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The Role of Water in Ecologically Sustainable Transportation

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As modes of transportation and transportation infrastructure have developed over the last millennium, so has the ability to overcome natural environmental obstacles. These environmental challenges included difficult terrain, water crossings, episodic and seasonal weather, and climate conditions. As both the modes and infrastructure of transportation advance at an ever-increasing pace, these historical environmental challenges have been progressively and successively overcome and new challenges have been confronted. In fact, in developed and urbanized countries such as the United States and those in Europe, transportation is now capable of altering the environment as opposed to the paradigm of the last thousand years, during which environmental conditions dictated the modes and infrastructure of transportation. Therefore, in the new millennium transportation will be ecologically integrated into the existing environment for the symbiotic benefit of both transportation and the environment. This ecological integration includes hydrologic, hydraulic, and water quality impact-response issues.

As the name indicates, the Hydrology, Hydraulics, and Water Quality Committee of the Transportation Research Board has been focused on the water quantity and quality impact-response phenomena associated with modern transportation modes and transportation infrastructure. As the committee has progressed, an integrated theme has been developed addressing the interrelated issues of rainfall-runoff processes, waterway and infrastructure hydraulics, scour and sediment transport, and runoff water quality and treatment. To date, significant research and technology transfer contributions have been made by the committee in all of these areas, providing guidance for the committee in the new millennium. New contributions must continue to be supported by the three fundamental areas of hydrology, hydraulics, and water quality since these areas relate to an integrated theme of ecologically sustainable transportation.

HYDROLOGY

Modes of transportation and transportation infrastructure are influenced by hydrologic processes that range in scale from pavement to watershed. Although significant advances have been made in analytical, numerical, and statistical hydrologic modeling at these scales, these modeling tools have advanced beyond the ability to provide rapidly and economically both spatial and temporal measurements of hydrologic processes. Recent advances in a new nationwide network of weather radar, including weather surveillance Doppler radar, have begun to provide necessary real-time meteorological observations across the United States. Such hydrologic process measurement systems provide hydrologists with real-time rainfall intensity and estimates of accumulated rainfall. Radar rainfall estimates from the new radar technology cover vast areas at a temporal and three-dimensional spatial resolution that would be prohibitively expensive to match with a conventional rain gauge network for extensive transportation systems. Current radar technology such as Doppler radar (WSR-88D) is capable of providing information on three-dimensional rainfall structure on a watershed scale. In the next decade, calibrated area-based data sets should become common and can be made available for hydrologic model calibration. Whether radar or future technologies for rainfall measurement are used, the combination of such efforts with geographic information system (GIS) tools provides future opportunities for detailed distributed hydrologic analysis at a range of scales.

In the last two decades GIS has played an increasingly important role in many facets of transportation, including hydrologic impact response. This role will continue to become more important as GIS tools are modified and advanced while peripheral tools such as WSR-88D allow the integration of hydrologic process data sets with GIS models. Toward this goal, a more fundamental examination of hydrologic processes for engineered solution will also require more detailed information about the surface and subsurface of the earth, watersheds, and transportation corridors. One important example is the need for more fundamental and detailed information on topography and related parameters.

Elevation and related parameters including slope, aspect, and drainage area that influence surface and subsurface hydrologic processes are important for both natural and human ecosystems. Parallel to the development of fundamental improvements in precipitation measurements and databases is the recent development of a National Elevation Database–Hydrologic Derivatives (NED-H). Both topographic measurement tools and digital terrain models with increasing resolution have provided valuable information for GIS-based hydrologic models. The imperative for such tools and measured data will only grow as computing and modeling capabilities continue to outpace the ability to supply required temporal and spatial parameter information. Integration of such state-of-the-art data gathering tools with GIS-based models has occurred in the last several years in hydrologic curricula at major universities around the country. These tools are now being developed and applied in national laboratories, national agencies, and many consulting firms.

The greatly improved measurement technologies of the future and the resulting databases and integration into models will have a wide variety of transportation-related applications. Elevation and topographic data derivatives, including intercepted radiation, precipitation, runoff transport of sediments, evaporation, soil moisture, and vegetation characteristics have applications in future transportation research. These applications include soil and sediment erosion and transport, infiltration modeling, rainfall abstraction evaluations, sediment yield modeling, dam and reservoir design, location of surface structures for control of erosion, drainage pattern delineation, stream flow modeling, location of aquifer recharge areas, and riparian area modeling.

Current and future needs related to hydrologic processes that influence transportation decisions will rely upon hydrologic unit or watershed delineation measurements and data. Such measurements provide information on hydrologic characteristics of interest in transportation such as water supply, peak discharge, and sediment loads. Such measurements are required not only for hydrologic processes but also for the coupled water quality and transport issues dealt with by transportation agencies. Current regulatory trends that emphasize a watershed approach to integrated implementation and enforcement of water quality protection require hydrologic and water quality data measurements for a range of scales across the watershed. With respect to hydrologic processes and related water quality processes from the pavement scale to the extensive watershed scale, the ability to develop methodology and models far exceeds the capability to supply required fundamental spatial and temporal parameter measurements. Therefore, to continue the progress made in the last millennium will require the development of hydrologic and related water quality measurement and data acquisition techniques from the pavement scale to the watershed scale, formatted into data structures that can be readily integrated into hydrologic models and methodologies.

HYDRAULICS

Modes of transportation and transportation infrastructure are influenced by hydraulic processes that range in scale from pavement sheet flow to stream crossings and extended water crossings. Over the last several decades the focus has been on the design and analytical methodologies for local conveyance systems such as inlets, curbs, gutters, catch basins, and piping between hydraulic structures and their outfalls. Many of these methodologies were based on design storm concepts. At larger scales such as the watershed, hydrologic and hydraulic models have been coupled. Methodologies for culvert design and stream crossings for transportation facilities have been developed. Over the last two decades, a primary focus has been bridge scour assessment and mitigation research. Although these issues will always need to be addressed, future transportation-related hydraulics research needs have several parallel themes to those of hydrologic research needs. For example, bridge and structure scour models have advanced to the point similar to that of hydrologic models: the ability to model hydraulics has far surpassed the ability to supply the fundamental hydraulic measurements and data.

There are three areas of future research needs in transportation-related hydraulics. The first is the development of hydraulic measurement tools, data acquisition systems, and data structures to provide the temporal and spatial data for hydraulic models. This need closely parallels future needs in hydrologic research. The lack of hydraulic measurements and data represents a limiting factor in the application of hydraulic and scour models for large-scale hydraulic systems and transportation structures. The second need is the continued development of models for sediment flow around transportation structures. Once again, this research goal can only be fully realized if sufficient measurement data can be provided for such models.

From a more holistic perspective, the third need is an ecologically based set of tools and methodology applied to stream and waterway crossings. More specifically, included in this area are the application of geomorphology principles to existing and proposed stream crossings and how the applications of such principles can be measured and quantified for future model development. This needs statement also encompasses future research in stream and water body ecology as influenced by transportation. Included in such ecologically based needs are current trends in mitigation banking for culvert installations and stream and waterway crossings by elevated transportation structures.

WATER QUALITY AND TREATMENT

The modern proliferation of traffic and transportation infrastructure can have a pronounced effect at scales ranging from pavement runoff quality to receiving water quality. Of the three committee focus areas, water quality research from a historical perspective is the most recent. This recent historical focus can in part be traced to the promulgation of the 1972 Clean Water Act (CWA) and subsequent legislation, specifically the Storm Water Phase I and Phase II regulations of the Environmental Protection Agency's National Pollution Discharge Elimination System. (Future directions in water quality and associated legislation will be dependent on reauthorization of the CWA by Congress.) With or without future regulatory directives, recent research has demonstrated the need for a transportation water quality focus and ultimately on effective control and treatment of storm water nonpoint pollution from transportation facilities. Water quality and treatment are intimately related to both hydrologic processes and hydraulic transport, and contributions in these areas are necessary to future water quality research.

During the last three decades, transportation-related water quality issues have focused on individual transportation site characterization of storm water quality. Traffic- and infrastructure-generated constituents of particular concern included solids and particulate matter, heavy metals, inorganic compounds (including sulfur, nitrogen, and phosphorus), organic compounds (including oil, grease, fuels, and fuel additives), waterborne pathogens, deicing compounds and grit, as well as hydrologic modifications to increase peak flow and flow volume. Recently there has been an effort to identify and utilize a nationwide network of research sites to characterize transportation-related water quality using a consistent set of sampling and analysis protocols. In addition, impacts on receiving water quality are beginning to be considered, although ecosystem impacts of transportation-related storm water are poorly understood in terms of both acute and chronic effects. Current research areas include developing methodology, tools, and techniques; these areas (1) reduce direct, indirect, and cumulative adverse impacts of transportation on ecosystems, including wetlands, habitat, and water quality, and (2) preserve and enhance human health, biological productivity, and ecological diversity. Specific future research initiatives include watershed- and ecosystem-based planning and management, environmental impact assessment, vegetation management, storm water management, erosion control, wetland assessment methods, highway density and ecosystem integrity, and rapid water quality assessment.

Parallel to water quality characterization has been a focus on treatment of transportation-related storm water. Treatment of storm water continues to pose unique challenges because of the unsteady nature of processes including rainfall runoff and mobilization and transport of heavy metals and other constituent loads. In addition, kinetics of heavy metal partitioning as a function of pH, residence time, and particulate matter characteristics can have a profound effect on the selection and effectiveness of treatment systems. Treatment systems for the clarification of runoff have included sedimentation (detention and retention) basins, constructed wetlands, vegetated filter strips, and infiltration systems such as porous pavement and infiltration trenches. Initially research focused on the modification of water quantity best management practices (BMPs) to also serve a water quality purpose. Examples included water quality designs for detention and retention basins that have been used traditionally for water quantity control. These BMP designs focused on the particulate-bound fraction of the nonpoint pollution constituents. Recently, BMPs have become more sophisticated and in some cases involve treatment train configurations.

With regard to transportation-related water quality and treatment, there are a series of future research needs. The first is the development of viable and economical measurement tools for water quality parameters, data acquisition systems, and data structures to provide the temporal and spatial data for water quality models. This need closely parallels future needs in hydrologic and hydraulic research. Water quality data requirements are as critical as those required for hydrologic and hydraulic research, but for current measurement technologies the situation is fundamentally more difficult. Progress has been slow because of the wide range of parameters required, chemical kinetics, and the difficulty associated with making accurate water quality measurements in a heterogeneous matrix as complex as storm water. The need for water quality measurements and data represents a limiting factor to the application of water quality models for storm water runoff from transportation facilities.

The second need is the continued development of water quality models adapted for the complex and dynamic chemical matrix of storm water. Once again, this research goal can only be fully realized if sufficient measurement data can be provided for the model. Currently there are efforts to integrate water quality models with other decision-making tools. A future direction is to fully integrate storm water models with hydrologic, hydraulic, and GIS-based models. Scales for such models would range from the pavement to the watershed, a current research focus. Watershed-based water quality models would allow integration of hydrologic and hydraulic processes and are in vogue with future environmental regulatory initiatives.

Although temporal and spatial storm water quality characterization is a necessary first step, its purpose must be directed toward an ecologically sustainable framework that integrates source control and treatment. For the goal of ecologically sustainable transportation this is probably the most important future research need. Source control would facilitate the gross reduction in pollutant discharges at their source—the vehicle and transportation infrastructure. What cannot or will not be solved through source control will be mitigated through a new paradigm in storm water treatment that would design or integrate ecologically sustainable treatment into existing transportation infrastructure as opposed to adding separate and isolated treatment infrastructure to the transportation system. Energy inputs to such treatment would be minimized, and it would be expected that many treatment systems could be essentially passive. Commensurate with this goal is the need to identify and quantify the physical, chemical, and biological treatment mechanisms that may be exploited along with the required modeling tools adopted or developed for the design of the passive treatment process. With advances in materials and process design, ecologically sustainable transportation is possible. As with water quality assessment, treatment effectiveness, and modeling, especially at a watershed or ecosystem scale, cannot accurately be assessed without advances in water quality measurement capabilities.

CONCLUSIONS

In conclusion, the future for ecologically sustainable transportation will require the ability to gather sufficient temporal and spatial measurements for increasingly sophisticated and integrated hydrologic, hydraulic, and water quality treatment models. From all perspectives discussed, future research will facilitate the integration of transportation into the environment. Such a vision promotes a holistic view of transportation in the next millennium while mitigating specific adversities (for example, flooding, bridge scour, and pollution) encountered in the development of the transportation system during the last millennium.