uploaded to the central database, any authorized Virginia DOT manager or user can see it.

The agency will also develop Survey 1-2-3 dashboards to provide managers with an organized display of key metrics related to BMP inspection and maintenance. Also, the associated Virginia DOT *Stormwater BMP Inspection and Maintenance Manual* is being updated to align with the new inspection app and to provide more comprehensive information about BMP maintenance.

Elaborating on the improved data collection procedure, the Virginia DOT inspector first requests data corresponding to a BMP ID number using the updated inspection app. Key identifying data are displayed on the tablet screen, including the name of the logged-in inspector, current date, BMP category (e.g., basins, infiltration, or manufactured devices), and specific BMP type (e.g., extended detention basin, bioretention, or grassed swale) (Figure 2). With the BMP identified, sets of inspection questions for the applicable BMP category can be accessed by the user (Figure 3). When the inspector clicks on a question set link, a drop-down menu of one or more subsidiary question sets opens (Figure 4).

Questions asked in each set explore a variety of potential problems the BMP may be experiencing (Figure 5). Skip mechanisms are built into the app so that, if the inspector indicates—by answering a question—that a BMP is completely functional, or if a line of questioning is not applicable for a given situation, the app foregoes additional, unnecessary questioning.

The depth of inquiry conducted by the app allows for the identification of specific maintenance needs. Each inspection question corresponds to an appropriate maintenance task in the database, and the app infers the urgency of a specific maintenance need from the inspector's responses to app questions. Scores that indicate maintenance urgency are assigned according to the following rubric:

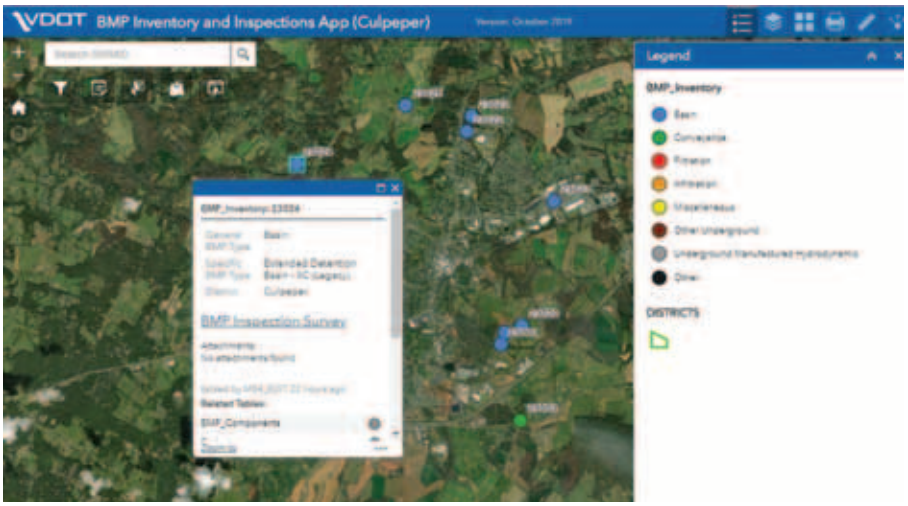

FIGURE 2 Identifying information for a selected BMP.

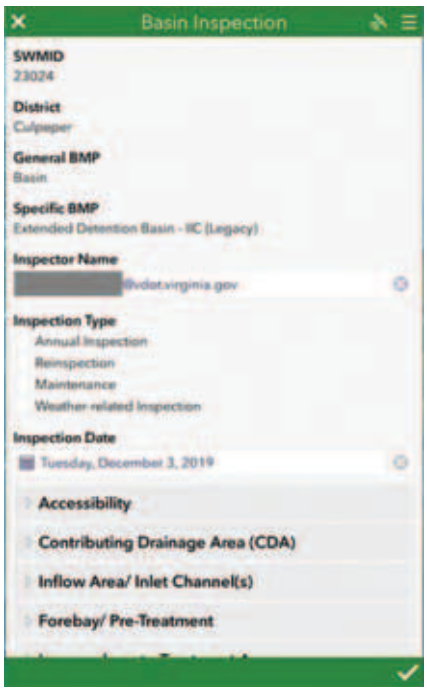

FIGURE 3 Inspection question sets displayed for the "Basins" BMP category.

FIGURE 4 Subsidiary question sets for "Inflow Area/Inlet Channel(s)."

FIGURE 5 Questions for "Inflow Area Surface Condition."

A = okay
B = only routine maintenance needed
C = straightforward corrective maintenance needed
D = significant maintenance needed
E = failure or emergency repairs needed

Ratings A, B, and C indicate full functionality. Ratings D and E indicate inadequate functionality. When the inspection is completed, the app will assign an overall score to the inspection based on the lowest rating of all BMP inspection criteria considered. For example, if the lowest rating for a given BMP was associated with "inflow area surface condition," and that rating is C, the overall BMP inspection score would be C.

The inspector can print the complete BMP Inspection Report, which shows all questions asked by the app—including the questions without response—and corresponding answers, as well as the BMP Maintenance Report, which shows only the questions and answers associated with maintenance tasks to be performed (Figure 6). The BMP Maintenance Report provides the basis for a work order that is sent to a Virginia DOT maintenance crew or contractor to accomplish the needed maintenance.

Work orders are managed by a different Virginia DOT database: the Highway Maintenance Management System (HMMS). HMMS allows the agency to track maintenance activities and costs over time, including those for stormwater management BMPs. Thus, the system enables Virginia DOT to track needed stormwater management BMP maintenance, tally BMP costs throughout the life of a BMP, ensure continued BMP functionality, and monitor Virginia DOT's regulatory compliance status with respect to stormwater management.

FIGURE 6 Example of a Virginia DOT BMP Maintenance Report.

The major outcome of these Virginia DOT data management efforts is a more meaningful connection of field evaluations of BMP performance to the agency's overall system of stormwater management. Quality data allow Virginia DOT to allocate maintenance resources to address the more important stormwater management issues proficiently and enable project designers to make better choices in the future with regard to employing BMPs to manage stormwater.

Conclusion

This article has detailed the successful experiences of three state DOTs in integrating stormwater infrastructure into state DOT processes. It is likely that many state DOTs are finding similar success by implementing change strategically. A state DOT seeking to integrate stormwater infrastructure into its processes should consider its goal attainable, given ample time and the lessons already learned by other state DOTs.

A state DOT seeking to integrate stormwater infrastructure into its processes should consider its goal attainable, given ample time and the lessons already learned by other state DOTs.

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CENTENNIAL QUOTE

"I grew up in an Eastern Airlines household, building model trains, planes, and ships. That led me to major in engineering at the Massachusetts Institute of Technology. But, my interest was more in transportation policy than engineering, so I launched Reason Foundation in 1978. Five years later, my introduction to TRB was an invitation to present a paper on reforming FAA's air traffic control system, which was then published in the *Transportation Research Record*. I soon joined TRB's Congestion Pricing Committee and took part in FHWA workshops on pricing, tolling, and private finance highway projects. TRB continues to be a great resource for my colleagues and me.

—ROBERT POOLE
Director of Transportation Policy, Reason Foundation, Plantation, Florida

Connecting Stormwater and the State Department of Transportation Mission

Photo: m01229, Flickr

SCOTT TAYLOR AND WENDY TERLIZZI

Taylor is Vice President, Michael Baker, Carlsbad, California. Terlizzi is Environmental Services Manager, Idaho Transportation Department, Boise.

Above: When a storm blows through California's Prairie Creek Redwoods State Park, a sublime system of actions and reactions quietly goes to work. Evapotranspiration of rainfall captured in the forest canopy releases water into the atmosphere. Tree roots and leaf litter create conditions that help rainwater infiltrate the soil. In a healthy forest, this process results in reduced stormwater runoff and replenished groundwater supply.

State department of transportation (DOT) mission statements define the organization. Most contain the elements of safety and mobility, and some mention the environment and environmental stewardship. In addition, they usually contain an underlying fiscal responsibility to the state taxpayers.

To effectively implement a stormwater program that is not inherently tied to the primary mobility business of the state DOT, a connection to the agency mission must first be established. For stormwater, the connection is typically made between the environmental responsibilities of the department and providing the most efficient transportation system for the people the agency serves. How water connects to the department mission is an important influence in the short-term initiation of the program, as well as the long-term cost, sustainability, and performance of the state DOT. It is in the state DOT's interest to build and maintain sustainable infrastructure for stormwater, since it will have a good return on investment for the agency and the public.

Construction and operation of public infrastructure can include hidden costs (such as water pollution from impervious surfaces) that are borne by the public in other ways, such as through adverse health effects. Sustainable infrastructure reduces or eliminates these hidden costs. Determining how to connect stormwater into the state DOT mission is a key part

It is in the state DOT's interest to build and maintain sustainable infrastructure for stormwater, since it will have a good return on investment for the agency and the public.

Photo: Patrick Hoesly

Downspouts direct a downpour straight onto an impervious parking lot. When pavement is impenetrable, rainwater picks up surface pollutants (in this case, from rooftops as well) and carries them via runoff to nearby streams and rivers.

Photo: Milwaukee Metropolitan Sewerage District

With enhancement completed in 2018, Underwood Creek now has reduced flood risk, improved biodiversity, and is reconnected to its flood plain.

Photo: Nicolas Buer, USGS

Throughout the United States, concrete channels line waterways such as Underwood Creek in Wauwatosa, Wisconsin. When this form of gray infrastructure no longer sufficiently controlled flooding, Milwaukee Metropolitan Sewerage District removed more than 4,400 linear feet of concrete lining and naturalized the creek with vegetation and through bioengineering, with an added benefit of creating aquatic habitat.

of building a sustainable program. Sustainable stormwater infrastructure is resilient to intense storms; can be operated, maintained, and repaired using local labor and resources; and minimizes its environmental impact.

Gray infrastructure—inlets, pipes, channels, and conveyance structures—are widespread and an important and necessary element of state DOT infrastructure. For as long as state DOTs have been building highways, stormwater has been a factor in the design. They configure methods to remove the water from the roadway surface as quickly and efficiently as possible to maintain the safety and mobility of the public. Modern stormwater management design centers on peak volume reduction and providing treatment while still providing for safety, which are the foundational principles of green infrastructure. New designs also include vegetated conveyances and impoundments; use of vegetation and natural materials to control erosion; and new materials, such as pervious pavement overlays, to improve roadway safety and water quality. Stormwater management is an ever-evolving practice, and there is much innovation yet to come in a state DOT setting. The following building blocks will support future designs.

Stormwater and Highways

Asset management provides the foundation to ensure that existing infrastructure is adequately maintained and assists in modifying that infrastructure when it needs to be replaced or updated. The future of state DOT managed drainage is moving toward implementation of green infrastructure (GI). When gray assets reach the end of their useful life, state DOTs have the opportunity to replace them with GI. Asset management programs can also be used to track costs and demonstrate the long-term resources needed to maintain each type of asset.

Urban settings offer less flexibility for integrating GI but no less opportunity for improvement in water quality. An interesting new application of permeable friction course (PFC) for water quality shows good promise in helping state DOTs deal with quantity and quality of stormwater, enabling agencies to comply with their National Pollutant Discharge Elimination System permits while they make the roads safer. PFC is a gap-graded overlay—usually less than 2 inches thick—placed as a wearing course over conventional hot-mix asphalt.

In 2019, TRB conducted a webinar on this topic.[1] New devices are also being developed to assist state DOTs with control of trash from storm drains. And research into full-depth permeable pavement, particularly in shoulder areas, is promising to assist in runoff volume reduction.

In most rural areas, GI application will provide state DOTs with the most favorable capital cost and competitive maintenance costs. Vegetated shoulders and swales reduce the volume of runoff and improve water quality, while eliminating the capital and operation and maintenance cost of inlet and piping systems. When replacing gray infrastructure with GI, rural areas allow the integration of the new features into the existing environment. This integration reduces installation costs as well as needed maintenance.

When compared with traditional gray infrastructure, GI also has the potential to provide higher efficiency for treatment and reduction in peak flows. *NCHRP Research Report 922: Stormwater Infiltration in the Highway Environment—Guidance Manual* discusses the pollutant load reduction associated with infiltration of stormwater.[2]

The use of salt to reduce or delay the formation of ice on roadways is a critical safety tool. However, the salt ends up in lakes, rivers, and water supplies through stormwater runoff. It also attacks concrete pavements and bridge structures. Salt use is highest in the Northeast and lowest in the southern states. Innovative practices are being implemented, including use of GPS to meter and distribute salt and salt alternatives.

Tire wear is another potentially problematic issue for state DOTs. Tire wear contributes to the load of microplastics in the environment. This emerging problem may require a focus on source control, such as modifying tires, since it is not practical to remove the particles once they are entrained in stormwater. An October 2017 article in the *International Journal for Environmental Research and Public Health* notes that tire wear emission ranges from 0.23 to 4.7 kilograms per year, with a global average of 0.81 kilograms per year (*1*). The article further notes that the relative contribution of tire wear to the total global amount of plastics deposited in the oceans is estimated between 5% and 10%.

Roadway maintenance and operations are also integral to stormwater and water quality. Pavement materials, construction wastes, paint, and appurtenances can all contribute to stormwater pollution. For example, zinc is one of the constituents of concern for highways, as it is picked up in runoff from zinc-coated storm drainpipes, guardrails, signs, and fencing. Pavement materials can also be a source of polycyclic aromatic hydrocarbons, and grind dust from concrete pavement operations can affect the pH of runoff water.

State DOTs have built robust stormwater programs to help guide maintenance and operations practices that ensure water

Photo: Alisha Goldstein, EPA

The first few feet of permeable pavers have been installed to replace an impervious concrete surface. One of many examples of green infrastructure, permeable pavers serve to capture and slowly release water into the ground, trapping pollutants in the process.

Photo: Michael Pereckas

Critical in the battle against dangerous conditions created by ice and snow, a road crew armed with a salt truck shovels at a particularly hazardous corner in Milwaukee, Wisconsin, in 2006. Salt reduces or delays ice formation on roads. But, snowmelt washes the salt into lakes, rivers, and the water supply. Today, innovative practices, such as GPS metering to distribute salt and salt alternatives, are being implemented to reduce its harmful effects.

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[1] On September 19, 2019, TRB presented the webinar, Open Graded Pavements: A Primer with Emphasis on Water Quality Benefits, found online at http://www.trb.org/ElectronicSessions/Blurbs/179484.aspx.

[2] *NCHRP Research Report 922: Stormwater Infiltration in the Highway Environment—Guidance Manual* can be found online at https://www.nap.edu/catalog/25705/stormwater-infiltration-in-the-highway-environment-guidance-manual.

quality is protected. Another aspect to consider is the safety of maintenance and operations personnel when they are performing the routine inspections and maintenance on best management practices.

Bridges are an especially important portion of the highway system that can have an outsized impact on water quality. In many cases, runoff from bridges flows directly to the receiving water through scuppers. This direct discharge of highway runoff affords few options for management. *NCHRP Report 778* studied the impacts of bridge deck runoff on the environment and options for reducing those impacts.[3]

Alternative Compliance Approaches

Managing stormwater is a daunting task when the state DOT has a small staff to cover the entire state. Agencies would be well served by integrating stormwater management throughout all of their processes (i.e., design, construction, and operations). It is also effective to work in partnership with other stakeholders, such as cities and counties. State DOTs operate systems with limited amounts of control over adjacent roadway right-of-way and have safety requirements that can preclude implementation of some types of stormwater management. Subsequently, the state DOT stormwater system may need to intermingle with land controlled by overlapping and adjacent stakeholders. Working in partnership with permittee jurisdictions and adjacent landowners can be an efficient and effective way to design and construct stormwater solutions.

NCHRP Research Report 840 on managing stormwater at a watershed scale was developed to assist state DOTs in determining when it is most appropriate to manage runoff in partnership with adjacent jurisdictions[4]. Many times, this is the most cost-effective solution that offers the best performance of a stormwater system.

Photo: Aaron Volkening

Water-loving wildflowers add a touch of beauty at the end of a concrete drainage inlet on Greendale, Wisconsin's Grange Avenue. Such bioswales offer residents immediate—and practical—benefits: great curb appeal and the knowledge that runoff from their streets meet state standards when stormwaters flow.

Paying for Your Stormwater Program

The interstate and rural intrastate highway systems are largely complete, but these systems were not constructed with the requirements of the NPDES stormwater program in mind. This means that as infrastructure is repaired, maintained, and rebuilt, state DOTs must integrate stormwater measures. Capital improvement budgets can fund some elements of the program, and operating funds are also important. But, large-scale retrofit of infrastructure will also require new funding sources.

The former TRB Standing Committee on Stormwater developed a webinar on alternative funding sources for state DOT stormwater programs in partnership with the U.S. Environmental Protection Agency (EPA) and highlighted the EPA's Water Finance Website.[5] The webinar also identified new potential funding sources, such as community-based public private partnerships for state DOTs. Congress has been allocating more funding under the State Revolving Fund specifically for stormwater projects, and there are several EPA grant programs available.

For state DOTs to effectively fund and manage stormwater programs over the long term, they need to successfully tie those actions back to the agencies' mission.

[3] *NCHRP Report 778: Bridge Stormwater Runoff Analysis and Treatment Options* can be found online at https://www.nap.edu/catalog/22395/bridge-stormwater-runoff-analysis-and-treatment-options.

[4] *NCHRP Research Report 840: A Watershed Approach to Mitigating Stormwater Impacts* can be found online at http://www.trb.org/NCHRP/Blurbs/175861.aspx.

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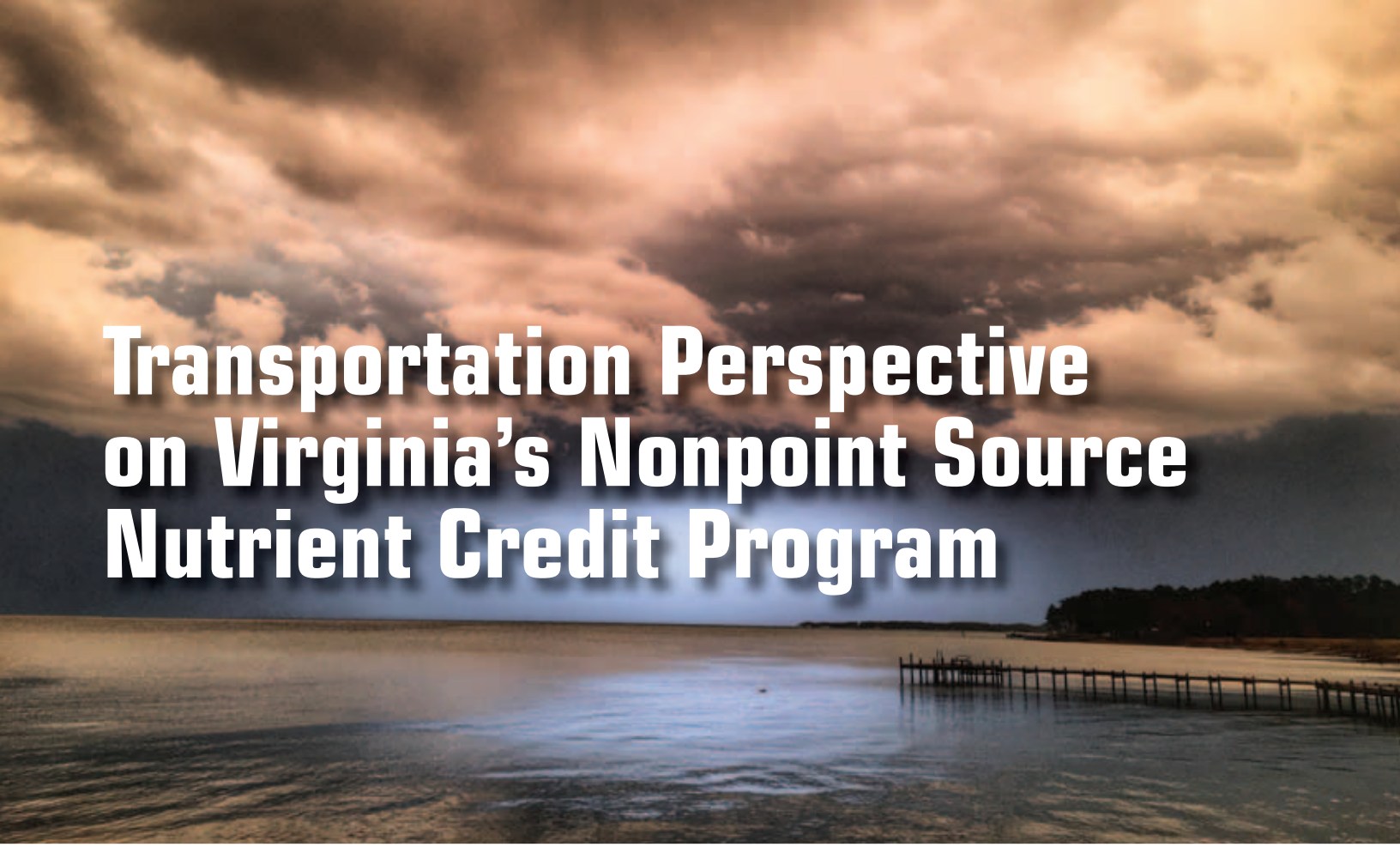

Transportation Perspective on Virginia's Nonpoint Source Nutrient Credit Program

Photo: Dennis Dimick

CHRIS SWANSON AND CLARK O'BANNON

Swanson is Assistant State Location and Design Engineer, Virginia Department of Transportation, Richmond, and O'Bannon is Manager, Solutions Analysis, Resource Environmental Solutions, LLC, Richmond.

Above: A storm rolls in over Chesapeake Bay from Godfrey Bay in Mathews County, Virginia. In 2005, Virginia issued a strategy to curb pollution from stormwater runoff in the Chesapeake Bay, whose vast ecosystem is vital to the region's health and economy.

In January 2005, the Commonwealth of Virginia issued the Chesapeake Bay Nutrient and Sediment Reduction Tributary Strategy to achieve and maintain the water quality necessary to support the Bay's aquatic living resources and to protect human health (*1*). Excess amounts of total nitrogen (TN), total phosphorus (TP), and total suspended sediment (TSS)—both from agricultural practices and from industrial facilities—were flowing into the Bay each year, damaging its fragile ecosystem.

TN is a common pollutant parameter for wastewater and stormwater runoff, since it is the sum of nitrate–nitrogen, nitrite–nitrogen, ammonia–nitrogen, and organically bonded nitrogen. Virginia's strategy document was an early step toward establishing baseline requirements for reductions in total TP, TN, and TSS reaching the Bay. Also in 2005, legislation created the Chesapeake Bay Watershed Nutrient Credit Exchange Program (*2*). The Exchange allows Virginia's regulated entities in the Bay watershed to use trading to meet required reductions of point and nonpoint source nutrients. The Exchange also allows point sources to purchase nutrient credits from nonpoint sources to offset new or increased nutrient discharges in excess of established load caps.

Generally, nutrient credits are created and managed by third-party providers who establish nutrient "banks," which are certified and regulated by the Virginia Department of Environmental Quality (VADEQ). Nutrient credits—the reduction in nutrients and sediment in an annual calendar year beyond established regulatory baselines—are listed on a registry maintained by VADEQ. Nonpoint source nutrient credits are perpetual (i.e., credits are purchased once and last in perpetuity), substituted at a 1:1 ratio (i.e., one pound of required postconstruction stormwater pollutant reduction is equivalent to one nutrient credit), and available in fractional increments.

Credits can be generated various ways, including best management practices (BMP) enhancements, land conversion, or

Photo: Eric Vance, U.S. EPA

Excess nitrogen and phosphorus cause an overgrowth of algae, also known as an algal bloom, in a Chesapeake Bay tributary. Significant increases in algae harm water quality and reduce the oxygen that fish and other aquatic life need to survive. Virginia's strategy document in 2005 helped establish baseline requirements for reductions in total nitrogen reaching the Bay.

stream restoration. Through 2019, more than 95% of all nutrient banks have been created through various land conversion practices (e.g., converting active agriculture fields into forest). Total TP, TN, and TSS credits are based on ratios established by VADEQ, and they vary depending on the location of the nutrient bank and the specific land-conversion practice in use. Some banks will generate a greater amount of TP per acre relative to TN or TSS and vice versa.

To be eligible as offsets for a given project, nutrient credits must be generated by a nutrient bank located within the same or adjacent eight-digit U.S. Geological Survey hydrologic unit code (HUC). If no nutrient credits are available in these HUCs, a credit generated in the same tributary (or river basin) may be considered for eligibility by VADEQ. However, credits generated in a different tributary from a project are ineligible for that project.

Virginia Department of Transportation and the Exchange

For the Virginia Department of Transportation (DOT), the Exchange is applicable to its postconstruction runoff control program and its municipal separate stormwater sewer system (MS4) program, both of which are regulated under the Virginia Pollutant Discharge Elimination System (VPDES) permit program.

In Virginia, the U.S. Environmental Protection Agency (EPA) has delegated its National Pollutant Discharge Elimination System program implementation authority to VADEQ. Virginia DOT is authorized to discharge stormwater from its MS4 under an individual VPDES MS4 permit for stormwater discharges within the urbanized areas of Virginia. As part of the original permit authorization, Virginia DOT developed and implemented an MS4 Program Plan with BMPs to address the six minimum control measures and the special conditions for applicable total maximum daily loads (TMDLs) outlined in the permit.

The six minimum control measures established as part of EPA's Phase II implementation include public education, public outreach, illicit discharge detection and elimination, construction runoff control, postconstruction runoff control, and pollution prevention and good housekeeping.

History of the Exchange

In its early days, even though inventory was available, the Exchange was used minimally by point source discharge operators. From 2014 to 2019, several factors changed that made nutrient credits a preferred alternative for required nutrient offsets. In 2014, VADEQ implemented the Virginia Runoff Reduction Method in its stormwater management (SWM) regulations, requiring greater runoff reductions for new projects than the previous technical criteria. In addition, the new generation of MS4 permits—individual and general—have special conditions to address the Chesapeake Bay Watershed TMDL. The increased need for reductions for each project prompted the operators to become more knowledgeable about the cost savings associated with the use of nutrient credit. Also, in 2015, subsequent

Photo: Tim Camarda

Mirror clear, the North Fork of the Shenandoah River reflects land and sky near Berryville, Virginia. In 2015, the Chesapeake Bay Watershed Nutrient Credit Exchange Program was expanded, establishing consistent standards throughout the state.

TABLE 1 Approved Nutrient Credit Banks in Virginia, Pre-2015 Through 2019

Watershed		Pre-2015	2015	2016	2017	2018	2019	Total
Chesapeake Bay	Credits Sold	309	552	737	1,115	1,290	1,286	5,290
	Banks Approved	15	6	22	16	39	32	130
Southern Rivers	Credits Sold	—	—	68	227	217	422	934
	Banks Approved	—	—	6	14	4	7	31
Total	Credits Sold	309	552	805	1,342	1,508	1,708	6,224
	Banks Approved	15	6	28	30	43	39	161

(Note: Data on total credit sales often do not align with annual intervals, in which case assumptions are made to allocate sales by year. Totals from 2019 are extrapolated from data as of August 2019, based on an average monthly rate for the year.)

legislation expanded the Exchange to all tributaries within Virginia—including the "Southern Rivers" tributaries that do not flow into the Chesapeake Bay—and established consistent statewide standards.

Combined, these changes resulted in an explosion of nutrient credit banks throughout the state. As of December 2019, there were 161 approved banks across the state's 14 tributaries, up from only 15 banks at the beginning of 2015 (Table 1). From these banks, approximately 9,200 pounds of phosphorus and 61,000 pounds of nitrogen have been made available for trading. Also, approximately 6,200 pounds of TP have been purchased and retired, with new transactions occurring almost every day (Figure 1).

In aggregate, through 2019, the economic impact of the nutrient trading market in Virginia exceeded $90 million, when assuming the retired credits from VADEQ's registry were purchased at an average cost per pound of phosphorus of $15,000 (credit costs can vary significantly depending on the location of the project, however).

Virginia DOT Research on Life-Cycle Costs

Before 2014, Virginia DOT met all its required nutrient reductions through the implementation of onsite BMPs—in this case, stormwater retention ponds. In 2014, Virginia DOT engaged the Virginia Transportation Research Council (VTRC) to perform a study comparing the total costs of onsite BMP implementation with the purchase of nutrient credits. The findings, published in the *Journal of the American Water Resource Association*, concluded that purchasing nutrient credits can be a cost-effective option on a dollar-per-pound basis, with an average cost savings of 51% on a dollar-per-pound basis.

As a result, Virginia DOT issued an Instructional and Informational Memorandum (IIM) outlining the applicability, feasibility, procurement process, recordkeeping, and reporting aspects of purchasing nutrient credits (*3*). The IIM states that nutrient credits are the preferred alternative for Virginia DOT SWM requirements.

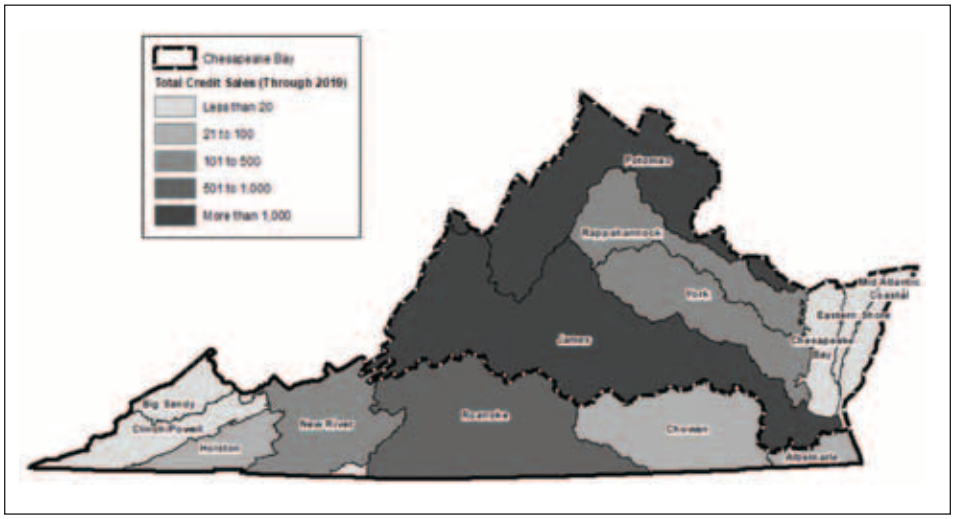

FIGURE 1 Nutrient credit sales in Virginia's tributary areas through 2019.

Postconstruction Runoff Control Program

The use of nutrient credits to achieve postconstruction stormwater compliance has its limitations, however. This is particularly the case when 1) there are local water quality restrictions or 2) offsite compliance options may cause or contribute to water quality degradation in the receiving stream.

Full or partial substitution of nutrient credits may be used to achieve compliance with postconstruction stormwater quality regulations, provided that 1) the site is in compliance with stormwater quantity regulations and 2) substitution of credits does not violate provisions of local stormwater management ordinances that are more stringent than the state regulations. For postconstruction purposes, Virginia DOT procures the credit purchase contracts using the invitation for bid (IFB) process, with phosphorus as the unit currency. The IFB allows Virginia DOT to secure a fixed rate in each tributary that is protected from market fluctuations, given increasing credit demand.

Nutrient credits may be substituted to achieve compliance with stormwater quality regulations under the following three scenarios:

1. Less than 5 acres (2.0234 square hectares) of land are disturbed;
2. The postconstruction TP removal requirement is less than 10 pounds (4.5 kg) per year; or
3. At least 75% of the required postconstruction phosphorus removal can be achieved using onsite BMPs, but full compliance with stormwater quality regulations cannot practicably be met onsite.

Virginia DOT MS4 TMDL Program

Aside from nutrient reduction requirements tied to each individual Virginia DOT project, as a Phase 1 MS4 permittee, the agency must also meet nutrient reductions for the Chesapeake Bay as defined by its TMDL permit. Virginia DOT considers nutrient credits to be one of many options to meet this need (for more on how Virginia DOT solved its TMDL problem, see the article by Tracey Harmon on page 24 of this issue).

Nutrient credits, as well as VADEQ's stormwater quality regulations (i.e., required nutrient reductions), are typically expressed in pounds of phosphorus removed annually. This is because VADEQ considers phosphorus a "keystone" pollutant, meaning that it exhibits some characteristics of a variety of both particulate and soluble pollutants, which makes it an indicator of urban pollutants in general (*4*). Although postconstruction SWM plans address TP reduction to demonstrate compliance with VADEQ technical criteria, it is assumed that other pollutants—including TN and TSS—are being reduced, as well.

After years of procuring credits on a basis of pounds of TP for its TMDL permit, as well as its postconstruction needs, Virginia DOT's TMDL team realized that the achieved percentage of total required TN reductions lagged behind the achieved TP reductions. Virginia DOT also procures nutrient credits using phosphorus as the unit currency; however, the MS4 TMDL program is equally interested in nitrogen credits. Consequently, the team has changed its focus to creative approaches for achieving maximum TN reductions, which still includes nutrient credit purchases. By signaling to the market that Virginia DOT is interested in TN, bankers were able to adjust and offer competitive pricing from banks in which the land conversion practices had a relatively higher TN:TP ratio.

Nutrient Trading: Looking Forward

Nutrient credits may be used to achieve compliance with postconstruction stormwater quality regulations, provided that the site follows stormwater quantity regulations and that substituting credits does not violate any more-stringent local SWM ordinances.

This aspect has been further expanded with new regulations, which are to become effective September 1, 2020.[1] VADEQ developed the new regulations to protect the water quality upstream of existing impaired waters. The decision of how to protect these areas must be made without the benefit of an intensive, site-specific stream study. The postdevelopment water quality design criteria for new development and redevelopment in the SWM regulations were not created on a site-specific basis. Furthermore, Virginia's SWM law provides for the use of nutrient credits to meet the criteria under certain conditions.

The use of nutrient credits upstream of local water quality impairments that may be due to nutrients—or that are due to nutrients for which a TMDL has not yet been developed—creates the risk of additional degradation of an already impaired stream.

Photo: D. Allen Covey/Virginia DOT

Crews install a stormwater drainage system along Cold Harbor Road near Mechanicsville, Virginia. Virginia DOT projects include nutrient reduction requirements.

[1] To see the full text of the regulation, visit https://townhall.virginia.gov/L/ViewXML.cfm?textid=14299.

Decision Support System

In consideration of the pending regulatory changes, as well as the growing demand for stormwater nutrient reductions, Virginia DOT once again engaged VTRC and the University of Virginia to develop a semiautomated decision support system (DSS) to better address the following challenges associated with nutrient credit transactions:

1. Determining how to adhere to the Exchange's regulatory requirements, which require specialized knowledge of spatial restrictions and lead to time-consuming training and oversight among Virginia DOT personnel;
2. Understanding how projects undertaken by Virginia DOT contractors currently implement a variable evaluation process to consider nutrient credit purchase; and
3. Finding the best course to follow if the supply of nutrient credits is limited, as when a nutrient banker's contract with Virginia DOT expires or when contracted banks are not located near construction projects.

A long-term goal is to share the decision support system with the Virginia Department of Environmental Quality, helping guide all stakeholders toward future planning that results in long-term success, both for Virginia DOT and for the nutrient banking community.

These three issues limit the net benefit of Virginia DOT's participation in the nutrient credit market. A long-term goal is to share the DSS with VADEQ, helping guide all stakeholders toward future planning that results in long-term success, both for Virginia DOT and for the nutrient banking community.

In the meantime, Virginia DOT has recognized the value of nutrient credit purchases to achieve cost-effective compliance with its VADEQ SWM requirements and Chesapeake Bay TMDL pollutant reduction requirements. In response, the agency has embraced this opportunity and developed policies and processes to enable nutrient credit purchases when these are determined to be the best option.

Photo: Aileen Devlin/Virginia Sea Grant

Lightning illuminates a leaden sky at Mill Creek in Hampton Roads, Virginia. The commonwealth's nutrient credit exchange program extends to the state's Southern Rivers tributaries, as well.

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RESOURCES

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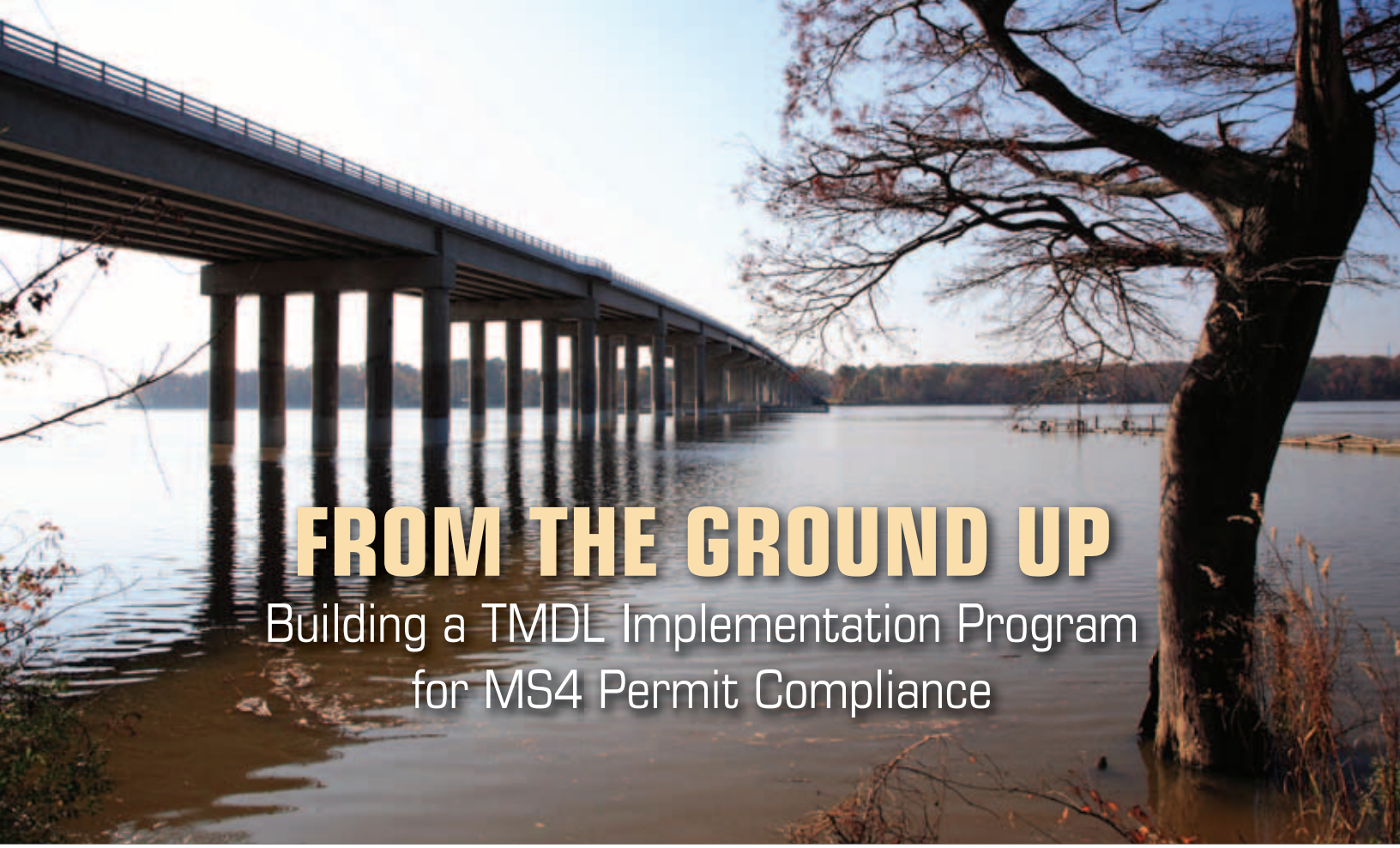
MS4 Program Plan for Urbanized Areas of Virginia. Virginia DOT, 2018.

Trading Nutrient Reductions from Nonpoint Source Best Management Practices in the Chesapeake Bay Watershed: Guidance for Agricultural Landowners and Your Potential Trading Partners. Virginia Department of Environmental Quality, 2008.



FROM THE GROUND UP

Building a TMDL Implementation Program for MS4 Permit Compliance

Photo: Al Covey, Virginia DOT

TRACEY HARMON

The author is TMDL Program Manager, Virginia Department of Transportation, Richmond.

Above: The Judith Stewart Dresser Memorial Bridge carries Route 5 over the broad expanse of the Chickahominy River, an 87-mile-long Virginia waterway that is part of the Chesapeake Bay watershed.

The Virginia Department of Transportation's (DOT's) municipal separate stormwater sewer system (MS4) permit contains specific conditions for the Chesapeake Bay Total Maximum Daily Load (TMDL) of pollutants. These conditions require that Virginia DOT estimate the existing loads and reduce the total nitrogen (TN), total phosphorus (TP), and total suspended solids from developed lands served by the MS4 permit. According to the permit, the 2010 Census–designated urbanized areas delineate Virginia DOT's service area (Figure 1).

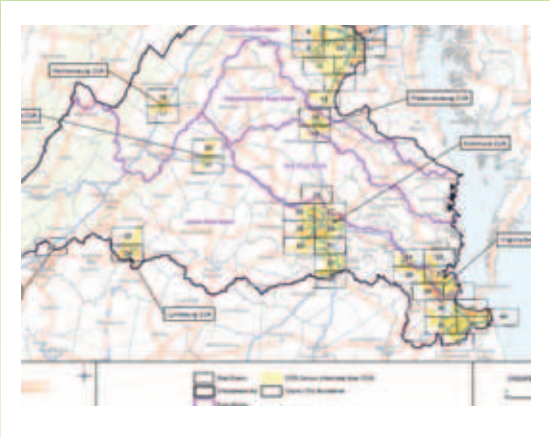
In Virginia, 11 urbanized areas encompassing 1,316,979 acres occur within the four major river basins contributing to the Chesapeake Bay watershed: the James River, Potomac River, Rappahannock River, and York River. Virginia DOT's service area covers 82,502 acres within the Chesapeake Bay watershed. Since part of its service area lies within each of these four river basins (Table 1), the permit requires Virginia DOT to determine its load and mandatory reductions for each basin.

The permit also requires Virginia DOT to develop an action plan with a schedule and list of best management practices (BMPs) to implement to achieve 36%

Photo: Tracey Harmon, Virginia DOT

A bare root seedling reaches skyward from a bed of wild grass in an I-295 interchange loop in the James River watershed. Virginia DOT planted it and other vegetation for nitrogen credits.

(a)



(b)

FIGURE 1 Maps of (*a*) the Chesapeake Bay watershed and (*b*) urbanized areas in Virginia's portion of the watershed.

reductions in each river basin independently by June 30, 2022.

Tables 2 and 3 (page 26) show the 36% reduction tables associated with the Potomac River Basin (Virginia DOT's largest service area by basin) and the Rappahannock River Basin (Virginia DOT's smallest service area by basin) in the action plan.

TABLE 1 Virginia DOT Service Area by River Basin

River Basin	Virginia DOT Service Area (acres)
James	29,404
Potomac	44,865
Rappahannock	3,914
York	4,274

Photo: Josh, flickr.com

Meandering 405 miles from the Potomac Highlands to the Chesapeake Bay, the Potomac River is Virginia DOT's largest service area by basin.

Implementation Planning

After determining the reductions required for permit compliance, Virginia DOT focused on how to achieve these reductions. Virginia DOT's BMP toolbox includes the following: 1) historical BMPs, 2) redevelopment on prior developed land, 3) stream restoration and stabilization, 4) outfall stabilization and restoration, 5) shoreline erosion control, 6) land cover conversion, 7) forest buffers, 8) street-sweeping and other annual pollutant removal efforts, 9) purchase of nutrient credits, 10) structural BMP enhancement and retrofits, and 11) incidental retrofits.

DUAL-BENEFIT APPROACH

Virginia DOT's approach to selecting BMPs focuses on the most cost-effective practices for achieving reductions, with an emphasis on practices that provide dual benefits to the agency or to other partners.

An example of a dual-benefit project opportunity involved an eroding stream channel between two Virginia DOT maintained roadways. Maintenance staff had invested hundreds of thousands of dollars in embankment stabilization efforts over several years, but erosion continued to threaten the roadway embankment, creating a significant safety hazard.

After evaluation, the TMDL team determined that a stream restoration project could provide a long-term solution to the problem, alleviating maintenance's annual expenditures on short-term remedies and generating 3,700 pounds of TP and 8,100 pounds of TN credits (see photos, page 27).

PARTNERSHIPS

Although the TMDL team identified and evaluated many project opportunities within Virginia DOT's right-of-way and properties and advanced some to implementation, they realized a need to pursue additional opportunities to achieve the required reductions.

One partnership involves the Virginia Department of Conservation and Recreation's (DCR's) Division of State Parks. Virginia DCR has long recognized the need for shoreline protection along several of its coastal properties. Virginia DOT now has a Memorandum of Agreement with Virginia

TABLE 2 Completed Potomac River Basin Calculation Table for 36% Cumulative Reductions

Pollutant	Subsource	2009 EOS Loading Rate (lbs/ac/yr)	Total Existing Acres Served by MS4 as of 6/30/2009	Loading (lbs/ac/yr)	MS4 Required Chesapeake Bay Total Loading Rate Reduction	36% of L2 Required Reduction by 6/30/2022 (lbs/ac/yr)	Cumulative Reduction Required by 6/30/2022 (lbs/yr)
Nitrogen	Regulated Urban Impervious	16.86	28,383	478,537	9%	0.546264	18,801
	Regulated Urban Pervious	10.07	15,156	152,621	6%	0.217512	
Phosphorus	Regulated Urban Impervious	1.62	28,383	45,980	16%	0.093312	2,811
	Regulated Urban Pervious	0.41	15,156	6,214	7.25%	0.010701	
Total Suspended Solids	Regulated Urban Impervious	1,171.32	28,383	33,245,576	20%	84.33504	2,477,611
	Regulated Urban Pervious	175.8	15,156	2,664,425	8.75%	5.5377	

Source: Chesapeake Bay TMDL Action Plan, Virginia DOT. Note: EOS = edge-of-stream.

TABLE 3 Completed Rappahannock River Basin Calculation Table for 36% Cumulative Reductions

Pollutant	Subsource	2009 EOS Loading Rate (lbs/ac/yr)	Total Existing Acres Served by MS4 as of 6/30/2009	Loading (lbs/ac/yr)	MS4 Required Chesapeake Bay Total Loading Rate Reduction	36% of L2 Required Reduction by 6/30/2022 (lbs/ac/yr)	Cumulative Reduction Required by 6/30/2022 (lbs/yr)
Nitrogen	Regulated Urban Impervious	9.38	2,451	22,990	9%	0.303912	905
	Regulated Urban Pervious	5.34	1,388	7,412	6%	0.115344	
Phosphorus	Regulated Urban Impervious	1.41	2,451	3,456	16%	0.081216	213
	Regulated Urban Pervious	0.38	1,388	527	7.25%	0.009918	
Total Suspended Solids	Regulated Urban Impervious	423.97	2,451	1,039,150	20%	30.52584	77,268
	Regulated Urban Pervious	56.01	1,388	77,742	8.75%	1.764315	

Source: Chesapeake Bay TMDL Action Plan, Virginia DOT.

Photo: Tracey Harmon, Virginia DOT

Photo: Ralph Tuck II, Whitman Requardt and Associates

After years of efforts and costly investment to stabilize an eroding road embankment (*above*) with short-term fixes, Virginia DOT launched a stream restoration project (*right*) that resulted in two clear benefits: it alleviated the maintenance staff's annual repair costs and generated 3,700 pounds of TP and 8,100 pounds of TN credits.

Photo: Tracey Harmon, Virginia DOT

Sun-bleached driftwood settles at the base of a stretch of shoreline in front of Belle Isle State Park's visitor center. Over the past 10 years, the shoreline has experienced 2 to 7 feet of loss per year. Partnering with Virginia DCR, Virginia DOT will stabilize the eroding shoreline by installing low breakwaters, sand backfill, and marsh plantings.

DCR to evaluate and pursue shoreline stabilization projects on select park properties experiencing severe shoreline erosion.

COST ESTIMATING

Throughout the planning and implementation processes, Virginia DOT's TMDL team used the TP cost-per-pound rate indicated in current Virginia DOT private nutrient bank credit contracts as a benchmark to evaluate the cost-effectiveness of BMP projects. The bank credit costs currently range from $11,800 in the James River to $16,000 in the Potomac River and serve as the threshold for maximum cost per pound of TP credit that Virginia DOT uses to determine which projects to pursue for TMDL crediting. However, Virginia DOT may choose to exceed that cost per pound of TP credit threshold in favor of other overriding dual project benefits.

The TMDL team also considers long-term maintenance and monitoring when estimating project costs, since credit purchases relieve those responsibilities. As Virginia DOT began completing projects,

TABLE 4 Virginia DOT's BMP Project Costs

Costs	Cost per Lb Nitrogen	Cost per Lb Phosphorus
Stream Restoration	$400–2,400	$1,100–5,200
Shoreline Stabilization	$1,700–2,900	$2,600–4,300
Land Cover Conversion	$700–1,500	$5,000–20,000
BMP Retrofits	$3,200–3,600	$14,000–16,000

TABLE 5 TN:TP Ratios Based on BMP Type

BMP Type	TN:TP
Land Cover Conversion	13.0
Redevelopment	7.6
Street Sweeping and Catch Basin Clean-Out	6.4
Retrofits	5.4
New Structural BMPs	3.7
Nutrient Credits	3.2
Stream Restoration and Stabilization	2.1
Outfall and Channel Stabilization	2.1
Shoreline	1.5

the TMDL team started using the costs from those projects to further refine the cost-estimating process and to prioritize projects for implementation (Table 4).

Compared with the cost to purchase nutrient credits, the TMDL team estimated that pursuing a combination of BMPs to achieve the 36% reductions would cost approximately $31.77 million less than credit purchases alone.

As Virginia DOT's TMDL team spread its message, more partnering opportunities unfolded—internally and outside of Virginia DOT. The list of potential external partners includes MS4 localities, federal facilities, public utilities, and nonprofit groups.

BMP Implementation

To carry out the BMP project implementation process, Virginia DOT utilizes several contracting mechanisms, including existing and new professional services contracts, nonprofessional services contracts, and low-bid contracts. Virginia DOT uses professional service contracts to conduct land and geotechnical surveys and develop designs and nonprofessional services contracts to develop and implement corrective action plans, conduct inspections, and monitor and report on project implementation based on task orders assigned.

These contract mechanisms have worked very successfully for program delivery and even resulted in one contractor submitting an unsolicited, full-delivery stream restoration project that will achieve 4,300 pounds of TP credits at a cost of $20.5 million. The scope of this consultant's turnkey project includes all property negotiations, plan development, construction, planting, monitoring, and long-term maintenance. Virginia DOT pays the contractor in phases tied to specific deliverables that demonstrate progress toward project completion, and Virginia DOT receives the nutrient credits as the restoration work progresses.

Nutrient Currency

While developing the action plan, Virginia DOT's TMDL team realized that the agency's TN reductions have lagged behind the TP reductions achieved. Consequently, the team changed its focus to creative approaches for achieving maximum TN reductions (Table 5).

Virginia DOT previously purchased TP credits—the typical nutrient currency—from nutrient credit bankers. Knowing that some banks generated TN in higher ratios to TP than other banks, Virginia DOT decided to test how the industry might approach selling credits using TN as the form of currency. The agency solicited and received bids for nitrogen credits that offered a more competitive rate than the comparable TP rate, so it purchased

Photo: Joseph Parfitt, Virginia DOT

During mowing season, Virginia DOT follows a less-is-more practice, as with a recently mowed shoulder along Route 288 in the James River watershed. By partially mowing the right-of-way during the growing season, the department saves mowing costs and can take credit for pollinator habitat. Virginia DOT also gets TMDL credits by maintaining the area as a meadow. The area beyond the shoulder will be mowed during the dormant season.

TN credits from banks in each of the four river basins.

At about the same time, Virginia DOT deployed a voluntary initiative to manage portions of the right-of-way as pollinator habitat via limited mowing (i.e., once per year during the dormant season). Seeing the dual benefits that the two programs could achieve cooperatively, the TMDL team partnered with the pollinator program and district roadside managers to map these locations.

The results of this collaborative effort far exceeded expectations. With mapping complete for four of the districts (Figure 2), the potential TN credits achieved through this land cover conversion practice (managed turf to unmanaged meadow) amount to more than 18,000 pounds of TN.

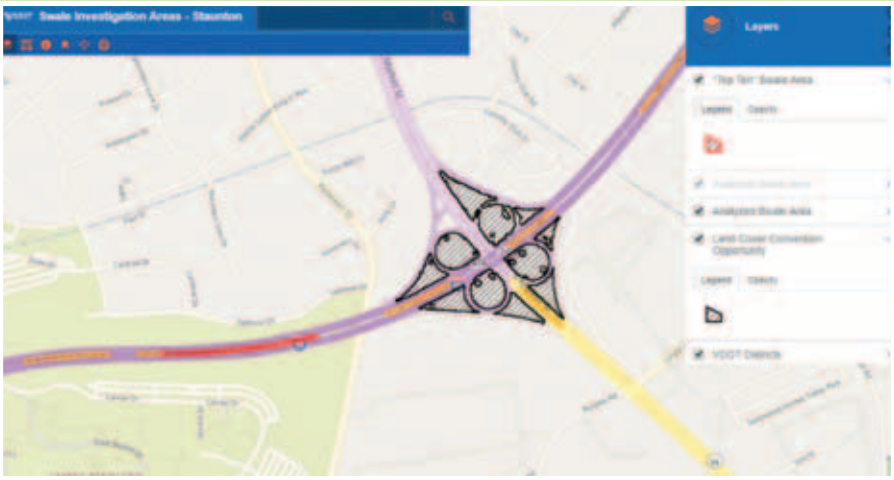


FIGURE 2 Combined mapping of potential land cover conversion and grass swale opportunities within Virginia DOT right-of-way.

Staffing

Staffing continues to rank as the biggest challenge to accomplishing the monumental efforts of planning and implementing the Chesapeake Bay TMDL action plan. Initially, the TMDL program consisted of one team member supporting the program on a part-time basis. Calculating the existing loads, developing, and implementing a plan for reducing those loads by 5% and 36%, respectively, proved to be quite a challenge for the small staff. So the MS4 Program enlisted the assistance of its professional services consultant to provide the staff and resources necessary to develop the action plan.

In 2016, Virginia DOT formally established the TMDL Program with two full-time positions. These staff members continue to use the MS4 Program's consultant services, as well as the Environmental Division's TMDL Implementation nonprofessional services contracts to support the planning and implementation roles. In 2019, recognizing the need for more support to effectively run the TMDL program, Virginia DOT contracted with two firms to provide staff augmentation on an on-call, as-needed basis.

TABLE 6 Virginia DOT's Chesapeake Bay TMDL Progress Through FY19

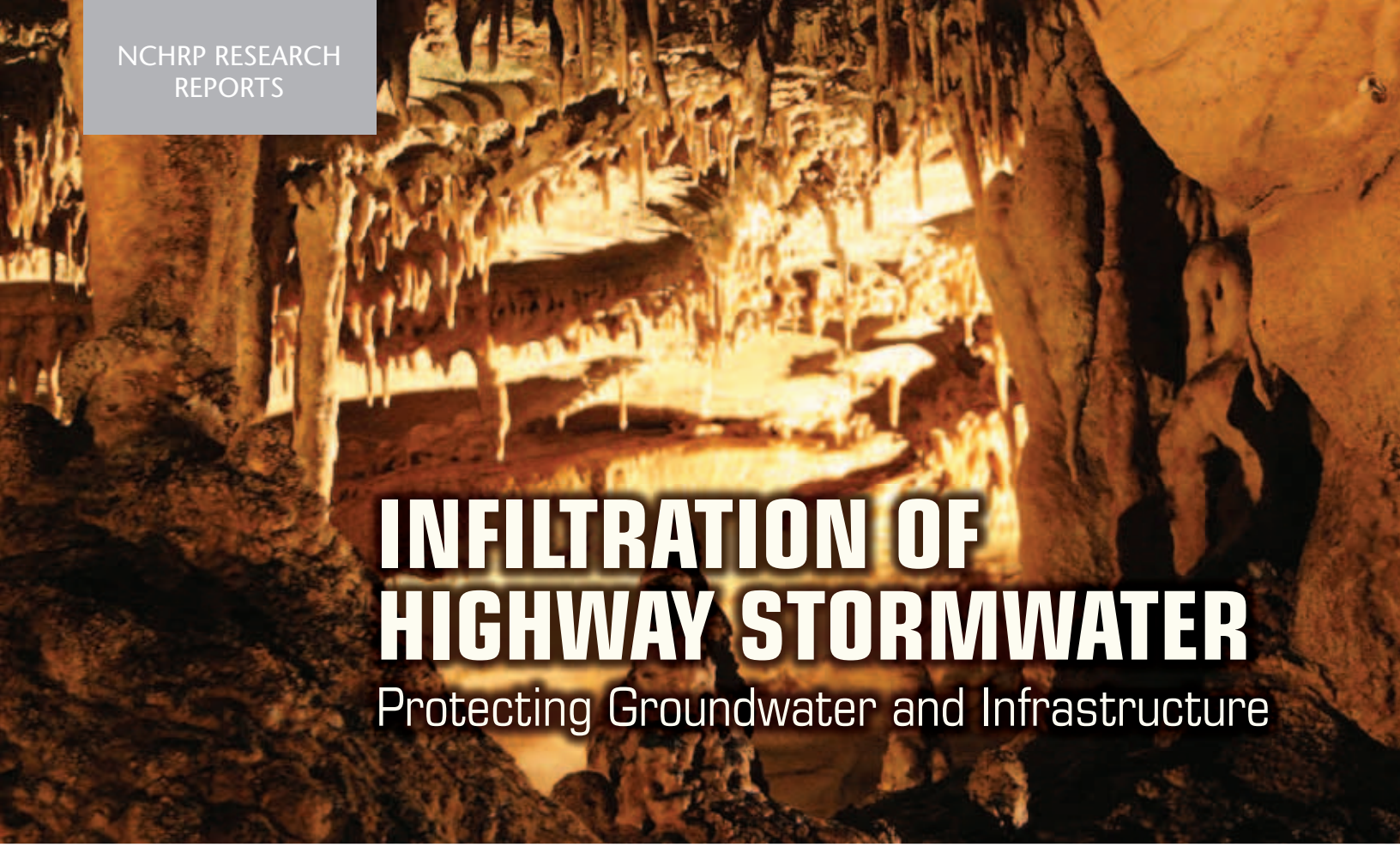
River Basin	%TN	%TP	Total Cost
James	38.16	27.85	$1.8M
Potomac	30.93	9.86	$7.6M
Rappahannock	120.92	21.11	$214K
York	19.94	7.27	$134K

Program Progress

Based on FY19 reporting to the Virginia Department of Environmental Quality, Virginia DOT has successfully achieved 20% to 121% TN reductions and 9% to 28% TP reductions across the river basins, at a total implementation cost of $9.7 million (Table 6). Virginia DOT anticipates achieving 9,779 pounds of TN and 3,815 pounds of TP by the end of the current permit year.

The TMDL Program will continue to pursue BMP opportunities and internal and external partnerships that provide dual or multiple benefits in the most cost-effective manner and will prioritize these opportunities using a scoring matrix. To that end, projections indicate that Virginia DOT will exceed the 36% reduction requirements in all four river basins by the end of FY21.

Virginia DOT's approach to selecting BMPs focuses on the most cost-effective practices for achieving reductions, with an emphasis on practices that provide dual benefits to the agency or to other partners.



INFILTRATION OF HIGHWAY STORMWATER

Protecting Groundwater and Infrastructure

Photo: National Park Service

ERIC STRECKER, TRACEY JANUS, AND AARON PORESKY

Strecker is Principal Engineer, Terraphase Engineering, Portland, Oregon; Janus is Geologist and Environmental Compliance Specialist, Texas Department of Transportation, Austin; and Poresky is Principal Engineer, Geosyntec Consultants, Portland, Oregon.

Above: Stalactites and stalagmites—formed over time when calcium salts from dissolved limestone are deposited by dripping water—create dramatically adorned subterranean chambers in Mammoth Cave, Kentucky. At more than 400 miles long, Mammoth Cave is the longest cave system in the world.

Stormwater National Pollutant Discharge Elimination System permits, sustainability and resiliency initiatives, and other pertinent regulations that apply to state departments of transportation (DOTs) increasingly have prioritized or mandated the consideration and use of infiltration best management practices (BMPs) in the highway environment.

There are growing, evidence-based concerns that, if appropriate factors are not adequately considered and addressed during planning, design, construction, and long-term maintenance, using infiltration BMPs for highway runoff may inadvertently lead to consequences to the natural and built environment. Some of these concerns include geotechnical and infrastructure issues; local increases in groundwater elevations and the impacts to infrastructure that can result; introduction, movement, or the presence of stormwater below ground pollutants; and unnatural base flows (especially in arid regions).

Additionally, state DOTs have encountered significant issues with failure of infiltration BMPs because of challenges in design, construction, or operations and maintenance. When implemented correctly, however, infiltration can have significant benefits: water supply augmentation; reduced downstream erosion and habitat degradation; enhanced (i.e., increased) dry-weather base flows in stream systems, where beneficial; and improved stream water quality.

With regard to infiltration practices, in some cases favorable conditions and proper pretreatment result in higher success rates. In other cases, feasibility clearly is limited because of such conditions as groundwater mounding (i.e., a localized increase in groundwater levels), poor soils, and other issues. Project locations with marginal feasibility tend to require more detailed investigations and careful design and implementation to meet design objectives while avoiding premature system failure.

This article summarizes new tools—developed via National Cooperative Highway

Photo: Tracey Janus

Profuse with speleotherms (stalactites, stalagmites, and other cave formations), the otherworldly wonder of Inner Space Cavern in Georgetown, Texas, was discovered in 1963, when a Texas Highway Department crew's drilling shaft accidentally pierced through the cave's roof. The unexpected discovery demonstrates the importance of thoroughly conducting geologic assessments when determining the feasibility of installing infiltration BMPs. You don't always know what's below the surface.

Research Program (NCHRP) projects—that can assist stormwater practitioners in evaluating infiltration BMPs for highway infrastructure projects. Highlighted are special considerations for utilizing infiltration BMPs in karst landscapes characterized by caves, sinkholes, swallets (i.e., stream-to-sinkhole features), underground streams, and springs.

Available Research and Guidance

Two recently completed NCHRP projects—NCHRP Project 25-41 and its report, *NCHRP Report 802: Volume Reduction of Highway Runoff in Urban Areas—Guidance Manual*, and NCHRP Project 25-51 and its report, *NCHRP Research Report 922: Stormwater Infiltration in the Highway Environment—Guidance Manual*—can help practitioners better understand the potential benefits and impacts of infiltration BMPs in highway settings (*1–2*). These guidance documents help practitioners identify potential limitations and environmental impacts of infiltration BMPs and design considerations for improving the success of infiltration BMPs. The two documents were developed to work together to provide comprehensive national guidance to state DOTs and other agencies.

Runoff Volume Reduction

NCHRP Report 802 provides an overview of issues in infiltration—the primary volume-control method used by state DOTs—as well as its benefits. It describes how reduction of stormwater has long been recognized as an effective method for controlling the impacts of urbanization on water resources. Key benefits of highway runoff infiltration discussed in the guidance include:

1. Reducing pollutant loads to receiving waters;
2. Reducing potential for downstream channel erosion;
3. Increasing groundwater recharge and augmenting water supply, stream base flows, or both; and
4. Reducing peak runoff flow rates.

The guidance discusses how implementing volume reduction approaches (VRAs) in highly urban settings presents challenges and constraints because of the limited space and lack of appropriate soils for typical stormwater management infiltration practices. Key questions are summarized in Figure 1. The team that developed *NCHRP Report 802* created a five-step process for evaluating runoff volume reductions for projects:

1. Establish volume reduction goals;
2. Characterize the project site and watershed;
3. Identify potentially suitable VRAs;
4. Prioritize VRAs; and
5. Select VRAs, and develop conceptual designs.

The manual was developed based on an extensive literature review, synthesis of available information, and focused technical analysis. The manual includes detailed white papers on infiltration testing or estimation methods, groundwater quality and water balance issues, geotechnical considerations, and permeable pavement considerations (Figure 2).

The accompanying volume performance tool is an Excel-based application that calculates planning-level estimates of long-term volume reduction—including the amount of runoff that is infiltrated, evapotranspired (i.e., surface- or soil-evaporated or transpired via plants), and discharged to surface conveyances—from user-provided location and planning-level project information. In most state DOT situations, infiltration would be the primary mechanism for reducing the volume of surface runoff. But, the tool also accounts for evapotranspiration loss, which can be a significant runoff loss mechanism (Figure 3).

The tool was based on results of thousands of long-term simulation analyses of rainfall and runoff using precipitation data from more than 300 precipitation gauges and considering various watershed and BMP designs. This provides coverage for each of the climate divisions in the contiguous United States. The application can be updated using additional precipitation stations and modeled data, allowing state DOTs to use the application as a starting point to develop their own application to meet additional needs they have, including increasing the density of climate gauges in their state. The project's final report and appendixes are available online as *NCHRP Web-Only Document 209* (*3*).

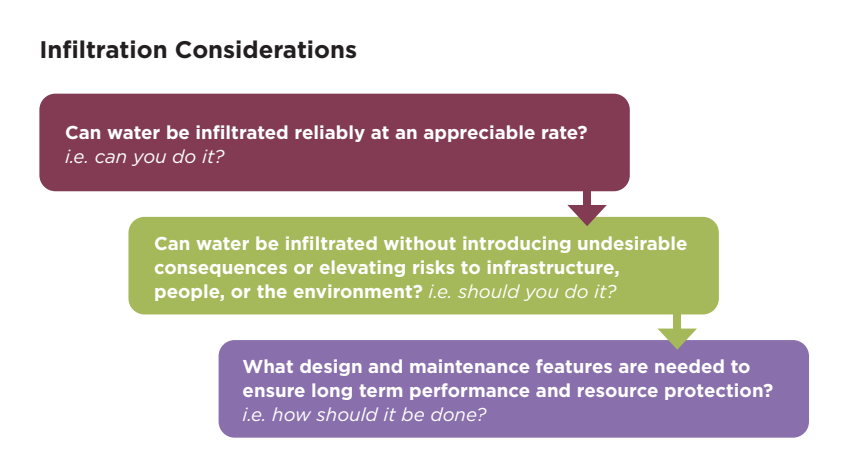


FIGURE 1 Questions to answer when considering and designing infiltration BMPs. (Source: *NCHRP Research Report 922*, slide 10.)

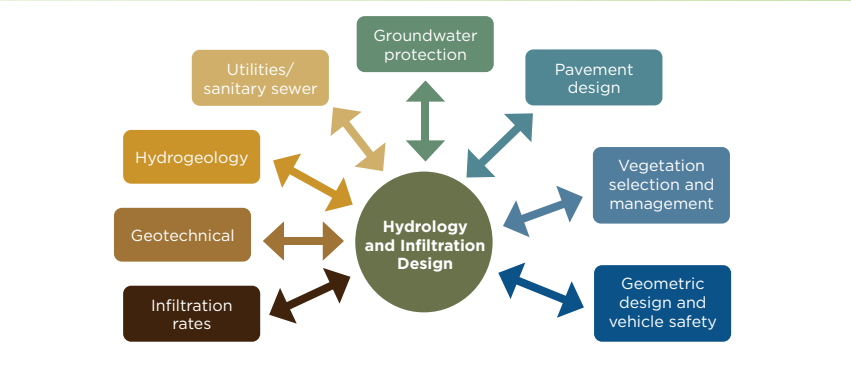


FIGURE 2 Considerations and potential investigations for selecting and designing infiltration BMPs. (Source: Eric Strecker and Aaron Poresky.)

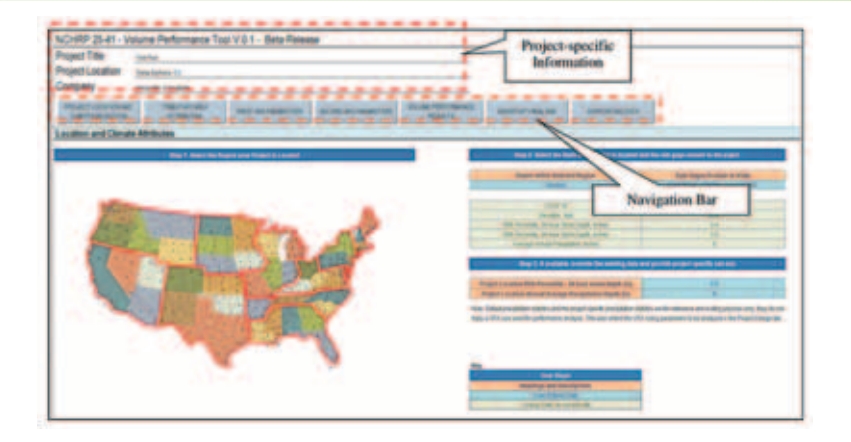


FIGURE 3 Screen capture of volume performance tool showing some of the input information and precipitation gauges included. (Source: *NCHRP Report 802*.)

Creating a Framework for Decisions

NCHRP Research Report 922 builds on *NCHRP Report 802* by providing more-detailed guidance that is based on a decision-making framework oriented around the phases of the project design and delivery process. The guidance addresses a broad range of issues and needs associated with selecting, siting, designing, and constructing infiltration BMPs for roadway stormwater mitigation. These include the following:

1. Limitations (e.g., cost, maintenance, regulatory, receiving waters, geotechnical, and so on);
2. Effects of climate, soils, topography, geology, vegetation, and land use;
3. Effects of pollutants of concern on surface water and groundwater quality;
4. Effects on surface water and groundwater quantity (e.g., recharge, base flow augmentation, and groundwater mounding);
5. Gaps in the body of knowledge; and
6. Options for improving the effectiveness and reducing risks from the use of infiltration BMPs (e.g., improving adaptability or resiliency to uncertain conditions).

The guidance was informed by an assessment of case studies of successful and not-so-successful infiltration systems installed by state DOTs throughout the United States. It was also informed by detailed interviews with state DOT program managers and design teams. From this, the research team identified key challenges faced by these groups and distilled some of the underlying factors that support the success of infiltration BMPs.

This research informed the development of the decision framework presented in *NCHRP Research Report 922*. This framework is intended to help state DOTs make early and efficient decisions about the use of infiltration, including identifying favorable, marginal, and clearly unsuitable sites. This helps focus state DOT investigation resources on the sites where they are most needed. It also identifies more-resilient design options for marginal or uncertain

conditions that can achieve some level of infiltration but that will continue to perform water quality functions with less investigative effort and less risk.

Several topical appendices provide focused technical guidance on key steps in this framework, including extensive guidance on which appropriate investigations to conduct and how to do so (e.g., detailed infiltration testing guidance). Three software tools offer users efficient planning-level calculations related to localized groundwater mounding, potential groundwater quality impacts, and BMP and subsurface clogging. Examples of outputs from two of these tools are shown in Figures 4 and 5.

NCHRP Research Report 922 also contains detailed fact sheets on 10 infiltration practices, providing helpful selection and design guidance by practice and BMP type, including conceptual layouts and state DOT examples. These fact sheets and the guidance include information about how to increase the resiliency of the designs so that infiltration BMPs can perform their overall mission—reducing pollution and runoff quantity issues—under a variety of circumstances. In essence, these materials will help reduce the pressure to conduct a precise site investigation and will avoid the need to first evaluate failure causes and then, in some cases, to rebuild failed systems—actions that are expensive and could cause compliance issues.

One appendix covers cold and arid climate design considerations. Another appendix provides a checklist for designers, construction managers, and contractors to help identify and mitigate issues during the construction phase. The guidance also includes case studies that utilized its approach and tools, as well as case studies on past failures of infiltration systems from which state DOTs can learn. These case studies were used early in the project to identify where additional guidance was needed and, therefore, helped inform the tools developed for *NCHRP Research Report 922*.

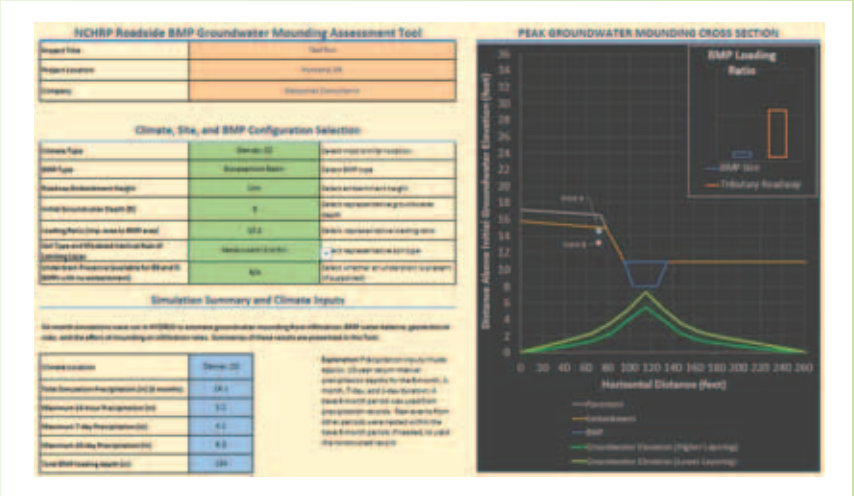


FIGURE 4 Example input and output visualization from *NCHRP Research Report 922* (Project 25-51) groundwater mounding assessment tool. Based on calibration of the HYDRUS model to four actual sites with groundwater and surface water data, the tool then was used to run various scenarios with precipitation gauges from around the United States to develop a planning-level tool that highway runoff system designers can use to evaluate the potential for localized mounding. (Source: *NCHRP Report 922*, slide 50.)

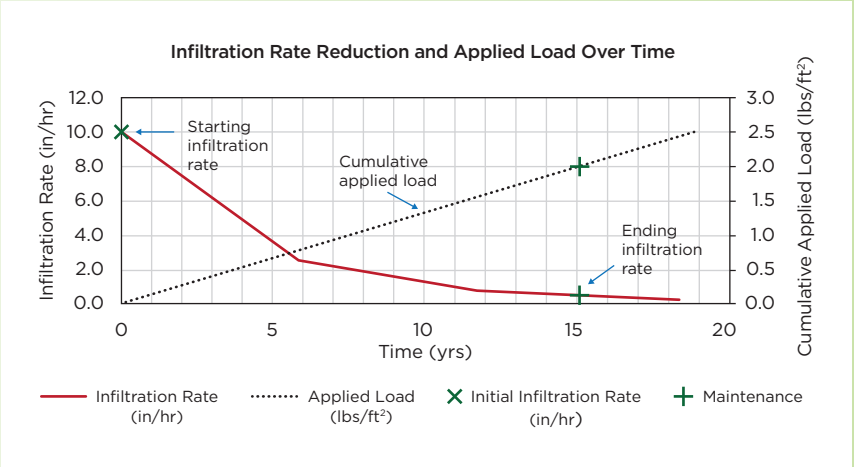


FIGURE 5 Example results from *NCHRP Research Report 922* (Project 25-51) roadside BMP clogging risk assessment tool for infiltration rate reduction and applied load over time. This tool can be used to predict when maintenance will be required, which then can inform long-term costs. (Source: *NCHRP Report 922*, slide 70.)

Infiltration BMPs in Karst Regions

Karst areas, also discussed in both *NCHRP Report 802* and *NCHRP Research Report 922*, are a unique and important type of landscape characterized by caves, sinkholes, swallets, underground streams, and springs. Some of the more spectacular (and famous) examples of karst landscapes are the cenotes of the Yucatán Peninsula in Mexico and the expansive South China Karst Region, a UNESCO World Heritage Site. These places and others like them were formed when soluble bedrocks like carbonates and evaporates were chemically dissolved over many thousands of years by the actions of naturally acidic waters.

Approximately 18% of the United States is underlain by karst formations and another 7.1% is underlain by pseudokarst—a little more than 25% of the United States in total (*4*). U.S. territories, including Puerto Rico and the U.S. Virgin Islands, also contain karst regions (*4*). Examples of prominent U.S. karst features include Mammoth Cave in Kentucky—the longest cave system in the world—and the Crystal Springs National Wildlife Refuge in Florida, a wintering ground for hundreds of Florida manatees.

IMPORTANCE OF KARST

Karst systems are important economic and environmental resources, playing a crucial ecological role as natural water distribution systems supporting underground and aboveground ecosystems. Many threatened and endangered species inhabit specific ecological niches within karst systems and are important ecological indicators of the health of those systems. Karst systems are also important economic resources. Drinking water resources from karst aquifers support millions of people in those regions nationwide. Many recreational and commercial activities, especially tourism and agriculture, rely heavily on healthy karst systems.

Karst systems recharged by surface waters can be especially susceptible to contamination from polluted sources such as highway stormwater runoff. In a typical aquifer recharge scenario, water slowly trickles through soil layers and contaminants are filtered out before the water enters a deeper aquifer, like water filtered through a backpacker's survival kit device.

In karst systems, however, water does not often have the luxury of filtering itself before entering the aquifer system. Discrete recharge features (such as caves, sinkholes, and swallets) provide much more direct pathways for contaminated runoff to drain directly into the aquifer system, similar to the way a kitchen sink drains as one washes dishes. Unless a strainer is used as a filter, everything goes down the drain. This is why water quality treatment measures in karst regions are important to reduce roadway pollutants as much as possible to minimize impacts to karst systems; however, these measures must be appropriate to the geologic setting.

CONSIDERATIONS FOR KARST REGIONS

When evaluating the appropriate use of infiltration BMPs in karst regions, state DOTs must consider the potential impacts to karst systems from failures, such as groundwater contamination and structural failures; whether the site conditions are conducive to infiltration, considering adequate soil thickness, the condition of the epikarst, and the distance to bedrock and water table; and whether the municipal and state regulations even allow infiltration systems and under what conditions.

Karst systems recharged by surface waters can be especially susceptible to contamination from polluted sources such as highway stormwater runoff.

In Central Texas, the Edwards Aquifer karst system is the single most important sustaining water resource for millions of Texans. Because of the importance of the resource, the Texas Commission on Environmental Quality (TCEQ) has implemented water quality treatment requirements over portions of the Edwards Aquifer. The treatment requirements are based on the percent removal of total suspended solids caused by the increase in impervious cover from the new development.

Additionally, in the regulated portions of the Edwards Aquifer, different requirements are applied to the different zones: the recharge zone, contributing zone, transition zone, and contributing zone within the transition zone. TCEQ's technical guidance manual for complying with the Edwards Aquifer rule requirements lists selection, design, and maintenance criteria for the various approved BMPs (*5*): capture–treat–release systems, such as the typical sand filter pond; permeable pavements; grassy swales and vegetated filter strips; and a variety of proprietary devices.

Infiltration basins and trenches were purposely excluded from the technical guidance manual, however, because of groundwater contamination concerns and the suitability of site conditions (i.e., soil type and geology). The technical guidance manual does include some infiltration BMPs, with limitations; namely, 1) that permeable concrete is excluded from the list of approved BMPs for the recharge zone and 2) that bioretention systems, wet and dry ponds, and permeable pavers must incorporate liners when utilized in the recharge zone.

The environmental criteria manual for the City of Austin, Texas, establishes similarly strict requirements for their Edwards Aquifer regulatory boundaries, including the use of impervious liners in BMPs in which surface runoff and groundwater connectivity could exist. It also limits the use of porous pavement–type BMPs to locations with pedestrian and low-volume vehicular traffic, such as parking lots (*6*). Additionally, they do not grant water quality credit for permeable friction courses.

Photo: Larry D. Moore

Cool waters flow from Comal Springs, the largest spring system in Texas. Seven major springs and many smaller ones emerge along portions of the Comal Springs Fault, bisecting Landa Park in New Braunfels. Comal Springs is part of the Edwards Aquifer karst system, one of the world's most prolific artesian aquifers and the greatest natural water resource for millions of Texans.

Texas is not the only place with restrictions on infiltration BMPs in karst regions. The Minnesota Pollution Control Agency's Construction General Permit prohibits infiltration in areas within 1,000 feet upgradient or 100 feet downgradient of active karst features and requires impermeable liners for BMPs located in active karst terrain (*7*). This regulation is not only to protect water quality but also to protect the karst structures and adjacent infrastructure.

In addition to the contamination concerns related to infiltrating stormwater runoff in karst landscapes, geotechnical concerns include the additional weight of water—known as hydraulic head—from structural BMPs. This weight can cause increased loading on unstable subsurface conditions, leading to cave roof and sinkhole collapses. Seeping from increasing or redirecting infiltration can reactivate subsurface karst features, causing them to unplug and collapse.

In 2018, part of a neighborhood road in Round Rock, Texas, collapsed, revealing a large cave underneath (*8*). The cave, later named Cambria Cave, had no natural entrance and predated the road and neighborhood. This particular karst feature was missed during design and construction, as is occasionally the case. The likely cause of the collapse was a leaking water line slowly dripping on an already-thin and structurally unsound cave roof. Although not caused by an infiltration BMP, this example demonstrates how karst systems can react to water's actions when not properly mitigated.

Sustainability of Infiltration Systems

Infiltration BMPs themselves can also be problematic from a long-term sustainability perspective. Research has demonstrated that infiltration BMPs can be susceptible to premature failure or substandard performance resulting from a variety of causes, including:

- Incomplete or insufficient feasibility studies;
- Clogging that is due to excessive sedimentation, lack of pretreatment (either during site construction or after construction is complete), or both;
- Soil compaction and unexpected groundwater mounding; and
- Lack of maintenance or other issues.

These inducements could leave karst systems or other subsurface strata susceptible to pollution and contamination issues. There are many potential consequences if incorrect considerations are made when selecting and implementing infiltration stormwater controls, especially in sensitive systems like karst regions, other challenging geologic conditions, or sole-source aquifers.

Photo: Minnesota Pollution Control Agency

A veil of greenery surrounds a cave opening at Stagecoach Spring near Watson Creek in southeastern Minnesota's karst region. Without filtering or protection, water flowing directly into the porous karst system makes it susceptible to contamination, reinforcing the importance of BMPs to protect groundwater resources.

Summary

Although infiltration can and does provide many benefits, in most cases infiltration BMPs require in-depth investigations—which can be extensive and costly—in order to avoid problems. Infiltration of highway runoff presents risks to state DOTs, the public, and the environment when proper evaluations are not conducted or when infiltration BMPs have not been carefully designed or constructed. National Cooperative Highway Research Program guidance and tools can provide great assistance to state DOTs looking to incorporate infiltration BMPs into their highway designs by scoping infiltration BMPs and determining their feasibility before investing time and personnel to conduct in-depth studies.

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Innovation Through Embracing Uncertainty

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Planning and designing stormwater management facilities for future climate change starts with embracing the uncertainty in the understanding of existing hydrology patterns. National Cooperative Highway Research Program (NCHRP) Project 15-61, Applying Climate Change Information to Hydrologic and Hydraulic Design of Transportation Infrastructure, explored techniques for estimating projected precipitation for design of stormwater management facilities and other infrastructure and encouraged better use of existing hydrologic uncertainty.

Figure 1 shows an example of the 24-hour duration design rainfall depths from the National Oceanic and Atmospheric Administration Atlas 14 for Denver, Colorado, for a range of annual exceedance probabilities. Atlas 14 also quantifies the uncertainty of these estimates based on historical observations by providing the 5% and 95% confidence limits. These confidence limits represent a range of possible values for this estimate. Today, designers do not typically consider these estimates in design.

Using one of the techniques developed under NCHRP Project 15-61, the figure also shows projections of precipitation for a future period (2050–2099). Though each case is different, in this case the projected values (dashed lines) show an increase over the historical values (solid lines) and that the increase is within the range of historical uncertainty. Therefore, embracing uncertainty by using the known variability in the historical record can help researchers and policy makers prepare more resilient stormwater management facilities in the face of climate change.

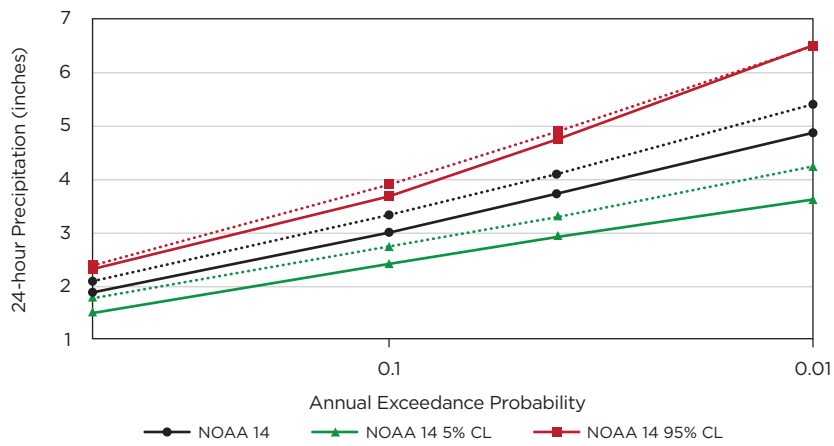
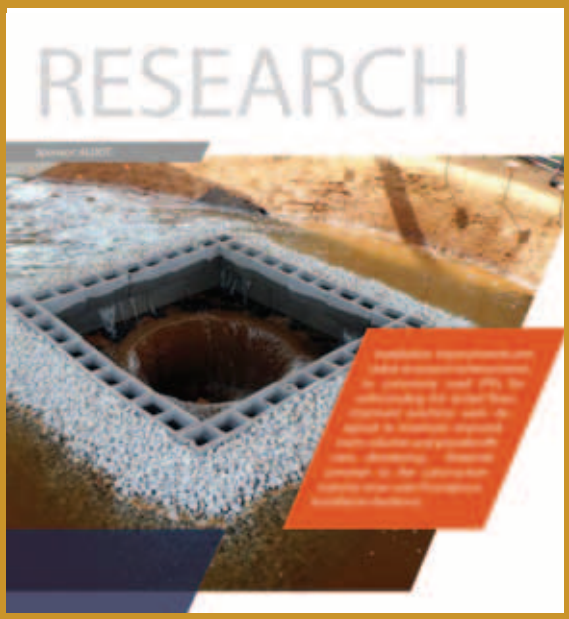


FIGURE 1 Twenty-four-hour duration design rainfall depths for Denver, Colorado. (Source: *NCHRP Project 15-61: Applying Climate Change Information to Hydrologic and Hydraulic Design of Transportation Infrastructure—Design Practices*, 2019.)

Innovation in Design-Based Guidance of Temporary Controls

The U.S. Environmental Protection Agency (EPA) has identified sediment as a major concern in roadway transportation projects. Therefore, the safe and effective protection of the nation's streams from sediment during construction is a concern for all state departments of transportation. Innovations are needed in design-based guidance of temporary erosion and sediment controls to help ensure permit compliance. Since most of these controls lack design-based guidance, they often are inappropriately installed and subjected to excessive flows or sediment loads that lead to failure.



Among the practices tested at AU-ESCTF are ditch checks, inlet protection, sediment barriers, sediment basins, and erosion control. (Image: AU-ESCTF)

For example, Ohio EPA guidance for inlet protection requires 12–18 inches of ponded water in most cases; however, these controls are not practical for most roadway projects. Ponded water can be a safety hazard if the water spreads out into traffic lanes. The construction industry has had to deal with these problems associated with sediment controls at inlets for many years.

Manufacturers responded to this issue by developing proprietary devices that specifically addressed the common concerns on roadway projects. Unfortunately, the guidance provided by Ohio EPA does not have specific performance criteria listed with which the Ohio Department of Transportation can assess the qualifications of these transportation-friendly controls. As a result, decisions about which inlet protection to be used on a project may be based more on cost, ease of maintenance, and safety rather than actual pollutant removal effectiveness.

In this case, design-based guidance from the state EPA would enable project managers to approve proprietary erosion and sediment controls with confidence. This type of guidance would ensure permit compliance with safe and effective alternative temporary erosion and sediment controls.

Innovation in Additional Research Applications

Sometimes additional research is needed to address local- or region-specific stormwater management concerns not otherwise addressed by federal or state guidance. For example, the Auburn University–Erosion and Sediment Control Testing Facility (AU-ESCTF) was developed in 2009 to partner with transportation agencies to develop performance-based guidance, testing, and training for the erosion and sediment control industry.

Through several research projects, AU-ESCTF researchers have investigated performance and optimized the design and installation of ditch checks, inlet protection practices, sediment barriers, sediment basins, and erosion control practices. Researchers focused on evaluating practices using large-scale testing methods and local hydrologic parameters, as well as typical highway construction layouts to determine testing flow and sediment introduction rates to mimic expected site conditions. Enhancements to practices based on performance testing results typically involved additional structural support, techniques to prevent undermining and scour, and dedicated mechanisms for controlled overtopping or bypassing when flows exceed design capacities.

This research has resulted in a suite of erosion and sediment control practices that are designed to withstand the hydrodynamic and static forces resulting from rainfall events in the southeastern United States, while maximizing the practices' desired performance. As research continues to evolve at AU-ESCTF, researchers are focusing on evaluating the treatment train—or practices installed in series—to understand their performance.

To disseminate its latest research findings, AU-ESCTF conducts annual training, since many professionals are not in the field during rainfall events to document and understand how practices fail. Hands-on installer workshops allow practitioners to learn proper installation methods and techniques. Field days showcase stormwater practices using live flow to demonstrate performance and typical failures.

More information about AU-ESCTF research can be found at http://www.eng.auburn.edu/research/centers/auesctf/index.html.

Five Pillars of Construction Stormwater Management

Photo: Barry Fagan

BARRY FAGAN

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Above: Contractor crews manage water, erosion, and sediment as work progresses—parts three through five of the five pillars approach.

The unique character of the transportation environment often presents challenges associated with managing construction stormwater runoff and protecting receiving waters. Traditional guidance and regulation do not always distinguish between residential, commercial, and linear development. If inappropriate and ineffective practices are implemented or expected by regulators, it can create inefficiencies for the transportation stormwater professional.

Transportation projects typically cross multiple watersheds and have many outfalls. The topography eliminates the possibility of utilizing the regional or single projectwide treatment approaches that sometimes are possible with nonlinear development. Available right-of-way and treatment areas typically are also more limited in a transportation setting.

Slope lengths and steepness, the types of soils encountered, seasons of construction, and proximity to surface waters usually are not all chosen at the discretion of the roadway designer and contractor. Many of these variables are beyond the control of the transportation stormwater professional and are not accounted for by a traditional approach to managing construction stormwater.

To fulfill its mission of providing for the movement of people and goods, a transportation agency must engage in activities that can negatively affect the environment. This potential for impact triggers environmental responsibilities in the form of regulatory requirements and social expectations (Figure 1). These responsibilities, if left unfulfilled, can lead to costly delays in project delivery and can affect the fulfillment of the agency's mission.

Traditional Erosion Control

Historically, construction stormwater management has focused primarily on the symptom of stormwater-related issues—sediment in the receiving water, sediment in the wetland, and sediment deposited on adjacent property. Sediment is still largely a primary target of management efforts,

even though the phrase "erosion control" is often used to describe this focus.

As stormwater management efforts evolved, practices from agricultural advancements in soil conservation were implemented for transportation-related development. An approach of supplementing sediment management with minimizing the detachment of soil particles became accepted as the basis for best management practices plans. The addition of erosion management and targeting the source of suspended sediments caused management efforts to become more effective.

Although this approach of simultaneously managing erosion and sediment is logical and more effective than managing sediment alone, transportation agencies still struggle to maintain regulatory compliance and to protect receiving waters during construction.

Different Approach

Faced with ever-increasing regulatory scrutiny and a realization that traditional stormwater management approaches largely were ineffective in a transportation setting, stormwater professionals at the Alabama Department of Transportation (DOT) began to explore approaches that were outside of those prescribed by regulation and existing guidance materials. In the 2000s, Alabama DOT engineers recognized the risk of combining the uncontrollable variables previously described with goals and standards intended to merely achieve regulatory compliance. This check-the-box approach led to several high-profile, expensive stormwater-related calamities on Alabama DOT projects.

As Alabama DOT realized that managing the source of suspended soil particles was more achievable than total capture and control of the particles in transport, the agency also began to recognize the role the runoff itself plays in the actions of erosion and sediment transport and deposition. Both erosive energy of stormwater and its sediment-carrying capacity can be significantly reduced by simply slowing the runoff.

Alabama DOT also began to see water entering its projects as worthy of protection and developed a mantra: "clean water in, clean water out."

Water is a common factor in erosion and sediment transport. Applying the knowledge of the benefits of slowed water, stormwater professionals began shifting from the unachievable goal of capturing all projects' waters to the more attainable goal of simply slowing down the waters as they ran over and across a construction site.

Alabama DOT also began to see water entering its projects as worthy of protection and developed a mantra: "clean water in, clean water out." The agency worked hard to develop ways to keep run-on and flow-through waters separated from runoff from areas where required soil-disturbing activities were taking place. Temporary open and enclosed diversions were employed to convey water across, under, and around areas where sediment-laden waters could cause these clean waters to become dirty and trigger a need for sediment control.

Soon, *managing water* became as important and critical to managing construction stormwater runoff as *managing erosion* and *managing sediment*.

But Alabama DOT didn't stop there. Construction stormwater professionals studied the Revised Universal Soil Loss Equation (RUSLE) to better understand the mechanics of soil loss and see how they could further improve Alabama DOT's program.

RUSLE is an erosion model developed principally by the U.S. Department of Agriculture's Agricultural Research Service. The model predicts the average annual soil loss resulting from raindrop splash and runoff from slopes, given rainfall, slope, soils characteristics, land cover types, and management practices (Figure 2). The units of the product of the model were particularly intriguing: tons per acre per year; in other words, the mass of transported soil per area of disturbance per duration of disturbance.

Alabama DOT questioned whether it could reduce the area of disturbance and the duration of disturbance in order to reduce the soil loss from its project. The agency decided that through *managing the work* of the contractor, it could.

Alabama DOT saw that its contractors were smart, capable, innovative, and ready to do just about anything the agency needed—if the work and the method of payment was fully described before bid submittal. Effectiveness lies more in how the contractor performs the work rather than what the contractor installs. Effectively managing the work of the contractor requires the acknowledgement and acceptance of a few basic points:

- The contractor works for the owner–agency, not the other way around;
- The interests of the owner are different from the interests of the contractor and should be considered and protected; and

FIGURE 1 Environmental responsibilities are directly connected to a transportation agency's mission.

$$A = RKLSCP$$

FIGURE 2 Revised Universal Soil Loss Equation. (A = average annual soil loss in tons per acre per year.)

Photo: Barry Fagan

Soil disturbance is limited and delayed as a contractor completes one section of roadway before advancing its clearing operations. The project demonstrates the second of the five pillars: managing the work to minimize the area and duration of erodible materials.

- The means and methods employed to construct the project can be directed by the owner to ensure favorable project outcomes.

The understanding that an agency must first tell the contractor up front revealed a practice that perhaps should have been the first to be implemented during the evolution of Alabama DOT's construction stormwater program. After some thought toward practical application, Alabama DOT declared *managing communication* to be the best management practice for managing construction stormwater.

Effectively communicating the priorities and expectations of leadership to the contractor can be more effective than any sediment barrier. Contractually directing the delay and limitation of soil disturbance is much more effective than any brand of erosion control blanket. Promoting the required continuous pursuit of permanent stabilization in specifications and mandatory pre-bid meetings can save money, minimize project conflicts, and promote environmental protection and regulatory compliance.

Photo: Barry Fagan

An Alabama DOT work truck serves as a reliable impromptu display for construction plans during a mandatory preconstruction onsite stormwater meeting. The gathering represents the first of the five pillars in action: managing communication.

Based on these experiences, Alabama DOT developed and implemented a new, fundamental approach for managing construction stormwater. This approach prioritized effectiveness over compliance and economy over prescription. It made sense to designers, inspectors, and contractors as Alabama DOT implemented the concepts into its training, processes, and specifications. The approach was coined "The Five Pillars of Construction Stormwater Management."

Photo: Barry Fagan

A contractor provides permanent stabilization as the work progresses. Alabama DOT requires continuous pursuit of final stabilization, including application of topsoil and permanent ground cover in vertical increments of 20 feet in excavation areas.

Five Pillars

The five pillars of construction stormwater management are to be implemented in order of effectiveness and economy. They include the following actions, in order:

1. Manage communication,
2. Manage work,
3. Manage water,
4. Manage erosion, and
5. Manage sediment.

A state DOT can choose to focus solely on *managing sediment*, but it runs the risk of soon communicating with regulators, neighbors, attorneys, and reporters about the lack of management in the other areas.

The five pillars have been implemented in planning and design, during construction, and while troubleshooting issues on ongoing projects and have been applied to many types of development projects, including transportation, residential, commercial, and even utility-scale solar facilities.

Over the past decade and a half, Alabama DOT has more fully fleshed out the five pillars approach and has added to it, as better practices have supplanted best management practices of yesterday. The approach has been shared with and adopted by transportation and other agencies and organizations across the United States.

Two state DOTs are currently working on new applications of the five pillars. Ohio DOT is using the concept to categorize its practices in a new construction stormwater manual developing and implementing stormwater pollution prevention plans. The agency has also drafted an update to its construction stormwater management specifications that will incorporate the five pillars. Hans Gucker, Ohio DOT's construction hydraulic engineer, has observed that the new framework is a means of strategically bringing and clarifying meaningful and effective change to the Ohio DOT construction stormwater program.

Nebraska DOT is currently incorporating the five pillars into a construction stormwater management chapter of its drainage design manual. Nebraska DOT highway environmental program manager Ronald Poe has encouraged adoption of the five pillars as a way to update Nebraska DOT's design standards to reflect the state of practice for managing construction stormwater in a transportation environment.

Conclusion

The five pillars of construction stormwater management represent a holistic and fundamental approach to managing construction stormwater in a transportation environment. The approach has been successfully implemented by transportation agencies and deployed on construction projects in linear and nonlinear settings. The five pillars may be applied at any stage of project development and delivery to enhance effectiveness, reduce risk, and promote regulatory compliance.

Photo: Michael Perez, Auburn University

Linear (*left*) and nonlinear (*right*) construction sites vary greatly in appearance and in stormwater management needs. A one-size-fits-all approach to regulation, implementation, or both may not be completely appropriate or effective.

What *Is* Green Infrastructure?

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Green infrastructure is defined and perceived in various ways, depending on the setting. This article provides a clearer understanding of the term as it is applied at the intersection of natural and built environments.

According to some, "green infrastructure" was first coined in the early 1990s as a means of elevating the status of natural systems to equal or above what has been viewed as traditional infrastructure. If professionals look comprehensively at the root of the term, then they may discover that definitions based on personal understanding may not be complete. What some have declared to be infrastructure is often simply a reflection of their own relatively limited experiences.

Generally speaking, infrastructure could be viewed as including the basic physical and organizational structures and facilities needed for the operation of a society or enterprise. This basic definition of infrastructure is timeless. However, it also allows for what constitutes an element of infrastructure to adapt to the operational needs of society as those needs also inevitably change over time. Unlike the fixed general definition of infrastructure, the face of infrastructure changes with nearly every generation.

The "green" of green infrastructure simply connects the term to the natural environment (Figure 1). More specifically, it represents the application of advancements in knowledge and the application of natural materials and processes in delivering infrastructure services. It also hints at current infrastructure needs and expectations of today.

Low-impact development, or LID, is sometimes used interchangeably with green infrastructure. The essential intent and benefits are similar, but there is a clear distinction between the two terms. Low-impact development is an approach to delivering infrastructure that minimizes impacts to the natural environment. Green infrastructure describes the elements that are being preserved or constructed.

Infrastructure—the basic physical and organizational structures and facilities needed for the operation of a society or enterprise

Green—of, or related to, the natural environment

Green Infrastructure—structures and facilities that utilize natural materials and/or natural processes to deliver services to help meet the current needs of society

FIGURE 1 Definition of green infrastructure.

Stormwater control measures—sometimes known as best management practices—are utilized to implement low-impact development and green infrastructure. Stormwater control measures include structural elements, such as permeable pavements and bioswales, as well as nonstructural approaches, such as designing new development to reduce the percentage of impervious surfaces (*1*).

Green infrastructure may represent built (or engineered) elements or describe preserved, protected, or restored natural ecosystems necessary to help meet society's current demands. Engineered green infrastructure elements may include bioretention swales and cells, permeable pavements, green roofs, rainwater harvesting facilities, and constructed wetlands. Natural green infrastructure might include healthy forests, natural wetlands, riparian buffers, and rivers and streams.

Natural green infrastructure often provides benefits—or ecosystem services—such as provisioning, regulating, and cultural services. Examples of benefits associated with these services are included in Figure 2. Some of the social, environmental, and economic benefits of engineered green infrastructure are also included in Figure 2.

Photo: Barry Fagan

Dappled with sunlight, Alabama's Chief Ladiga Trail represents a nonstormwater-related function of green infrastructure. Its natural setting provides all of the ecosystem benefits that go along with healthy forests.

Photo: Barry Fagan

Pervious concrete surrounds the softscape of a bioretention planter, which serves a vital function on this Nashville, Tennessee, street. Natural materials, such as vegetation and soil, and natural processes, such as infiltration, detention, transpiration, and evapotranspiration, help manage stormwater runoff.

- Food, raw materials, and energy supply
- Water treatment and purification
- Urban stormwater quantity and quality management
- Flood mitigation
- Subsidence mitigation and groundwater recharge
- Air pollution abatement and quality enhancement
- Heat island reduction
- Energy cost reductions
- Increased urban biodiversity
- Animal, pest, and disease control
- Greenhouse emissions reduction
- Carbon sequestration
- Climate resiliency
- Infrastructure sustainability
- Community placemaking for recreation and social connection
- Therapeutic, cultural, and spiritual services
- Educational services
- Varied physical and mental health benefits to humans with associated cost reductions
- Enhanced social mobility and connectivity
- Increased property values

FIGURE 2 Benefits of green infrastructure and other ecosystem services

The "green" descriptor also serves to differentiate nature-based infrastructure elements from more traditionally constructed gray infrastructure, such as closed storm sewer systems and ditches with rigid linings. For example, in the context of the infrastructure service of managing stormwater and wastewaters, gray infrastructure often describes those constructed facilities that do not incorporate natural processes or natural materials or do not provide collateral benefits associated with greener solutions.

Green infrastructure tends to reduce negative stormwater runoff-related effects of development through infiltration, transpiration, evapotranspiration, retention, detention, and peak flow rate attenuation. Gray infrastructure may cause these effects of development to increase. Green infrastructure also helps to reduce the negative societal impacts of heat, air, and noise pollution by providing shade, dispersing and diluting airborne pollutant concentrations, and buffering noise.

The work of those who manage and deliver infrastructure where natural and built environments meet must reflect a mindset of flexibility, stewardship, and a holistic view of societal needs. Advancements in the awareness of the benefits of green infrastructure and in the technology of its application have created more opportunity than ever to maximize returns on infrastructure investment.

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Keeping the Water Clean

How Transportation Agencies Manage Roadway Stormwater Runoff

Photo: NC Wetlands

ANNA LANTIN

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Above: An effective TMDL management plan would offer innovative approaches to stormwater management, like this constructed stormwater wetland in Apex Nature Park near Raleigh, North Carolina.

State transportation agencies own and operate streets and highways that extend for many miles and cross rivers and streams, bodies of water, watersheds, and jurisdictions. Transportation authorities are required by the Clean Water Act (CWA) to manage the stormwater runoff that discharges to the nation's waters through regulated municipal separate stormwater sewer systems (MS4s) along streets, roads, and highways.

When a water body does not meet established water quality standards, the state transportation agencies contributing to the water body impairment may be subject to mandates in CWA Section 303(d), Impaired Waters and Total Maximum Daily Loads (TMDLs).

According to the U.S. Environmental Protection Agency, TMDL "establishes the maximum amount of a pollutant allowed in a waterbody and serves as the starting point or planning tool for restoring water quality." State departments of transportation (DOTs) and local agencies are mandated by TMDLs to comply with these stringent water quality regulations (Figure 1). Agencies commit resources, including extensive

Photo: MN Pollution Control Agency

The Clean Water Act mandates that state DOTs manage stormwater runoff. As stormwater makes its way through the streets and storm sewers, it picks up nutrients, dirt, salt, fertilizers, pesticides, oil, bacteria, and trash along the way. Reducing runoff pollution helps minimize the impact of stormwater on the watershed.

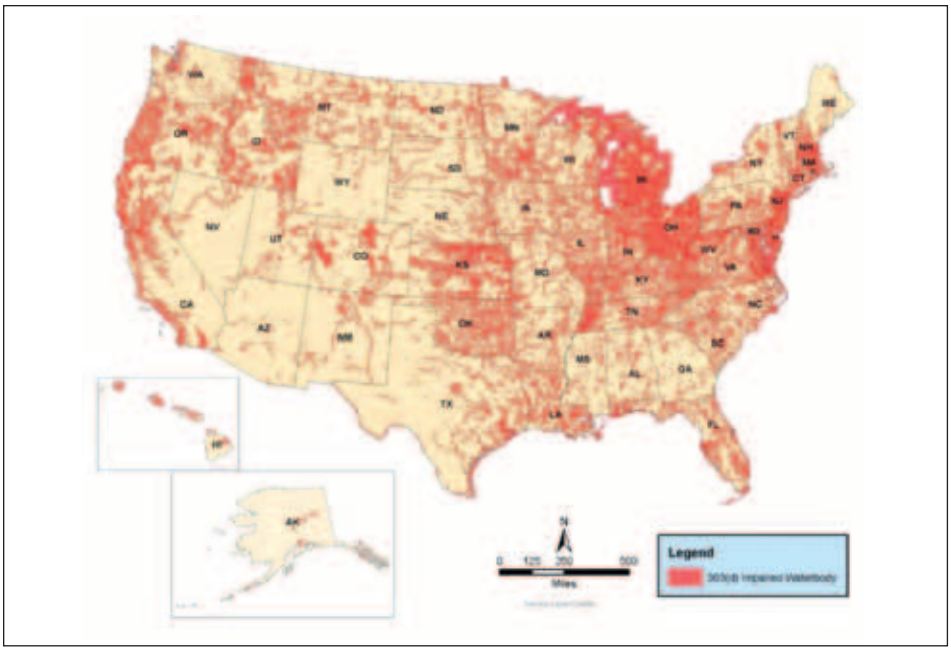

FIGURE 1 Impaired bodies of water in the United States.

staff time and capital, to implement institutional controls and other best management practices (BMPs). State DOTs or MS4s are named as stakeholders in TMDL management plans and are required to achieve their designated waste load allocation (WLA). As the number of impaired bodies of water continues to grow and the WLA compliance deadlines become more aggressive, state DOTs could benefit from tools that provide practical information on strategic options to address TMDL requirements.

TMDL Plan Objectives

TMDL management plans are designed to achieve the following objectives:

- Identify common pollutant sources to establish appropriate WLAs in TMDL analyses;
- Discuss the approaches that were used to determine the significance and contribution of stormwater pollutants from runoff relative to other land uses within a given watershed, so that appropriate WLAs are set in TMDL analyses and compliance strategies;
- Summarize the approaches to analyze performance and the practical feasibility of implementing traditional structural and nonstructural BMPs commonly used by state DOTs and MS4s to achieve water quality improvement to the watershed; and
- Highlight innovative approaches (e.g., stormwater banking, pollutant trading, offsite mitigation, offsite source control, and other holistic compliance strategies) that can be quantitatively demonstrated to provide an equal or greater benefit to the watershed and receiving waters than traditional structural and nonstructural BMPs.

Compliance Challenges for State DOTs

Across the nation, state DOTs and other transportation agencies increasingly are being named designated management agencies or stakeholders in TMDL implementation plans. As such, state DOTs are increasingly challenged to treat stormwater runoff from highways and meet TMDL WLAs within impaired watersheds. Because of varying site constraints and poorly defined highway pollutant source contributions, it can be extremely difficult to evaluate and select TMDL compliance approaches that are feasible for state DOTs to implement and that contribute to measurable improvements in receiving water quality and ecological function.

Implementing stormwater BMPs in highly urbanized areas presents several challenges, including right-of-way availability, site constraints, geotechnical requirements, safety, and cost. These constraints limit the capabilities of a state DOT to implement control measures to treat the runoff from its right-of-way. Furthermore, although highways can be a significant source of some pollutants, they may only be a minor contributor to other pollutants, or the pollutant of concern may have its origins outside the highway right-of-way and be unrelated to the operation or maintenance of the road. Consequently, the state DOT may have little to no control over the source of the pollutant.

The portion of the total pollutant load attributable to the state DOT may be small compared with the total load reduction needed, resulting in a nominal improvement in the receiving water and primary pollutant sources remaining unaddressed. Understanding highway runoff contributions and identifying the sources of pollutants is critical for developing cost-effective TMDL management plans that make the best use of public funds. Often, a combination of strategies is needed to mitigate impacts on receiving waters and to meet overall TMDL goals.

Across the nation, state DOTs and other transportation agencies increasingly are being named designated management agencies or stakeholders in TMDL implementation plans.

Photo: Mississippi Watershed Management Organization

Dust rises as a street sweeper lumbers down an avenue in Northeast Minneapolis, Minnesota. Successful TMDL plans integrate a combination of strategies to mitigate runoff impacts on receiving waters.

Photo: Will Parson, Chesapeake Bay Program

Effective control strategies for metals and toxic pollutants would prevent erosion and prohibit or minimize the discharge of fine sediment, such as microplastics found in Maryland's Patapsco River.

Compliance Strategies

Regulatory agencies and MS4s could achieve more efficient control strategies through a comprehensive analysis of pollutant sources, BMP performance, the identification of water body impairments, and actual watershed loads. Examples of these strategies by pollutant category are described in the following sections.

SEDIMENT AND NUTRIENT CONTROL STRATEGIES

The sediment, nutrient, and mercury TMDLs typically identify the significant or primary sources of these pollutants within the watershed. If a control strategy prevents the discharge of sediment, then it will be effective in controlling the release of particulate-bound nutrients (e.g., organic nitrogen and phosphorus). MS4s can achieve this by intercepting and filtering runoff, avoiding concentrated flows in natural channels and drains, and preventing modifications to natural runoff flow patterns.

METALS AND FINE PARTICULATES CONTROL STRATEGIES

Toxic pollutants and heavy metals tend to adhere to fine sediment such as particles from tires, brake parts, and road surfaces. Therefore, the appropriate control strategies for metals and toxic pollutants will prevent erosion and prohibit or minimize the discharge of fine sediment. MS4s can achieve this by intercepting and filtering runoff, avoiding concentrated flows in natural channels and drains, and preventing modifications to natural runoff flow patterns.

DISSOLVED FRACTION METALS CONTROL STRATEGIES

The fraction of metals that is not bound to particulates exists in a dissolved state as free metal ions, inorganic complexes, or bound to dissolved organic chemicals. Although fine particulate removal also reduces dissolved fraction metals, additional control strategies may be necessary for the control of dissolved metals.

Typically, the treatment for dissolved fraction metals requires physical structures that prevent contaminated runoff from reaching receiving waters, such as infiltration systems that allow runoff water to percolate into the soil.

BACTERIA CONTROL STRATEGIES

Bacteria TMDLs generally include requirements for dry- and wet-weather flows. Dry-weather nonstormwater discharges may significantly increase bacteria loading in receiving waters. Therefore, bacteria TMDLs generally include a dry-weather TMDL component that requires the implementation of control strategies.

The prohibition of nonstormwater discharges can be achieved via infiltration, diversion, or other methods. Wet-weather stormwater discharges also add significant bacteria loads to receiving waters affecting beneficial uses such as water-contact recreation. To address this pollutant, MS4s can implement control strategies to prevent or eliminate the discharge of bacteria, including source control and preemptive activities such as street sweeping, cleaning up illegally dumped materials, public education campaigns for litter, and structural BMPs such as retention and detention devices, infiltration devices, and diversion of stormwater.

CHLORIDE CONTROL STRATEGIES

If elevated levels of chloride exist in receiving waters, they can affect the classification of the waters' beneficial use. MS4s that discharge salt from roadways, especially during cold-weather applications, may contribute to increased chloride in runoff. The control strategies that MS4s can use to prevent chloride include institutional controls, alternative products, or containment and treatment devices.

NCHRP Research Report 918

Approaches for Determining and Complying with TMDL Requirements Related to Roadway Stormwater Runoff

NCHRP Research Report 918: Approaches for Determining and Complying with TMDL Requirements Related to Roadway Stormwater Runoff provides practitioner-ready guidance on how state DOTs can develop and implement effective strategies for compliance with a National Pollutant Discharge Elimination System permit that includes a TMDL requirement. The guidance also describes how to select and prioritize cost-effective compliance strategies for relevant pollutant types and site conditions, including offsite, watershed-level strategies. The guidebook is relevant to stormwater practitioners and decision makers engaged in evaluating and complying with TMDL requirements.

Priority pollutants (Table 1) were selected based on state DOT TMDL WLAs that had the majority of classifications. Although other pollutants are likely of interest in certain situations, the pollutants listed in Table 1 are assumed to represent the primary constituents for TMDL development for all state DOTs.

Roadway runoff pollutant concentrations are influenced by contributions from stormwater run-on, vehicle deposition, atmospheric fallout, and highway maintenance (Figure 1). An understanding of the magnitude and controllability of these sources is an essential step in determining equitable WLAs and planning management actions. The report presents data sets that state DOT practitioners can use to assess the impacts of land use, soil type, and atmospheric deposition on downstream water quality.

TABLE 1 TMDL Pollutant Categories and Pollutants Targeted for Analysis in *NCHRP Research Report 918*

Pathogens *E. coli* Fecal Coliform	**Metals** Aluminum (Al) Arsenic (As) Cadmium (Cd) Copper (Cu) Iron (Fe) Lead (Pb) Manganese (Mn) Mercury (Hg) Zinc (Zn)	**Organic Enrichment / Oxygen Depletion** Biochemical Oxygen Demand (BOD) Dissolved Oxygen (DO)
Nutrients Nitrogen, Total Nitrogen (TN), Nitrate/Nitrite ($NO_{2,3}$ as N) Nitrogen , Total Kjeldahl Nitrogen (TKN) Phosphorus, Total Phosphorus (TP), Dissolved Phosphorus (DP)		**Salinity / Dissolved Constituents** Chloride (Cl) Total Dissolved Solids (TDS)
		Sediment Total Suspended Sediment (TSS)

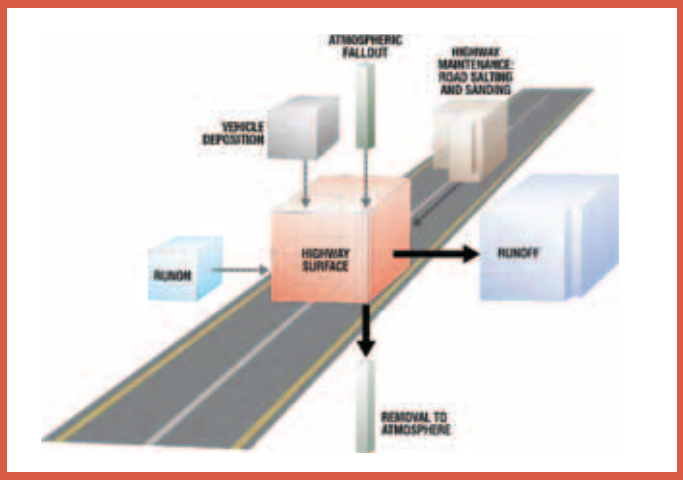

FIGURE 1 Concept of roadway pollutant load mass balance.

The report includes:

- An introduction to how TMDL requirements are negotiated and how state DOTs can effectively engage in the TMDL development process;
- Detailed information on how state DOTs can calculate their responsibility for pollutants of concern, taking into account the contributions of other land uses, stormwater pollutants that are deposited from the atmosphere, sources directly related to the use of the roadway, and soil characteristics;
- Step-by-step guidance on how to select stormwater treatment options that are matched to the pollutant types and with the performance capability to attain TMDL compliance;
- Information on evaluating the cost effectiveness of selected strategies; and
- The potential for alternative and innovation solutions, such as trading programs, that allow state DOTs and other partners to develop an overall, watershed-level collaboration to meet water quality requirements.

NCHRP Research Report 918 draws from a detailed and extensive review of research and practice to provide guidance to state DOTs seeking an evidence-based approach to TMDL compliance.

The link to download the report can be found at www.trb.org/NCHRP/Blurbs/179158.aspx.

State Water Quality Requirements Addressed Through the Use of an Innovative Pavement

MICHAEL BARRETT

Barrett is Research Professor, Cockrell School of Engineering, The University of Texas at Austin.

FIGURE 1 Visual comparison of the reduction in spray from PFC containing crumb rubber (left-hand lane) and continually reinforced concrete pavement (right-hand lane).

Requirements for stormwater treatment often are difficult to address in the limited space available in highway rights-of-way (ROWs). This is especially true in urban areas where the pavement of many roadways extends almost to the edge of the ROW. Texas Department of Transportation (DOT) had an opportunity to investigate how pavement type affects the quality of stormwater runoff.

Problem

The Clean Water Act enacted by Congress in 1972 requires an assessment of waterbodies to determine whether they meet water quality standards for their intended uses. U.S. Environmental Protection Agency (EPA) data from 2004 to 2016 indicate that more than 43,000 waterbodies do not meet standards and are considered impaired (*1*). The pollutant responsible for the impairment is termed the "constituent of concern." A Total Maximum Daily Load (TMDL) is developed for each of these systems to determine the total discharge of the constituent of concern that would allow the waterbody to meet standards. Entities, including state DOTs, must then reduce their discharge of that constituent.

Stormwater runoff is a common source of many pollutants. For state DOTs, reducing their discharge requires implementing stormwater treatment facilities within the ROW to treat the runoff prior to discharge to a natural waterbody. Because of space constraints in the ROW, state DOTs often struggle to implement these facilities, particularly in urban areas. In addition, the State of Texas has also adopted requirements for stormwater treatment from new highways located in the Edwards Aquifer recharge and contributing zones. The Edwards Aquifer extends from north of Austin through San Antonio, a highly developed area where implementation of stormwater treatment facilities is also limited by available ROW—especially for projects involving roadway expansion.

Solution and Application

Texas DOT funded a multiyear study, conducted by the University of Texas at Austin, to determine the quality of runoff from various pavement types, including permeable friction course (PFC) and conventional hot-mix asphalt, as well as a PFC containing crumb rubber. This was the first study in the United States to investigate the potential water quality benefits of PFC. PFC is known in many states as open-graded friction course (OGFC). PFC is a roughly 50-millimeter-thick porous asphalt overlay with widely recognized benefits, including reduced noise, elimination of splash and spray, and better friction characteristics in wet weather. The reduction in spray is readily apparent in Figure 1, in which the left-hand lane is PFC containing crumb rubber and the right-hand lane consists of continually reinforced concrete.

Several locations in the Austin area were selected to compare stormwater runoff quality from roadways paved with PFC to those paved with conventional asphalt. The monitoring results showed that runoff from the PFC pavements had substantially lower concentrations of total suspended

solids (TSS), phosphorus, copper, lead, and zinc compared with conventional asphalt pavement (*2*). The reduction in TSS, which is the regulated constituent for the Edwards Aquifer area, is especially high, exceeding 90% reduction. Figure 2, from a site on Loop 360 in Austin, provides a dramatic example of the lower TSS concentrations—storm by storm—compared with conventional asphalt from two sites located less than 100 meters apart.

Additional studies of the pollutant removal abilities of PFC have been conducted by other researchers in North Carolina and California (*3–4*), as well as in European countries such as The Netherlands and France (*5–6*), with similar findings. One of the surprising findings of the North Carolina DOT study was that the sites monitored were nearly 10 years old, yet they provided the same water quality benefits as new PFC in Texas. This was the case even though no maintenance was performed to restore or preserve the permeability (*3*). At 10 years, North Carolina DOT determined that the structural life of the pavement had been reached, so it was milled and replaced.

These results indicate that the water quality benefits will last for the entire structural life of the pavement without any maintenance. These pavements will clog at the lower traffic speeds typical of city streets, however, and in these cases the impact of tires on standing water is insufficient to redistribute the accumulated sediment. Texas DOT funded research indicates that 55 mph is sufficient to keep the pavement porous and permeable.

Benefits

This research showed that roadways paved with PFC/OGFC produced runoff with substantially reduced concentrations of solids, phosphorus, and metals compared with conventional pavement. Texas DOT presented the results of this monitoring effort to the Texas Commission on Environmental Quality, which approved the use of PFC to meet state standards for pollutant reduction on the Edwards Aquifer. This means that Texas DOT now has a way to achieve compliance with regional water quality standards by treating the runoff within the pavement itself and that no routine maintenance is required when used on roadways with a posted speed limit of 55 mph or greater. The only potential downside is that PFC costs approximately 25% more than conventional asphalt. It has been widely used in Texas just for the benefits associated with better visibility and greater safety, however.

PFC may provide a solution for other agencies, as well. Since the runoff is treated within the footprint of the roadway, no additional ROW is required. That makes implementation relatively easy compared with other approved stormwater treatment systems. Potential cost benefits may depend, in part, on the cost of additional ROW and materials needed to install more traditional treatment systems. The PFC option can be especially beneficial for state DOTs responding to TMDLs, where retrofit of existing highways in urban areas may be required and where space is extremely limited. Further, many state DOTs already have a standard specification for PFC/OGFC, which means that they can achieve the environmental benefits using a paving system that they have already approved.

For more information, contact Michael Barrett, The University of Texas at Austin, at 512-968-6783 or michael.barrett@utexas.edu.

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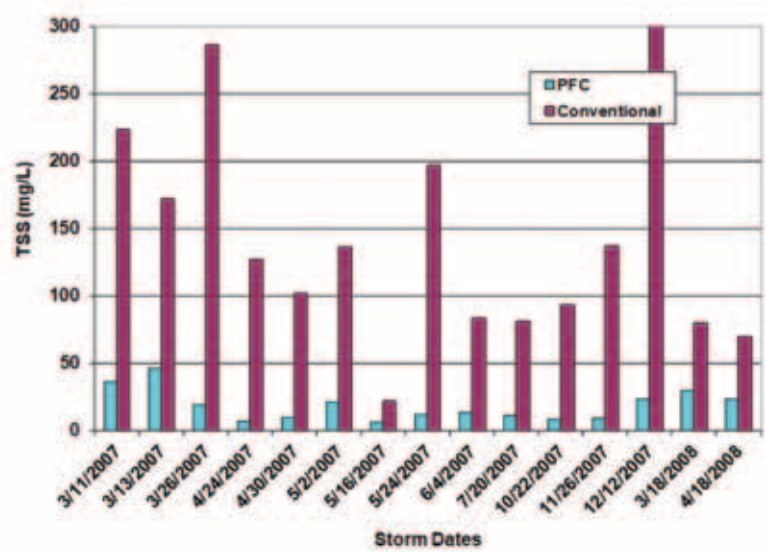


FIGURE 2 Example of lower TSS concentration—storm by storm—in PFC compared with conventional asphalt from Loop 360 in Austin, Texas.

Brian K. Currier

California State University, Sacramento

Brian K. Currier's transportation career began during an undergraduate fellowship at the University of California (UC), Davis' Institute of Transportation Studies, where he helped model electric and hybrid vehicle performance. But Currier's true interest was in environmental engineering, and he went on to earn his bachelor's and master's degrees in civil and environmental engineering from UC Davis.

After graduating, Currier worked with the university to coordinate research efforts on the seminal California Department of Transportation (Caltrans) best management practices retrofit pilot study, which involved multiple engineering and environmental firms, clean water stakeholders, regulators, and Caltrans experts. He presented that work at the 2001 Transportation Research Board (TRB) Annual Meeting.

In his current position as a research engineer at California State University, Sacramento, Office of Water Programs (OWP), Currier continues to combine his interest in environmental engineering and transportation. His day-to-day state department of transportation (DOT) research involves improving inlet design, trash removal, maintenance reduction, and stormwater treatment. "As a researcher, I contribute to the base of knowledge that can then be used to improve practices at transportation agencies with diverse needs and conditions," he notes.

One such study looked at installation practices for cured-in-place storm drain pipe. "A failure in California caused regulators to fear the technology and threaten a moratorium," Currier explains. "We performed laboratory and field experiments, adapting the test procedures that Bridget Donaldson at the Virginia Transportation Research Council developed—learning from and building on the work of others. We found that the issue was a failure to follow—and enforce—the specification. By following a specification with modest improvements, the resulting rinse water was fairly benign to aquatic life within a day in dry conditions. In this case, the research allowed a practice to remain in use rather than to invent a new technique."

After more than 20 years in the transportation research industry, Currier has developed a clear understanding of the benefits of research and the multiple roles of a researcher. "We make time to volunteer where we see potential for meaningful impact," he comments. "For state DOTs, two particular areas of benefit are to seek efficient solutions through cooperative management of stormwater with municipalities and to advance pollutant source control beyond reducing environmental exposure to reducing pollutants in the environment—think reducing copper in brake pads. In these two areas, the return on investment for state DOTs is substantial compared with going it alone to meet ever-tightening water quality standards."

"Research is wasteful if it doesn't empower the right audience."

Currier points out a less-obvious role of a researcher: providing institutional knowledge in specialty areas. "A long-term relationship between a state DOT and researchers can help avoid substantial expense in relearning lessons in technical practice and regulatory compliance that are difficult to capture in department manuals," he explains.

Another role of research, Currier adds, is to empower people with knowledge: "Research is wasteful if it doesn't empower the right audience. We need to work across disciplines to supply the public—as well as government and elected officials—with the information needed to evolve policy *and* technology. Consequently, the highest benefit for researchers is the nontechnical work of developing relationships needed to empower others."

Currier's involvement with TRB and other transportation organizations fosters just such relationships. He contributed to forming the Stormwater Committee, of which he has been vice chair since 2017; serves on National Cooperative Highway Research Program Project Panel 25-61; and is a member of the Standing Committee on Hydraulics, Hydrology, and Stormwater. Since 2015, he has been on the board of directors of the California Stormwater Quality Association, and the organization has presented him with multiple awards. He has also presented peer-reviewed papers at many professional conferences and published his work in industry journals. Since starting with OWP in 2002, he has been the principal investigator on more than $7 million in research.

"Research also means learning from mistakes," Currier admits. "We tend to devalue our failures, but documenting why something *didn't* work is critical. That goes for sharing personal lessons, as well. In my case, focusing solely on technical work was alienating and translated into terse communication and failure to value and promote others.

"Today, I recognize that every milestone in my career is due to someone's personal endorsement rather than my technical accomplishments," he continues. "Make a list of those who promoted you, and you will be inspired to promote others. So, thank you, Ken, Ed, Steve, Bruce, Pamela, Lisa, John, and others who have promoted me—overtly and subtly."

Mark W. Horner

Florida State University

Mark W. Horner's research focuses on questions of how effectively transportation systems serve and facilitate the accessibility needs of different geographies and population groups. "I'm particularly concerned with how well our most disadvantaged and vulnerable populations are represented in this nexus," he notes.

As Professor of Geography at Florida State University (FSU) and Associate Dean for Research in FSU's College of Social Sciences, Horner teaches courses in transportation, geographic information systems, and graduate-level research design. "My role as Associate Dean for Research is multifaceted, but a key responsibility is facilitating externally funded research within our college," he adds.

The topic of accessibility has extensive applications in the transportation field, and it is an important factor underlying many research questions, Horner observes. Transportation systems provide accessibility. They offer people the means of reaching the goods and services that they need to sustain their daily lives—for example, buses to reach supermarkets or private vehicles to take children to daycare—and in emergency situations such as hurricanes, when people need to evacuate their homes and depend on roadways to reach relief services.

"There also is a transportation dimension at work when we think about people getting health care, for instance. It's a great example of accessibility as a part of the set of considerations that go into people reaching a doctor's appointment," Horner comments. "The value of research is that it can shed light on needed improvements and modifications that can help our systems work more equitably and fairly overall.

"With very detailed geographical data that we have available today on transportation systems, passenger demand, activity and opportunity locations, and other key information, we are in an excellent position to better understand the nuances of how our infrastructure affects people's well-being," he adds. "From finding new jobs to purchasing healthy food, it is essential for people to have good transportation options."

Over the course of his career, Horner has secured funding for and participated in projects totaling more than $5 million, with work sponsored by the National Science Foundation, the U.S. Department of Transportation (DOT), Florida DOT, and other agencies. He was part of a team that made FSU a University Transportation Center (UTC) in 2014 and then served as the center's associate director, focusing on the safety and accessibility of aging populations.

"Research can shed light on needed transportation system improvements and modifications that can help accessibility be more equitably and fairly realized."

Horner attended his first TRB Annual Meeting as a graduate student in the 1990s. After attending many TRB standing committee meetings, he realized his research interests aligned with the mission of the Social and Economic Factors of Transportation Committee, which he joined in 2009. He chaired the committee from 2011 to 2017.

Horner also served on TRB's Geographic Information Science Committee (formerly the Geographic Information Science and Applications Committee) from 2011 to 2017. He currently is a member of the Disaster Response, Emergency Evacuations, and Business Continuity Committee, as well as the Economic Development and Land Use Committee. Recently, Horner also was appointed to serve as one of an inaugural group of associate editors of the *Transportation Research Record: Journal of the Transportation Research Board*.

All of Horner's degrees are in geography, including his PhD, which he received from The Ohio State University in 2002. As an undergraduate, he did not focus his studies on transportation but took classes in statistics, geographic information systems, urban planning, and mapping as part of his geography major. This broad skill set resulted in an offer of a graduate research assistantship with David Hartgen at the Interdisciplinary Center for Transportation Studies at the University of North Carolina at Charlotte. "Working at the Center as a master's student allowed me to participate in a range of applied, real-world transportation projects with partners from Idaho, Arkansas, the local Charlotte community, and other groups," Horner recalls. "That experience ignited my interests in transportation as a career path.

"Some of the most rewarding research I've done has been interdisciplinary work with our UTC at FSU. Collaborations brought together a diverse group of faculty, graduate students, and community partners to explore issues at the intersection of aging populations and their safety and accessibility," Horner affirms.

Outside of TRB, Horner serves as an associate editor for the journal *Transportation* and on the editorial boards of the *Journal of Transport Geography*; *Journal of Transport and Land Use; Computers, Environment, and Urban Systems*; and *Travel Behavior and Society*. He has held leadership positions with the American Association of Geographers and was affiliated with the North American Regional Science Council. He has authored more than 85 peer-reviewed journal articles and has presented and authored more than 100 conference papers nationally and internationally.

TRANSPORTATION INFLUENCERS

Nicholas Kehoe

Nicholas Kehoe is Director, Transportation Technology, Toxcel, Blacksburg, Virginia. He is a member of TRB Standing Committees on Freight Transportation Planning and Logistics and on Truck and Bus Safety and of the Young Members Coordinating Council.

How did you first hear about or become involved in TRB?
I was serving as a graduate research assistant at the Virginia Tech Transportation Institute. Since I was part of the program, my colleagues encouraged me to attend the 2010 TRB Annual Meeting. Except for one or two times when I had other obligations, I have attended the Annual Meeting each year since.

How has TRB informed your career so far?
TRB has enhanced my ability to network with my peers. After I participated in TRB for a few years, I found Standing Committees that aligned with my interests and work and was fortunate enough to join one. I volunteered to help with anything I could. By offering my help, I became more familiar with the process and involved in activities. Over time, I became involved in other Standing Committees, as well as the Young Members Council. I've met peers with different backgrounds, which has helped me become more professionally well-rounded.

What was one of your most memorable Annual Meeting moments?
The last few Annual Meetings have been held at the same time as the college football national championship. In recent years, the competing teams have been the same. As such, it was almost like déjà vu, and it was fun to joke about it with friends.

Transportation Influencers is a new section in *TR News*, highlighting the journey of young professionals active in TRB. Have someone to nominate? Send an e-mail to TRNews@nas.edu.

MEMBERS *ON THE MOVE*

Jennifer Martin recently joined Parrish & Partners, LLC, as a senior project manager. She is a member of the Environmental Issues in Aviation Committee.

Christy Yaffa joined the Federal Aviation Administration Denver Airports District Office as a community planner. She is a member of the ACRP Project Panel on Performance Measures.

In Memoriam

Rebecca S. McDaniel, technical director of the North Central Superpave Center at Purdue University, has died. She was an active contributor to many Technical Activities Division standing committees and chair of the Asphalt Materials Section, and she served as member or chair of numerous NCHRP studies.

Kirk Zeringue, special studies research administrator at the Louisiana Department of Transportation and Development, died in late June. He was a member of the NCHRP Project Panel on Enhancing Pedestrian Volume Estimation and Developing HCM Pedestrian Methodologies for Safe and Sustainable Communities.

E-Bike Pitch Wins Annual Transportation Entrepreneur Contest

GINGER GOODIN

The author is a Texas A&M University Regents Fellow and Senior Research Engineer, Interdisciplinary Research Group, Texas A&M Transportation Institute, Austin.

Kevin McLaughlin sees a bright future for e-bikes—electric bicycles—and wagers that his business model will help travelers switch from cars to e-bikes in the United States and Canada. McLaughlin's vision won this year's Six-Minute Pitch contest at the TRB 99th Annual Meeting, held in January in Washington, D.C.

McLaughlin is the founder and CEO of Zygg, North America's first e-bike subscription service. Zygg is designed for people taking trips that are too long for conventional bicycle use—but who want to avoid driving a car or making multiple transit transfers.

Sponsored by the TRB Young Members Council since 2013, the Six-Minute Pitch is a transportation version of the TV show "Shark Tank." Four entrepreneurs propose a new transportation technology product or service in 6 minutes or less to a panel of industry entrepreneurs and investors, who judge the ideas on their commercial viability and how well the product or service brings transportation research into practice to meet real-world challenges.

Photo: Kevin McLaughlin

E-bike subscription service Zygg won the Six-Minute Pitch contest in January.

"Our goal is to get more people riding electric bikes, especially for trips of 3 to 20 miles," McLaughlin comments. "We believe there are enormous benefits for climate change, congestion, personal health, as well as economic and social benefits." He notes that technology advancements have focused attention on street space use along with changes in consumer demand and civic attention.

"Scooters were a start," McLaughlin observes. "I fully believe that we are going to move from 'bike lane' to 'slow lane' for new modes, but there is still much work to do through political, social, and cultural channels."

Updates from the National Academies Transformation Initiative on Diversity, Equity, and Inclusion

Many studies, webinars, and other activities at TRB and the National Academies of Sciences, Engineering, and Medicine have explored research in social science, medicine, transportation, and other fields that can shed light on the factors that drive systemic racial inequities—not only in society at large, but also within the sciences, engineering, and medicine—with the goal of finding solutions based on evidence.

More information on this research can be found at https://www.nationalacademies.org/topics/resources-on-diversity-equity-and-inclusion.

CENTENNIAL QUOTE

"I believe we should do what we love! My passion for transportation engineering dates back to when I saw my father start his first job as a junior transportation engineer. From then on, there was no looking back. I scored straight As in all transportation-related classes while working on my bachelor's degree. Then I decided to go to graduate school and to get a PhD in the field I fell in love with.

—MAHMOUD ARAFAT
PhD Candidate, Florida State University, Tallahassee

Other Six-Minute Pitch competitors included

- Ken Kershner, Cofounder and CEO of Trio Motors, whose mission is reducing greenhouse gas emissions through vehicle miles traveled and trip reduction;
- Nima Kargah-Ostadi, Transportation Data Scientist at Transconomy, which integrates the latest advances in computational research into practice-ready solutions for transportation asset management; and
- Regina Clewlow, Cofounder and CEO of Populus, a data platform for cities to manage the future of mobility.

Judges included Sean O'Sullivan of SOSV, Gabe Klein of Fontinalis Partners, David Zipper of the Taubman Center for State and Local Government at the Harvard Kennedy School, and W. Celeste Davis Stragand of Ford Mobility. Panelists commended all entrants for addressing practical traveler and system needs with a focus on sustainability.

The Six-Minute Pitch is organized and hosted by Shana Johnson, Foursquare Integrated Transportation Planning; Susan Paulus, Lakeside Engineers; and the author.

Telly Awards for TRB Centennial Video

The award-winning video, "Your Future in Transportation," was produced by TRB and the Texas A&M Transportation Institute.

A video on the future transportation workforce, created as part of TRB's centennial celebration, has received three 2020 Telly Awards, which annually showcase the best work created within television and across all types of video production. The video, "Your Future in Transportation," highlights the excitement, challenges, and fulfillment of a career in transportation.

The video was produced as a partnership between the Texas A&M Transportation Institute and TRB. It was recognized for excellence in the following three categories:

- General Recruitment (Gold Award)
- Craft Writing (Silver Award)
- General, Not-for-Profit (Silver Award)

The award-winning video was one of more than 12,000 entries from all 50 states and across five countries. TRB turns 100 years old on November 11, 2020, and its centennial celebration promotes the value of transportation research and celebrates the achievements of TRB's volunteers, sponsors, affiliates, and staff.

To view the video, visit https://www.tellyawards.com/winners/2020/non-broadcast/general-recruitment/trb-centennial-video/232288.

CENTENNIAL QUOTE

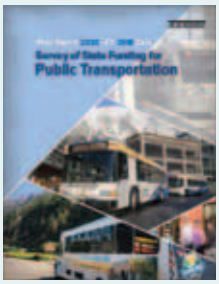
"On a summer evening in 2007, I glanced at the TV while eating dinner and saw the news bulletin: the I-35W bridge in Minneapolis had collapsed. The road over the Mississippi was so far above the river, strong and unmovable. You would be forgiven for not realizing you had traveled 1,800 feet suspended in the air. I had to be in south Minneapolis the next morning. I would have driven down 35W with tens of thousands of my neighbors without so much as a second thought. Over the next few days, the traffic patterns fascinated me. Transportation officials had 3 hours to ensure the safety and mobility of more than 25,000 Minnesota Twins fans seated just blocks from the collapse, with detours in place before the end of the 9th inning. Then, road crews had 10 hours to deploy significant signage to help 140,000 Minnesotans find a new route for the morning commute, coordinating with local news to disseminate information in an age before widespread smartphone use. Transportation engineers can spend decades exploring a single mobility solution but must also be prepared to deliver solutions in minutes. Out of the smoke and waves of the collapse emerged my calling. I fell in love with transportation."

—SHANNON WARCHOL
Senior Engineer, Kittelson & Associates, Inc., Pittsburgh, Pennsylvania

2019 AASHTO Salary Survey

This survey provides job classifications and salary information on positions currently used by the transportation industry. This document contains 82 matched titles divided into five broad job categories. For each title, a brief description, number of incumbents, salary range, benefits, and actual salary is included.

To download a free copy, visit the AASHTO Store online at https://store.transportation.org, and search by the publication's item code, SS-19-OL.



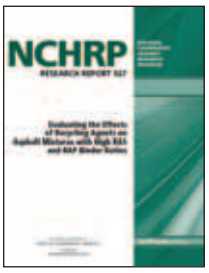
Survey of State Funding for Public Transportation—Final Report

Using FY2018 data, this annual report provides a snapshot of state-by-state investment in public transportation from federal, state, and local funding sources. Many tables and charts enable the reader to understand how different funding and tax mechanisms are used in each state to support transit operations and capital projects.

To order a copy, visit the AASHTO Store online at https://store.transportation.org, and search by the publication's item code, SSFP-14-UL.

The titles in this section are not TRB publications. To order, contact the publisher listed.

TRB PUBLICATIONS



Evaluating the Effects of Recycling Agents on Asphalt Mixtures with High RAS and RAP Binder Ratios
NCHRP Research Report 927

This report presents an evaluation of how commercially available recycling agents affect the performance of asphalt mixtures incorporating reclaimed asphalt pavement (RAP) or reclaimed asphalt shingles (RAS) at high recycled-binder ratios.

2019; 282 pp; TRB affiliates, $78.75; nonaffiliates, $105. Subscriber category: materials.

Identification of Factors Contributing to the Decline of Traffic Fatalities in the United States from 2008 to 2012
NCHRP Research Report 928

This volume analyzes the specific factors in the economic decline that affected fatal crash risk, while taking into account the long-term factors that determine the level of traffic safety.

2019; 106 pp; TRB affiliates, $58.50; nonaffiliates, $78. Subscriber categories: planning and forecasting, safety and human factors.

Unsignalized Full Median Openings in Close Proximity to Signalized Intersections
NCHRP Research Report 929

This report details transportation agencies' efforts to better quantify the operational and safety performance associated with unsignalized full median openings located near upstream and downstream traffic signals that have at least one turning bay.

2019; 102 pp; TRB affiliates, $54.75; nonaffiliates, $73. Subscriber category: design.

Research Roadmap for Transportation and Public Health
NCHRP Research Report 932

This report provides a broad overview of highly relevant research needs, as well as implementable tools for state transportation agencies and partners at the intersection of transportation and public health in the United States. It provides a plan for funding research over the next decade that can lead to greater consideration of health issues in transportation contexts.

2019; 60 pp; TRB affiliates, $46.50; nonaffiliates, $62. Subscriber categories: highways, public transportation, research.

To order the TRB titles described in Bookshelf, visit the TRB online bookstore, www.TRB.org/bookstore, or contact the Business Office at 202-334-3213.

Transportation Network Companies (TNCs): Impacts to Airport Revenues and Operations—Reference Guide
ACRP Research Report 215

This report identifies strategies and practical tools for adapting airport landside access programs to reflect the evolution of such ground transportation modes as TNCs and automated vehicles.

2020; 116 pp; TRB affiliates, $58.70; nonaffiliates, $78. Subscriber categories: aviation, terminals and facilities, passenger transportation.

Building and Maintaining Air Service Through Incentive Programs
ACRP Research Report 218

This guidebook offers advice for using incentive programs for growing and maintaining commercial air service. The development, execution, and monitoring of air service incentive programs can be complex,

can involve multiple stakeholders, and must address federal compliance issues.

2019; 54 pp; TRB affiliates, $44.25; nonaffiliates, $59. Subscriber categories: aviation, economics, planning and forecasting.

Analysis of Recent Public Transit Ridership Trends
TCRP Research Report 209

This report presents a current snapshot of public transit ridership trends on bus and rail services in U.S. urban and suburban areas, focusing on what has changed in the past several years. It also explores strategies that transit agencies are considering and using for all transit modes in response to changes in ridership. Ten case studies present individual strategies that transit agencies are using to mitigate ridership losses and increase ridership overall.

2019; 108 pp; TRB affiliates, $58.50; nonaffiliates, $78. Subscriber categories: public transportation, passenger transportation, planning and forecasting.

Stray Current Control of Direct Current-Powered Rail Transit Systems: A Guidebook
TCRP Research Report 212

This report allows transit agencies and design and maintenance practitioners to influence new system construction, extensions, and maintenance and operation of existing systems.

2019; 111 pp; TRB affiliates, $58.50; nonaffiliates, $78. Subscriber categories: public transportation, energy, safety and human factors.

Multimodal Fare Payment Integration
TCRP Synthesis 144

This synthesis documents the current practices and experiences of transit agencies dealing with the complexities of multimodal fare payment convergence.

2019; 86 pp; TRB affiliates, $51.75; nonaffiliates, $69. Subscriber categories: public transportation, passenger transportation.

Current Practices in the Use of Onboard Technologies to Avoid Transit Bus Incidents and Accidents
TCRP Synthesis 145

This synthesis documents the current practices in the use of the various onboard technologies on transit buses to prevent incidents and accidents, with a primary objective of determining whether these technologies are effective in actual practice. The examination shows that transit agencies are implementing many approaches proactively, including piloting and the use of collision avoidance technologies such as forward-collision warning, emergency braking, lane-departure warning, and electronic stability control.

2019; 86 pp; TRB affiliates, $51.75; nonaffiliates, $69. Subscriber categories: public transportation, passenger transportation, security and emergencies.

Transit Security Preparedness
TCRP Synthesis 146

This synthesis identifies current practices that transit systems can use to enhance their security measures and to identify opportunities to apply security technology applications used in other industries to the transit environment.

2019; 140 pp; TRB affiliates, $60; nonaffiliates, $80. Subscriber categories: public transportation, passenger transportation, security and emergencies.

Attracting, Retaining, and Advancing Women in Transit
TCRP Synthesis 147

This synthesis explores the strategies that have been deployed in transit and other related industries to attract, retain, and advance women in a variety of roles.

2019; 66 pp; TRB affiliates, $67; nonaffiliates, $50.25. Subscriber categories: public transportation, administration and management.

Transportation Research Record 2673
Issue 12

User preferences for bicycle infrastructure in communities with emerging cycling cultures, accessibility measurement for project prioritization in Virginia, and defining psychometric variables in the use of automated vehicles are among the topics presented in this volume.

2019; 901 pp. For more information, visit http://journals.sagepub.com/home/trr.

Transportation Research Record 2674
Issue 1

Authors present research on such topics as evaluating the traffic capacity of the Zion–Mount Carmel Tunnel in Zion National Park, Utah; accelerating traffic assignment with customizable contraction hierarchies; and an operational and safety impact analysis of implementing emergency shoulder use for hurricane evacuation.

2020; 329 pp. For more information, visit http://journals.sagepub.com/home/trr.

Transportation Research Record 2674
Issue 2

Highlights from TRB's 1st International Conference on 3-D Printing and Transportation are presented in this volume, along with research on a thermoelectric energy harvesting system for roadway sustainability, forecasting Class I railroad fuel consumption by train type, and pavement image data sets.

2020; 339 pp. For more information, visit http://journals.sagepub.com/home/trr.

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INFORMATION FOR CONTRIBUTORS TO **TR NEWS**

TR News welcomes the submission of articles for possible publication in the categories listed below. All articles submitted are subject to review by the Editorial Board and other reviewers to determine suitability for *TR News*; authors will be advised of acceptance of articles with or without revision. All articles accepted for publication are subject to editing for conciseness and appropriate language and style. Authors review and approve the edited version of the article before publication. All authors are asked to review our policy to prevent discrimination, harassment, and bullying behavior, available at https://www.nationalacademies.org/about/institutional-policies-and-procedures/policy-of-harrassment.

ARTICLES

FEATURES are timely articles of interest to transportation professionals, including administrators, planners, researchers, and practitioners in government, academia, and industry. Articles are encouraged on innovations and state-of-the-art practices pertaining to transportation research and development in all modes (highways and bridges, public transit, aviation, rail, marine, and others, such as pipelines, bicycles, pedestrians, etc.) and in all subject areas (planning and administration, design, materials and construction, facility maintenance, traffic control, safety, security, logistics, geology, law, environmental concerns, energy, technology, etc.). Manuscripts should be no longer than 3,000 words. Authors also should provide tables and graphics with corresponding captions (see Submission Requirements). Prospective authors are encouraged to submit a summary or outline of a proposed article for preliminary review.

MINIFEATURES are concise feature articles, typically 1,500 words in length. These can accompany feature articles as a supporting or related topic or can address a standalone topic.

SIDEBARS generally are embedded in a feature or minifeature article, going into additional detail on a topic addressed in the main article or highlighting important additional information related to that article. Sidebars are usually up to 750 words in length.

POINT OF VIEW is an occasional series of authored opinions on current transportation issues. Articles (1,000 to 2,000 words) may be submitted with appropriate, high-quality graphics, and are subject to review and editing.

RESEARCH PAYS OFF highlights research projects, studies, demonstrations, and improved methods or processes that provide innovative, cost-effective solutions to important transportation-related problems in all modes. Research Pays Off articles should describe cases in which the application of project findings has resulted in benefits to transportation agencies or to the public, or in which substantial benefits are expected. Articles (approximately 750 to 1,000 words) should delineate the problem, research, and benefits, and be accompanied by the logo of the agency or organization submitting the article, as well a one or two photos or graphics. Research Pays Off topics must be approved by the RPO Task Force; to submit a topic for consideration, contact Stephen Maher at 202-334-2955 or smaher@nas.edu.

OTHER CONTENT

TRB HIGHLIGHTS are short (500- to 750-word) articles about TRB-specific news, initiatives, deliverables, or projects. Cooperative Research Programs project announcements and write-ups are welcomed, as are news from other divisions of the National Academies of Sciences, Engineering, and Medicine.

BOOKSHELF announces publications in the transportation field. Abstracts (100 to 200 words) should include title, author, publisher, address at which publication may be obtained, number of pages, price, Web link, and DOI or ISBN. Publishers are invited to submit copies of new publications for announcement (see contact information below).

SUBMISSION REQUIREMENTS:

- **Articles** submitted for possible publication in *TR News* and any correspondence on editorial matters should be sent to the *TR News* Editor, Transportation Research Board, 500 Fifth Street, NW, Washington, DC 20001, 202-334-2986 or 202-334-2278, and lcamarda@nas.edu or cfranklin-barbajosa@nas.edu.
- Submit **graphic** elements—photos, illustrations, tables, and figures—to complement the text. Images must be submitted as TIFF or JPEG files and must be at least 3 in. by 5 in. with a resolution of 300 dpi. Large photos (8 in. by 11 in. at 300 dpi) are welcomed for possible use as magazine cover images. A detailed caption must be supplied for each graphic element.

Note: Authors are responsible for the authenticity of their articles and for obtaining written permissions from publishers or persons who own the copyright to any previously published or copyrighted material used in the articles **as well as any copyrighted images** submitted as graphics.

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