NATIONAL COOPERATIVE
HIGHWAY RESEARCH PROGRAM REPORT **264**

GUIDELINES FOR THE MANAGEMENT OF HIGHWAY RUNOFF ON WETLANDS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT 264

GUIDELINES FOR THE MANAGEMENT OF HIGHWAY RUNOFF ON WETLANDS

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AREAS OF INTEREST:

ENERGY AND ENVIRONMENT
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TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C.
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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local government agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the bases of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the Academy and its Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the National Academy of Sciences, or the program sponsors.

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FOREWORD

By Staff
Transportation Research Board

The guidelines contained in this report for the management of highway runoff on wetlands cover many functions: wetland creation and maintenance, wildlife considerations, regulatory controls, wetland monitoring, modeling techniques, and highway construction, design, and maintenance practices affecting the relationship between highway runoff and wetlands. The report also addresses the feasibility of using certain wetland types for mitigating the effects of highway runoff on wetlands, and it summarizes a companion agency document that more fully covers the interaction of wetland systems and highway runoff, and the effects of highway runoff on wetlands. Additionally, the report includes an extensive bibliography with entries grouped by major subject areas. All those concerned with environmental impacts on wetlands and the management of runoff from highways near wetlands should find the report interesting and beneficial. Those who have a general interest in the functioning of wetlands should also find this report and its companion an extremely useful source of information.

Many state and federal agencies value wetlands as a natural resource and have enacted considerable legislation to ensure their natural benefits such as in providing wildlife habitats, recreational areas, flood storage, and nutrient sinks. Also, interest increases on possibly creating and managing wetlands to enhance the environment. However, wetlands can be adversely affected with impacts ranging from partial disturbance, to changes in their characteristics and functions, to elimination. An area of mounting concern is the impact of highway runoff.

Under NCHRP Project 25-1, "Effects of Highway Runoff on Wetlands," the EnviroEnergy Technology Center of Rexnord, Inc., was asked to identify the interactions between wetland systems and highway runoff, to identify the effects of highway runoff on wetlands, and to develop guidelines for the practical management of highway runoff on wetlands. The researchers thoroughly reviewed a substantial amount of information on wetland ecology, the function of wetlands, highway runoff constituents, and other related subjects having either a direct or indirect, but transferable, relationship to the requirements of the research objectives. Although no one situation is exactly like another, the results of this research should provide excellent background for understanding the characteristics of wetlands, their functions, and the effects of highway runoff. Practical guidance for the management of runoff from highways in close proximity to wetlands was developed and should be of considerable interest and use. This guidance includes the management of runoff from the highway to and in the wetlands. A possibility also addressed is the use or creation of wetlands to mitigate the effects of highway runoff.

In addition to this report, a companion agency document, which is the main research report and titled, "Effects of Highway Runoff on Wetlands," has been distributed to all Program sponsors. It is available to others on a loan basis or for purchase of Xerox copies upon written request to the Publications Office, Transportation Research Board, 2101 Constitution Avenue, N.W., Washington, D.C. 20418. The agency research report is recommended as an excellent, comprehensive source document on the subject research and related areas.

CONTENTS

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The research described in this report was performed under NCHRP Project 25-1 by Rexnord, Inc., EnviroEnergy Technology Center, and the Department of Botany, University of Wisconsin-Milwaukee. Rexnord Inc. was the contractor for this study. The work performed by the University of Wisconsin-Milwaukee was under a subcontract with Rexnord Inc.

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GUIDELINES FOR THE MANAGEMENT OF HIGHWAY RUNOFF ON WETLANDS

SUMMARY

The overall objectives of the research conducted under NCHRP Project 25-1 were:

1. To identify the interactions between wetland systems and highway runoff.
2. To identify the effects—beneficial or otherwise—of highway runoff on wetlands.
3. To develop guidelines for the practical management of highway runoff in wetlands.

The results of this research are documented in two reports: the research report, "Effects of Highway Runoff on Wetlands" and *NCHRP Report 264,* "Guidelines for the Management of Highway Runoff on Wetlands." The research report covers the approach used to address the research objectives and presents a discussion of the literature findings dealing with the first two objectives. That report is not published in the regular NCHRP report series (see Foreword for availability).

This report (*NCHRP Report 264*) presents the management guidelines. The discussion in the report addresses three major topics: (1) interaction between highway runoff and wetlands and impact effects, (2) feasibility of using wetlands to treat highway runoff, and (3) management considerations in the control of highway runoff in, and use of, wetlands.

The material in the following pages of the guidelines provides a chapter for each of the elements considered important to wetland management.

Chapter One provides background information and a brief presentation of the interactions between highway runoff constituents and wetlands and the effects of their impact. An overview covering the major wetland processes (physical, chemical, and biological) that are important to basic wetland functions in the retention or cycling of highway runoff constituents is included.

The discussion in Chapter Two centers around the feasibility of using specific wetland types to mitigate the effects of highway runoff. The results of the research indicate that under certain conditions wetlands may indeed be appropriate to treat highway runoff. The type of wetland used, the quality and quantity of pollutants from the highway, and such site characteristics as topography and drainage patterns, geologic history, and biology of specific wetland species are the primary considerations. The literature survey revealed considerable variability in highway runoff quality and in the ability of wetlands to withstand impact from highway runoff constituents or to treat highway runoff constituents. Treatment capacity and potential impacts, therefore, are best evaluated on a system (highway/wetland) by system basis.

Chapter Three is concerned with wetland creation and maintenance. To contain highway runoff and trap pollutants, it may often be necessary to "modify" an existing wetland or create a new wetland adjacent to the roadway. Generalizations concerning an appropriate technique for wetland development are risky; each site has a unique combination of topographic, edaphic, and climatic characteristics. However, in any development, four areas must be considered: site selection and development, choice of appropriate wetland species, selection of planting methods, and maintenance prac-

tices. Knowledge of the physical conditions of the region and the biology of locally common wetland plant species are essential data required by the planner to choose the appropriate techniques. Detailed planning is required if wetland creation is to be successful. Poor site location, morphometry, and site preparation will result in a wetland with low productivity and treatment ability, and poor aesthetic and recreational values.

Chapter Four deals with wetland wildlife. Wetlands provide habitat for a great variety of wildlife. The species comprising these wildlife populations vary by region, and within any region, with the nature of the wetland. The plant communities that are present, the proportion of vegetation to open water, size, connection to other wetlands or water bodies, degree of water level fluctuation as well as highway design and maintenance techniques are all important. This report suggests the development of wetlands for retention and treatment of highway runoff and by implication, the development of wildlife habitat. Chapter Four describes wetland wildlife and discusses highway-wildlife interactions including the effects of runoff from highways on these organisms. It also describes other wildlife management considerations including water quality criteria and habitat preferences. The discussion limits wildlife considerations primarily to vertebrates including a great diversity of forms: birds, mammals, reptiles, amphibians and fish. However, the influence of highway runoff on the plant and invertebrate components of the several wetland food webs cannot be ignored.

One of the most significant management aspects of wetland utilization for amelioration of highway stormwater runoff effects concerns legal constraints imposed on such utilization. These constraints accrue from both statutory and judicial law on the federal, state, and local levels. Although it is beyond the scope of these guidelines to review the common law constraints (judicial), it must be pointed out that statutory laws are very often subject to judicial review for interpretation or even superseded or bypassed on common law grounds. Similarly, local ordinances of judicial controls cannot be ignored. Chapter Five briefly describes the myriad of federal statutes and programs that affect the protection and/or use of wetland activity. Also included in this chapter is a review of the responses by state transportation agencies to a question in a questionnaire concerning their perceptions of state policies regarding highway interactions with wetlands.

Chapter Six describes methods of field data collection. Any assessment, regardless of the objective or level of evaluation, will require data collection. The best data on which to evaluate a system are obtained from field monitoring programs. Field monitoring programs may be required for initial wetland classification and inventory, for planning purposes, for obtaining baseline data and data quantifying the characteristics of runoff from the operating highway for potential impact assessments, and for evaluating pollutant removal effectiveness in the wetland. Information is presented in this chapter on direct field measurement, use of remote sensing, and application of pollution indices.

Chapter Seven of this document includes discussions on a few of the many models available that may facilitate the assessment of highway runoff/wetland interactions. In many cases extensive field monitoring programs to collect the required data will be prohibitive because of cost, time, or other constraints. Provided some basic data are available, modeling is an alternative means of initially evaluating a particular system or evaluating system change. An alternative to using strictly field data or strictly predicted data from a model for evaluation is to implement a selected field monitoring program supplemented by modeling techniques. Additional field data can then be used for model validation. This method is commonly used in evaluating environmental impacts to a particular system. Assessment of highway runoff and wetland interactions calls for the need to address: (1) economic and cultural considerations, (2) water quality/biological considerations, and (3) hydrological considerations.

Chapter Eight discusses highway construction, design features, and maintenance practices which should be considered in evaluating highway-wetland interactions and in managing highway runoff in wetlands. Although the scope of this research did not include an evaluation of the effects of highway construction on wetlands, planners and agencies performing an overall evaluation of the interaction between highways and wetlands may be required to assess the effect of highway construction or modification on an existing wetland. The purpose of the section on highway construction in this chapter is to familiarize those individuals with this information. The sections dealing with design features and maintenance practices contain specific recommendations regarding improvements in both areas.

Appendix A provides a state-by-state summary of specific wetland-related statutes that are intended to serve as an illustrative guide to the types and variability of regulatory schemes in these states.

Appendix B includes a comprehensive bibliography by subject area:

- Processes and Pathways
- Runoff Constituents and Aquatic Ecosystems
- Runoff Characteristics
- State and Federal Regulations
- Wetland Creation and Maintenance
- Wetland Monitoring
- Assessing the Interactions of Highway Runoff and Wetlands
- Wetland Vegetation and Classification
- Case Studies

CHAPTER ONE

HIGHWAY RUNOFF AND WETLAND INTERACTIONS AND THEIR IMPACTS

INTRODUCTION

Across the country millions of roadway miles pass through or near receiving waterways and wetlands. Large volumes of runoff from the highway right-of-way are eventually discharged to a variety of large and small watersheds. Highway runoff is a potential source of many pollutants foreign to the receiving watersheds. Subsequent pollution occurs mainly through the natural hydrologic cycle. Thus, consideration of the effects of highway systems on the environment plays an increasingly important role in the planning, design, construction, and operation of our transportation system.

Growing scientific and public awareness of wetland values has resulted in legislative action to regulate and preserve those ecosystems. Regulation and preservation of wetlands are currently the responsibility of Federal agencies, including the U.S. Army Corps of Engineers, U.S. Environmental Protection Agency, U.S. Fish and Wildlife Service; and of state and local agencies, including State Departments of Natural Resources and Regional Planning Commissions. In relationship to highway systems and their interactions with wetlands, Executive Order 11990 (May 24, 1977), "Protection of Wetlands," and DOT order 5660 1A (August 27, 1978), "Preservation of the Nations' Wetlands," require Federal agencies to avoid the long-and short-term impacts associated with the destruction or modification of wetlands and to avoid construction in wetlands unless proposed action includes all practicable measures to minimize harm to the wetland. In response to these orders, Public Law 95-217, "The 1977 Amendments to the Clean Water Act," and Public Law 82-624, "Fish and Wildlife Coordination Act," require research to investigate the impact of highways on wetlands and the development of abatement measures.

The possibility of creating and managing wetlands to trap pollutants and enhance the environment has also gained attention. Recent investigations of wetlands have shown that these ecosystems may perform many important functions. They are among the most productive areas in the world, and they provide habitats and breeding areas for many species of fish and wildlife. Thus, wetlands provide recreational, economical, and aesthetic benefits. In addition, wetlands serve as hydrological recharge areas and aid in flood control. Wetlands have also been shown to act as "sinks" that may effectively trap many runoff constituents from surrounding terrestrial systems. In this regard, it may be feasible to use wetlands to mitigate the effects of highway runoff. This mitigation potential combined with other wetland values may provide an economically attractive method of controlling highway runoff pollution when compared to the high cost of structural and source control measures that would otherwise be necessary to control this widespread nonpoint pollution source.

To evaluate the impact of highway runoff on wetlands and the feasibility of using wetlands to mitigate the effects of highway runoff, it is necessary to identify the interactions between highway runoff and wetlands. An understanding of these interactions and their impacts is essential for adequate environmental assessment, as well as for later management of highway runoff.

INTERACTION BETWEEN HIGHWAY RUNOFF CONSTITUENTS AND WETLANDS

Wetland processes occurring in the sediment, sediment/water interface, water column, and biological components all interact to determine the fate of highway runoff constituents. The substrate of wetlands plays a dominant role in the retention of highway runoff constituents. However, wetlands are still poorly understood ecosystems. Part of the problem exists because until recently the general consensus was that wetlands were of little value. Current research has for the most part reversed this type of thinking, and one is beginning to recognize the importance and complexity of these systems.

Highway runoff constituents that are of major concern include heavy metals, deicing agents, hydrocarbons, pesticides, and fertilizers. A more complete breakdown of highway runoff constituents and their sources is given in Table 1. Primary accumulation by plants, litter, and the sediments seems to be more important before accumulation into the fauna. Some evidence does suggest that accumulation from overlying waters can be important in certain circumstances.

Heavy Metals

Aquatic plants can temporarily immobilize heavy metals. Rooted aquatics absorb metals from the sediments. Other plants may absorb metals from the water column as well as from the sediments. Metals may also be adsorbed onto plant surfaces. Decomposing plant litter and substrate additionally serve as a sink for heavy metals.

Plants respond uniquely to exposure to large concentrations of heavy metals. The accumulation of metals by plants and their subsequent release into the water column or onto the detrital material increases the possibility of fluxes of metals from the wetland. The chemical and physical characteristics of the environment influence the speciation and availability of heavy metals to consumer populations. Metals can accumulate in the food chain, but our understanding of this is incomplete. Few long-term studies have examined the recycling of heavy metals in wetlands. Most of the detailed work needed to make long-term predictions has been done only in estuarine systems. Generalizations based on such data may not necessarily be true for freshwater wetlands.

Deicing Agents

At concentrations produced by deicing materials washed from roadways, salt has its greatest effect in freshwater wetlands. Salts can be damaging to many kinds of plants and animals. At best, salt is tolerated by some wetland organisms. Most systems, however, cannot effectively retain or "detoxify" salt.

Most deicing salts are extremely mobile and readily migrate away if hydrologic conditions in the least permit. Without circulation, however, salt can accumulate and eventually reach toxic levels, even for tolerant species.

Hydrocarbons

Hydrocarbons in highway runoff may be expected to accumulate in the sediment or associate with plant and animal surfaces in wetlands if the circulation of water is sufficiently slow. Adsorption to surfaces is dependent on the nature of the hydrocarbon pollutant and increases as solubility of the pollutant decreases and the adsorbing particle size decreases and its organic content increases. Humic material has been shown to adsorb hydrocarbons effectively. The migration paths of petroleum products in wetlands (particularly at the low levels expected from chronic highway inputs) is not well understood. The behavior of petroleum products in the food chain of wetlands (especially freshwater) from runoff is not well documented in the literature. The role of dissolved organic material is not clear, as its increasing presence may inhibit adsorption of hydrocarbons. Turbulence and the activities of burrowing animals may serve to mix sedimented hydrocarbons.

Ultraviolet radiation has the effect of oxidizing straight chain molecules and increasing their solubility. However, other physical removal processes include volatilization and agglomeration/sedimentation. Bacteria are responsible for most hydrocarbon decomposition. Most are facultative aerobes and rely on aerated conditions, such as are found at air–water interfaces and associated with plant surfaces. Decomposition of hydrocarbons involves the degradation of straight chains first, followed by branched compounds, with significantly less degradation of the relatively persistent aromatics and cycloparaffins. The presence of higher plants enhances the retention of hydrocarbons by retarding circulation and physically filtering water, as well as by promoting aerobic conditions.

Animals ingest hydrocarbons as they feed on associated food material. Retention is a complex function of such variables as exposure, feeding mechanisms, the equilibrium of hydrocarbons between water and body lipids, and internal metabolism. Bioaccumulation has been noted in birds. Certain animals, notably

Table 1. Common highway runoff constituents and their primary sources.

Constituent	Primary source
Particulates	Pavement wear, vehicles, atmosphere, highway maintenance
Nitrogen phosphorus	Atmosphere, roadside fertilizer application
Lead	Leaded gasoline (auto exhaust), tire wear (lead oxide filler material), lubricating oil and grease, bearing wear
Zinc	Tire wear (filler material), motor oil (stabilizing additive), grease
Iron	Autobody rust, steel highway structures (guardrails, etc.) moving engine parts
Copper	Metal plating, bearing and bushing wear, moving engine parts, brake lining wear, fungicides and insecticides applied by maintenance operations
Cadmium	Tire wear (filler material), insecticide application
Chromium	Metal plating, moving engine parts, brake lining wear
Nickel	Diesel fuel and gasoline (exhaust) and lubricating oil, metal plating, bushing wear, brake lining wear, asphalt paving
Manganese	Moving engine parts
Bromide	Auto exhaust
Cyanide	Anticake compound (ferric ferrocyanide, Prussian Blue or sodium ferrocyanide, Yellow Prussiate of Soda) used to keep deicing salt granular
Na, Ca	Deicing salts, grease
Cl	Deicing salts
SO_4	Roadway beds, fuel, deicing salts
Petroleum	Spills, leaks or blow-by of motor lubricants, antifreeze and hydraulic fluids, asphalt surface leachate
PCB,	Spraying of highway right-of-ways, background atmosphere deposition, catalyst in synthetic tires.
Pathogenic bacteria (indicators)	Soil, litter, bird droppings, and trucks hauling livestock or stockyard waste
Rubber	Tire wear
Asbestos	Clutch and brake lining wear

Source: Ref. (1 through 13)

some fish, adapt to the presence of hydrocarbon contaminants. In general, animals serve to transport hydrocarbons, internally, on surfaces, and through sediment-mixing activity.

Pesticides

Roadside wetlands receive pesticides when they are implemented in weed and insect control, and runoff brings such chemicals into the system.

Organochlorine pesticides may be taken up by a variety of plant species; because such compounds concentrate in lipids, their uptake depends on the species' lipid content and habitat. Submergent and floating-leaved plants are particularly susceptible. Most organochlorine pesticides are relatively persistent, particularly where circulation does not permit downstream migration. Such contaminants are passed to herbivores or re-released to the system upon plant death and decay. Pesticides buried in the sediment may be mixed to the surface by the activities of burrowing animals. In general, pesticides are not easily stored or detoxified in wetlands and, thus, harm wetland organisms.

Fertilizers

Nutrient uptake by plants occurs as a result of growth and the demand for nutrients during this process. Nutrient absorption occurs through roots from the sediments on water column or via folliar tissue in the water column. Both plants and algae respond to increased nutrient levels with increased growth and/or increased nutrient uptake (luxury consumption). Plant uptake is species specific and rate of uptake and response to differing nutrient levels will vary among species. Stimulation of plant growth by increased nutrient supplies occurs seasonally; thus vegetation can only be a temporary sink for nutrients. Certain groups of plants grow exceptionally well in nutrient-rich conditions. Examples include species of *Typha* (cattail), *Phalaris* (reed canary grass), and Myriophyllum (milfoil). Many of these are nonnative species, and are considered to be "weeds." Increased nutrients can cause such species to increase in abundance and, thus, shift community make-up. Other functional changes, such as altered hydrology and shifts in animal usage, may follow.

IMPACTS TO WETLAND ECOSYSTEMS

Impacts on wetlands due to highway runoff can be defined in several different contexts. In its simplest definition, an impact is any effect or change to the wetlands as a result of highway runoff. These changes may be hydrological (changes in water level), water quality (changes in parameter concentrations in water and sediments), and biological (changes in biota present). It should be remembered that a change in one of these components often leads to changes in the other components. For example, a change in water level (hydrological impact) may result in a change in water quality, which in turn could affect the biota present.

Hydrological Impacts

Limited data exist on the specific effects of highway stormwater discharges on the hydrologic regimes of receiving waters, especially wetlands. Most research has involved the more generalized area of urbanization impacts, of which highway discharges are usually a small part.

In general, urbanization will increase the volume of total runoff, as would be anticipated due to the increase in the percent imperviousness of the watershed. However, modifications of drainage patterns affecting infiltration, percolation, storage, and discharge can either increase or decrease total runoff volumes contingent upon localized conditions. Other hydrological effects might include size of flood peak, and channel size (due to increase in peak flow) and a decrease in the lag time (i.e. time of concentration).

Similarly, the paved surface of a highway will increase the percent impervious of a wetland watershed. A short-term hydrological effect would be most dramatic for a highway whose runoff is discharged directly to the wetland (conduits, paved ditches, or drain pipes from bridge decks) compared to highway runoff which is channeled through an extensive network of grassy ditches. Impacts of highways on the surrounding hydrogeologic environment can include the following:

1. Beheading of aquifers.
2. Development of extensive groundwater drains where cuts extend below the water table.
3. Changes in ground and surface water divides and basin areas.
4. Reduction of induced streambed infiltration due to sedimentation.
5. Obstruction of groundwater flows by abutment, retaining walls, and sheet pilings.
6. Changes in runoff and recharge characteristics.
7. Loss of flood plain area where highways have been constructed parallel to streambeds.

Water Quality Impacts

A water quality impact in this context can be described as a change in concentration in wetland water of a particular highway runoff constituent. The severity of this change can be estimated by comparing the water quality during or after runoff events with criteria established by the federal government or, more importantly, with state or local water quality standards. Such criteria and standards are often based on a designated use for the water body such as drinking water supply, cold water fishery, and so forth.

Highway runoff effects on water quality of receiving waters have been less frequently documented than for the more generalized urban stormwater runoff. Actual field investigations of highway runoff impacts on wetland water quality are even more scarce. The following general observations on water quality impacts are pertinent to wetland systems:

1. Impacts on dissolved oxygen content of receiving waters due directly to stormwater runoff have not been documented in the technical literature. Most studies could not isolate stormwater oxygen demand from other sources. Comparisons between biochemical oxygen demand (BOD) loadings from runoff and treatment plant effluents are not valid because of differences in the nature of materials responsible for oxygen demand.
2. Nutrient impacts can be viewed from two perspectives. The first is possible violation of public health or aquatic life protection criteria or standards. In this regard, only ammonia, nitrate, and elemental phosphorus criteria exist. Few studies document levels in excess of those recommended by EPA which can be associated primarily with stormwater runoff. The second perspective is that of prevention of accelerated growth of nuisance aquatic plants that often detract from the recreational use of a water body. From this perspective, nutrient loadings from urban runoff sources have been identified by several researchers as being responsible for such accelerated primary productivity. Such effects from highway runoff alone have not been documented. However, some insights into the effects of nutrient loads from highway runoff or wetlands may be obtained from urban runoff studies.
3. The application of deicing agents to highways has been frequently shown to increase salt ion concentrations in nearby

soils and water bodies. The effects are less pronounced for flowing water systems (lotic series) where storm and melt waters have sufficient dilutive capacity to keep chloride levels below the criterion of 250 mg/1. For systems where water exchange is more gradual, such as lakes and wetlands, (lentic series) salts have been shown to accumulate, in some cases to chloride concentrations an order of magnitude higher than the water quality criteria value. Another significant and often reported effect of salts on lentic series is the inducement of unnatural salinity stratification. In some cases, this stratification has been of sufficient strength to prevent the usual spring turnover. Finally, very little is known of the fate or potential impact of toxic anticaking additives to road salts (sodium ferrocyanide and ferric ferrocyanide).

4. In spite of the prevalence of metals in highway and urban stormwater runoff, few studies have shown elevated water column concentrations of dissolved metals. The high association of metals with particulates and frequently demonstrated sediment enrichments of metals implies a rapid removal by sedimentation. In most cases, it is difficult to compare receiving water concentrations with recommended criteria because of the lack of hardness data. Environmental Protection Agency water quality criteria for metals are expressed as a logarithmic function of water hardness. Toxicity bioassays have shown that freshwater aquatic organism responses to metals are related to the hardness of the water used in the experiment.

5. There are very little data available on receiving water concentrations of petroleum hydrcarbon-related pollutants. Again, the high affinity of hydrocarbons for adsorption onto particulate matter verifies the sediment enrichments of these materials seen in several investigations.

Biological Impacts

The effects of highway runoff on the biota of streams, lakes, and wetlands have received only cursory attention in the scientific literature. Most research has been concerned only with physical and chemical parameters of receiving waters. In this regard, urban runoff has been studied more extensively than highway runoff. Four broad categories generally are used in describing pollution and its effect on biota:

1. *Siltation*—accumulation of particulate matter in an aquatic system.
2. *Acute toxic pollution*—toxic effects from high-level, short-term exposure to toxic pollutants.
3. *Chronic toxic pollution*—long-term, low-level exposure resulting in a biotic response of bioaccumulation to a toxic level.
4. *Eutrophication*—accelerated accumulation of nutrients and organic matter.

These groups are directly applicable to highway and urban runoff as well as to other pollution sources. The magnitude or type of biological effect depends on the type of pollutant and the quantity in both time and space.

CONCLUDING COMMENTS

The literature review revealed no study which comprehensively addressed all aspects of interaction of highway runoff constituents and wetlands. However, several state highway departments and wetland researchers indicated that such research is anticipated in the near future. The literature search identified several studies which investigated the utility of wetlands as a treatment system for urban runoff. Recent concern over the pollution potential of nonpoint urban runoff has initiated research to evaluate economical methods for controlling this complex and widespread source of pollution.

Case studies are presented in detail in Chapter Two and Appendix C of the agency research report for NCHRP Project 25-1 entitled, "Effects of Highway Runoff on Wetlands" (see Foreword for availability). Included in the case studies are several ongoing studies that are investigating the effects of highways on wetlands by collecting preconstruction, construction, and postconstruction data.

The fate of deicing salts in the environment after application to highways has been fairly well documented in the literature. Generally, the water quality of surface water bodies receiving highway runoff have not exceeded levels considered environmentally dangerous. However, a study performed in Maine indicates that the sodium chloride present in highway runoff may eventually cause some farm ponds to be unsuitable for livestock. Hydrogical factors appear to be extremely important in determining the water quality concentrations of sodium or chloride. Enrichment of soluble salts in water occurs during dry periods or with ice formation in shallow ponds or marshes. The effect of such enrichment on biota has not been studied. Most studies showed a buildup of sodium in substrates near highway runoff discharge points. Elevated sodium and chloride levels were also observed in macrophytes growing in these substrates. However, a biological impact was not observed in any of the case studies. Of recent concern are the anticaking additions found in deicing salts which include Yellow Prussiate of Soda (sodium ferrocyanide) and Prussian Blue (ferric ferrocyanide). Of those two anticaking additives, sodium ferrocyanide can photodecompose to yield simpler cyanide compounds that are potentially more harmful to aquatic animals than are the original cyanide complexes.

Because of the large number of highway receiving water crossings, and because commodities are carried on highways in a large number of separately controlled units, the potential is high for accidental spills on highways that can cause water pollution. One case study documented the effects of a 3,800-liter fuel oil spill on the vegetation in a freshwater marsh. Annual species were most severely affected by the oil during the season following the spill, while perennial species declined during the second year. Submerged macrophytes compared to floating and emergent plants were somewhat protected from the shock effect of the oil spill. In general, the marsh began to recover only after the gradual breakdown and flushing of oil from the system.

Several studies utilized algal bioassays to assess the effects of highway runoff. These studies concluded that highway runoff does have the potential to significantly affect the algal component of aquatic communities. The impacts can be inhibitory or stimulatory depending on the chemical composition of the runoff. Metals cause inhibition of algal growth. The nutrient load in highway runoff was found generally to be stimulatory, but the presence of metals dictated the final results. Data from one of the case studies indicated an inverse association between the concentration which inhibits algal growth by 50 percent and the vehicles traveling during the storm.

Studies showed that metals, especially lead which has a low solubility, generally exceed background levels in sediments and aquatic plants near the source of highway runoff. However, long-term or short-term impacts of metals to aquatic macrophytes were not demonstrated in these case studies. One study showed that sediment loads of lead, nickel, and zinc were highly correlated to traffic volumes. Lead and zinc concentrations in sediments were highest in the spring, gradually decreasing over the remainder of the year. The high spring concentrations were attributed to metal-laden-snowmelt runoff from the roadsides and surrounding regions of particulate deposition, and subsequent adsorption to trapped sediments in the stream. The decrease of lead and zinc concentrations in sediments over the remainder of the year was probably due to uptake by other components of the system and the gradual tendency toward an equilibrium by sediment-water interactions.

Case studies indicated that direct discharge into wetlands should be avoided. Surface runoff should be conveyed to the wetland via grassy drainage channels that will remove a large percentage of highway runoff constituents prior to discharge into the wetland. Data indicate that the objective of maintenance operations should be to nurture vegetation in drainage channels rather than to remove it in order to increase velocities. Maintenance should be directed towards preventing succession from grasses to larger growth.

Appendix B of this document presents an extensive bibliography by subject area. The contents are divided into the following categories:

CHAPTER TWO

FEASIBILITY OF USING WETLANDS TO MITIGATE THE EFFECTS OF HIGHWAY RUNOFF

INTRODUCTION

Fish and Wildlife Service Classification System

The U.S. Fish and Wildlife Service defines wetlands as "lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water. . . . [W]etlands must have one or more of the following three attributes: (1) at least periodically, the land supports predominantly hydrophytes; (2) the substrate is predominantly undrained hydric soil; and (3) the substrate is nonsoil [organic] and is saturated with water or covered by shallow water at some time during the growing season of each year" (*14*). This is a general definition, but it does include most wetlands and emphasizes those properties that are important in predicting the functions of a wetland and the fate of highway runoff pollutants.

The wetland classification system developed by Cowardin et al. (*14*) groups wetland and deep water habitats into distinct units by their physical and biological attributes. The classification has been structured so that any level of the hierarchy may be used to classify a particular habitat. Depending on which level of the hierarchy is used, a habitat can be identified in progressively greater detail.

The classification system is a hierarchical scheme, with five systems branching into successive subsystems, classes, and subclasses. The five systems (marine, estuarine, riverine, lacustrine, and palustrine) are the most general, each being distinguished by the influence of dominant hydrologic, geomorphic, biological, and chemical factors. Each system is subdivided into more specific categories—subsystems. Subsystems are characterized by more specific hydrological influences, such as tides or lake periphery water. The next more specific division is a class. This division groups similar habitat by dominating physical factors usually distinguished from one another by geological water basin properties or general descriptions of plant types present. Their subsequent branching to subclasses is based on the dominant plant and animal types present. The subclass specifically delineates the class into a unique entity that gives the user an idea of the general appearance of the habitat or the life form present. Each final wetland classification to be identified is the corresponding hierarchical classification, i.e., system: marine; subsystem: intertidal; class: aquatic bed; subclass: rooted vascular plants; modifiers: inorganic soil, regularly flooded; dominance: turtle grass. Also noted are modifiers that can influence the final wetland classification type. Modifiers are based on water regime, water chemistry, soil, or special properties modifiers. These modifiers, if present, should be noted in the final classification description.

Revised Classification Scheme

The Fish and Wildlife Service (FWS) classification (*14*) was designed to provide a logical scheme with categories for virtually all types of wetlands. However, this system can be cumbersome in deciding the use of a particular wetland to treat highway runoff constituents. Since many FWS wetland types have generally similar properties (for these purposes), a simplified classification scheme, as shown in Table 2, facilitates recognition of such groups and focuses attention on a limited number of properties that are important in determining wetland function pertinent to the amelioration of highway runoff pollution. They are: (1) vegetation life form, (2) substrate type, and (3) hydrologic regime. Once these properties are identified for a particular site, predictions about its utility for filtering runoff constituents can be made.

Table 2. Suggested functional grouping of wetlands.

Life Form	Substrate	Water Regime
Aquatic	Inorganic	Tidal Deep Shallow
	Organic	Tidal Deep Shallow
Moss-Lichen	Organic	Surface Saturated
Emergent	Inorganic	Tidal Deep Shallow Surface Saturated
	Organic	Tidal Deep Shallow Surface Saturated
Scrub-Shrub	Inorganic	Tidal
	Organic	Tidal Deep Shallow Surface Saturated
Forest	Organic	Tidal Deep Shallow Surface Saturated

Life Form

The dominant life form of a wetland is determined by the plants with the greatest mass—usually the most common species. The functioning of these plants will control the overall functioning of the wetland. "Life form" refers to the appearance of the mature plant, leaf shape, size, and whether the plant is woody or herbaceous (the above-ground portions dying back each year). Five life forms with relatively distinct properties may be easily identified: aquatic, moss-lichen, emergent, shrub-scrub, and forest. Mixtures of species and life forms are to be expected in wetlands, particularly in shallow-water, surface-saturated, and drier hydrologic conditions. The planner, familiar with the natural history and general above- and below-ground form of the common plants at a site should be adequately equipped to evaluate their dominance. The features of wetlands that are important in pollution retention will differ somewhat from those important to wildlife habitat or to aesthetic properties. Cover, the areal extent of above- and below-ground plant parts, is probably the most important parameter to consider in determining dominance; density and frequency of stems are descriptors of species aggregation and evenness of distribution. It must be remembered that, in considering a wetland community's ability to retain water-borne pollutants, the following relevant properties will come to bear: (1) the potential uptake and release of mineral nutrients and other material by plants, (2) the potential for retention of water and sediment caused by the density of stems and roots, and (3) uneven functioning as a result of uneven plant distribution and variation in substrate. For instance, woody plants—shrubs and trees—will probably not play significant roles in the functions (in the restricted sense) of a wetland if coverage is less than 50 percent. The system as a whole (vegetation, sediments, hydrologic regime) must be considered in determining the importance of a species or life form to the way that a particular site functions. However, the interaction between plant stems and roots and the sediment and water column may determine efficiency of the system in several respects. Similar emergent plant communities may behave differently in deep water as contrasted to shallow water or inorganic sediment compared to sand. Taller plant cover may be required in deep water for attaiment of effects similar to those in shallow water. There are no simple formulas for predicting how different densities or cover of a particular species will function.

Substrate

The nature of the substrate may be at least as important as the vegetation in the retention and cycling of nutrients and pollutants. Organic sediment differs substantially in behavior from inorganic material. Inorganic substrates consist primarily of mineral particles: gravel, sand, silt, and clay in various mixtures. Such sediments contain less than 12 to 18 percent organic matter. Most, but no all, wetland sediments contain some organic matter; if organic matter makes up more than 12 to 18 percent of the sediment, it is considered to be an organic soil. Organic soils vary in composition. Peat contains a high proportion of fibrous material that is slow to decompose; in muck, the organic material is more decomposed and fibers cannot be easily distinguished.

Water Regime

Recognition of the water regime is critical to understanding wetland function. Wetlands may be distinguished as being tidal, or covered by deep or shallow water, or having sediments saturated with water. Regular water level fluctuations are common in marine coastal wetlands. Seiches in large lakes (such as the Great Lakes) may have similar effects. Water level fluctuations serve to expose sediment to the air periodically, increase circulation in and near the sediment, and transport material upstream and downstream. Sedimentation patterns are greatly affected by tidal movements and by currents.

The depth of water in wetlands varies through the year and from year to year. Criteria for distinguishing deep from shallow water are somewhat arbitrary and relate to a variety of wetland conditions as varied as accessibility to fish and other aquatic vertebrates and invertebrates to the potential for turbulent water flow. Most classification schemes suggest that a minimum of 18 cm (6 in.) of water distinguishes a deep water wetlands. Shallow water (less than 18 cm) is less likely to support aquatic vertebrates and more likely to become anaerobic. Shallow water is more susceptible to occasional drawdown below the sediment surface.

As the name implies, surface-saturated sediment seldom experiences prolonged periods of standing water; this may occur seasonally or sporadically following flooding. An important feature of saturated sediment is the extensive contact between water and roots, benthic organisms, and sediment particles. Whether a sediment retains pollutants may depend on the extent of water-pollutant-particle interaction.

The remainder of this chapter discusses the primary considerations in treating highway runoff—the type of wetland used, the quality and quantity of pollutants from the highway, and the climatic and geographic characteristics including topography and drainage patterns, geologic history, and biology of specific wetland species.

SPECIFIC WETLAND TYPES

The results of the literature search indicate that the following wetland types may, indeed, be appropriate to treat highway runoff:

1. *Moss-Lichen Type—Organic Substrate, Surface Saturated*—Mosses and lichens lack conducting tissue, and are restricted in stature. In wetlands, lichens and most mosses are found where the organic substrate is saturated to the surface and with seasonal flooding. They usually occur as a low carpet, although a few species of moss form hummocks. Bogs are peatlands in which much of the surface is covered by various species of Sphagnum moss; the adsorptive and acidic properties of such wetlands are partially provided by the living and dead organic material of the mosses. It is important to note that the moss-lichen type is the most difficult to maintain because peat has a high capacity for storage and any fluctuation in hydrology invites invading species and system deterioration.

2. *Emergent Type—Organic Substrate, Shallow or Surface-Saturated*—Erect herbaceous hydrophytes grow rooted in wet sediment with leaves and stems extending above the water surface. Many reproduce vegetatively by underground rhizomes as well as by seed. Marshes, meadows, fens, wet prairies, and sloughs are dominated by emergent plants. Many species of emergent plants are fast-growing and absorb nutrients efficiently. The above-ground parts of these plants die back every year and return some nutrients and organic matter to the system.

3. *Shrub-Scrub Type—Organic Substrate, Shallow or Surface-Saturated*—Low growing woody plants dominate the life form of this wetland type and include shrubs, young trees, and stunted mature trees. This community is often found along the somewhat dried landward portions of wetlands between emergent wetland communities and the upland. At intervals, high water may kill the shrub community; as the water level falls, the area of dead stems is invaded again by shrubs and trees. Usually, the woody community has an understory of mosses or emergent plants. Shrub-scrub species may be deciduous or evergreen; thus, these communities are variable in function. Shrub-scrub species make up shrub swamps, shrub carr, thickets, bogs, and pocosins.

4. *Forest Type—Organic Substrate, Shallow or Surface-Saturated*—Tall trees (greater than 6 m) are typical of wetland forests, where they make up the swamps, hummocks, heads, bottoms, and lowland forests. Forested wetlands may have an understory of shrubs and a ground cover of emergent plants or mosses.

QUALITY AND QUANTITY OF POLLUTANTS

The research revealed considerable variability in highway runoff quality and in the ability of wetlands to withstand impact from highway runoff constituents or to treat highway runoff constituents. Therefore, treatment capacity is best evaluated on a system (highway/runoff) by system basis.

The literature survey indicated that heavy metals are a major constituent in highway runoff. Chan et al. (*15*) present a range of heavy metal removal potential for wetlands as follows:

1. 0.001 to 0.38 kg/ha of cadmium, with highest removals by *Potamogeton crispus* and *Salicornia pacifica.*
2. 0.007 to 1.58 kg/ha of copper, with highest levels by *Justicia americana* and *Salicornia pacifica.*
3. 0.13 to 103.4 kg/ha of iron, with highest levels by *Carex stricta.*
4. 0.026 to 1.01 kg/ha of lead, with the highest levels by *Salicornia pacifica* and *Pharlaris arundinacea.*
5. 0.001 to 1.714 kg/ha of zinc with the highest levels by *Phragmites communis, Carex stricta* and *Scirpus lacustris.*

Damman (*16*) studied the mobilization and accumulation of heavy metals in a freshwater bog and swamp. The annual growth of *Sphagnum flavicomans* in an oligotrophic bog contained 0.162 kg/ha Pb, 0.035 kg/ha Cu, 0.162 kg/ha Zn, and 0.008 kg/ha Ni. The amounts of zinc and copper in the annual growth assimilation was 50 percent of the lead and more than 30 percent of the nickel input. The heavy metals, copper, lead, nickel, and zinc, were accumulated only to a limited extent in the hummocks of the red maple swamp; the swamp apparently did not act as a sink for lead and zinc.

The ability of salt marshes to remove nutrients and heavy metals from dredged material disposal area effluents has been studied by Windom (*17*). The vegetation in the marsh studied was composed of short *Spartina alterniflora* and had a peak standing above-ground biomass of approximately 700 g/m^2 dry weight. Nutrients (nitrogen and phosphorus) and metals (iron, manganese, cadmium, copper, nickel, and zinc) were removed from the effluent during overland flow in salt marshes. During the period of this study the mean metal concentrations of the effluent from the experimental salt marsh were between 15 and 32 percent lower than the mean metal concentrations of the input (Table 3). Excluding periods when concentrations were near ambient, the mean phosphorus and nitrogen removal efficiencies were above 30 percent.

Lee et al. (*22*) describe the average nutrient and heavy metal removal by selected plant species (Table 4). Detailed data on the heavy metal uptake by naturally occurring saltwater and freshwater marsh plants, particularly for the species *Cypera* and *Spartina*, are presented in Simmers et al. (*23*). The removal potential of nitrogen, phosphorus, and heavy metals by wetland vegetation (Tables 4 through 15 is summarized in Chan et al. (*15*). Table 15 presents a summary of pollutant removal effectiveness by various wetlands. The data show that the pollutant removal effectiveness varies significantly with pollutant and wetland type.

CLIMATIC AND GEOGRAPHIC CHARACTERISTICS

Knowledge of such regional and local variables as climate, topography and drainage patterns, geologic history, soils, and the biology of specific wetland species are important considerations for the planner in predicting the functions of a wetland and the fate of runoff pollutants. Recommendations and caveates for using wetlands to treat highway runoff include:

1. *Topography and drainage considerations*—Direct discharge into wetlands should be avoided. Surface runoff should be conveyed to the wetland via grassy drainage channels that will remove a large percentage of highway runoff constituents prior to discharge into the wetland.

If highway stormwater runoff is discharged directly into a receiving water body (i.e., if dilution alone is used to reduce the impact of highway runoff on the receiving waters), a solution of 80 percent (four parts dilution/one part runoff) is needed to avoid an oxygen debt (*59*). At sites where average daily traffic (ADT) exceeds 10,000 vehicles per day, a dilution of 100/1 is required to protect biota from heavy metals, a level recommended by the U.S. Environmental Protection Agency (*60*). This means that inputs of highway runoff to a receiving water body should not exceed 1 percent of the system's total volume.

Runoff from a highway should enter the wetland as sheet flow to distribute constituents across a wide area. Runoff migration through the wetland should be relatively slow. Low slopes or impoundments could be used to slow movement and retain water in plant populations and over soil.

Water level in the retention area should be shallow or surface-saturated to permit aeration of the substrate. Alkaline conditions (wherever possible) in water and substrate will enhance retention of metals and improve conditions for microbes.

The wetland basin should be hydrologically separate from other aquatic systems, which might otherwise become contaminated. Systems which mix regularly, such as wetlands along flowing channels, and wetlands adjacent to tidal creeks, should be avoided. These types of wetland systems have little capability to assimilate runoff constituents and mitigate any deleterious effects.

Table 3. Ranges in concentration of elements in effluent from disposal area during experiments (*457*).

	Conc. in effluent (g/1)			Ambient concen. (g/1)	Range Source Ref.
	Min.	Max.	Mean		
Nitrogen	270	16400	3170	70-300	18
Phosphorus	15	115	44	9-60	18
Iron	10	3000	760	5-50	19
Manganese	250	14000	2030	5-60	19
Cadmium	0.1	0.6	0.26	0.1-0.4	20
Copper	2.2	29	8.1	0.1-3.9	21
Nickel	1.0	5.2	2.2	0.7-16	21
Zinc	8	24	12	0.5-10	21

[a] Mean of all effluent analyses.

Distance of wetland to highway is also an important consideration if atmospheric deposition of highway-generated pollutants and the overland migration of metals to the wetland is to be minimized. Distance ranges from 5 to 35 m from edge-of-pavement depending on the average daily traffic (less than 2,000 to 116,000 vehicles per day, respectively). Data (*61*) indicate that if the ratio of impervious roadway surface/total watershed area is less than 0.01, and if either the traffic volume is less than 10,000 ADT or highway drainage is over a vegetated ditch, the impact to a receiving water can be considered insignificant.

Road deicing salts should be prudently used in the vicinity of wetlands. Alternatives, such as sand or cinders, should be considered. Hydrocarbon-based and other persistent pesticides should not be used when they may be runoff to a wetland. Dense roadside vegetation should be controlled by mowing; the litter produced and left on the soil surface may serve to trap runoff constituents.

A common maintenance procedure is to keep highway drainage channels clear of vegetation by scraping or herbicide application so as not to impede stormwater flow. However, maintaining vegetated channels appears to reduce contamination by promoting sedimentation and possibly by creating other conditions conducive to dissolved constituent removal. Data in the literature indicate that the objective of maintenance operations should be to nurture vegetation in drainage channels rather than to remove it in order to increase velocities (*62*). However, because of reduced velocities, the drainage channels may require enlargement to prevent back-ups and possible flooding.

2. *Substrates*—Adsorption behavior of metals onto oxidized (aerobic) sediment particulate matter has been shown to be strongly dependent on iron and manganese hydrous oxides and organic (humic and fulvic materials) surface coatings. The degree of adsorption increases dramatically in alkaline conditions.

Anaerobic sediments are also capable of effective metal removal through sulfide precipitation. Methylmercury formation typically occurs in anaerobic sediments.

Petroleum hydrocarbon-based materials (including many pesticides and herbicides) are strongly adsorbed by clays and organic substrates, especially humic materials. Petroleum hydrocarbons are much more readily decomposed in aerobic sediments than anaerobic sediments. Heterotrophic bacteria are largely responsible for this decomposition.

3. *Specific wetland species*

a. Vegetation—Vegetation should be relatively dense to provide for ample surface area for adsorption, absorption, microbial colonization, aeration, etc. Wetlands with native vegetation are most desirable, and a diversity of species is desirable; monocultures should be avoided. Species of plants that are slow to decay are desirable. The litter carries on many useful functions. Examples are species of woody plants and emergent herbaceous perennials, such as *Carex* spp., *Typha, Juncus, Spartina, Phragmites* and others. Emergent perennial species are preferred because many of these can withstand sudden contamination; underground parts persist to later growing periods. Many are adapted to shallow conditions and are highly productive.

b. Wildlife—Wildlife production areas should not be used. Wetlands that contain rare, threatened, or endangered species, plant or animal, should be avoided.

Changes in the water regime affect not only the vegetation community but wildlife habitat as well. Changes in wildlife use should be anticipated if hydrologic conditions in the wetland are to be changed.

It is not advisable to encourage wildlife, particularly the mobile types, such as fish, birds, muskrats; although, in an artificial (created) wetland, wildlife colonization is to be expected.

Table 4. Average nutrient and heavy metal removal by selected plant species (*22*).

Plant Species	Reference	Nutrient Removal (kg/ha)						Heavy Metal Removal (kg/ha)				Dry Weight Yield (kg/ha)
		N	P	Fe	Mn	Zn	Cu	Pb	Ni	Cd	Cr	
				Freshwater plants								
Eichornia	24	297	20	30.2	20.2	2.68	13.44	0.44	0.33	0.14	0.24	16,016
crasspies	25	1980	322	19.0	296.0	4.0	1.0	-	-	-	-	75,000
Alternanthera	24	381	43	21.3	13.4	2.35	15.90	1.12	0.44	0.16	0.40	17,360
philoeroides	25	1779	198	45.0	27.0	6.0	1.0	-	-	-	-	-
	26	185	24	-	-	-	-	-	-	-	-	6,737
Justicia	24	179	76	4.5	3.4	1.12	0.67	0.22	0.22	0.02	0.12	3,360
americana	25	2293	136	123.0	13.0	30.0	3.0	-	-	-	-	-
	26	386	24	23.0	2.0	4.0	0.5	-	-	-	-	24,580
Myriophyllum spicatum	24	189	11	29.1	15.7	1.68	1.34	0.44	0.11	0.08	0.16	-
Zizaniopsis miliacea	24	114	11	12.3	6.0	0.67	0.56	0.11	0.11	0.06	0.40	3,472
Typha latifolia	25	2630	403	23.0	79.0	6.0	7.0	-	-	-	-	-
				Saltwater Plants								
Spartina alterniflora	27	43	5	2.6	0.12	0.06	0.07	-	-	-	-	2,670

Note: Dash indicates no data available in reference.

Table 5. Nitrogen removal potential of emergent aquatic vegetation.[a]

Species	Removal Potential (kg/ha) Above-ground	Below-ground	Total Biomass	Study Area
CATTAILS				
Typha spp.	0.76			Poland; very acid lake
	5.71			Poland, acid lake
T. glauca	12	207	207	New York; winter biomass in wetlands
T. latifolia	220	94.50	315	Wisconsin; marsh
	509			Czechoslovakia; fishpond
	53.40			S. Carolina; power plant cooling pond
	53-310			Wisconsin; marsh
T. augustifolia	130-330			Wisconsin
	245-467			Czechoslovakia; fishpond
T. domingensis	97.8			S. Carolina; power plant cooling pond
REEDS				
Phragmites communis	1.37			Poland; acid lake
	3.34-15.98			Poland; eutrophic lake
	181-409	350-640		Czechoslovakia; fishpond
		830		Delaware; salt marsh, maximum biomass
	8-11			Poland; lake, three months biomass - unmown/mown
	137-409	354-640		Czechoslovakia; fishpond
	800			Ukraine; maximum productivity in a eutrophic lake
	118-347			Poland; a range of lakes
RUSHES				
Juncus gerardii		940		Delaware; salt marsh, maximum biomass
		680		Maine; salt marsh, maximum biomass
J. roemerianus		1230		Georgia; salt marsh, maximum biomass
J. effusus			100-250	S. Carolina; power plant cooling pond
SEDGES				
Carex lacustris	32	40	73	New York; wetlands
	11	77	88	Wisconsin; marsh
C. rostrata	32	40	73	New York; wetlands
C. lanuginosa	9	169	178	New York; wetlands
Carex spp.				Michigan, wetlands
Cyperus esculentus	10-26			Connecticut; lakes
Scirpus fluviatilis	53	154	173	Wisconsin; marsh
S. validus	128.40			S. Carolina; power plant cooling pond
S. americanus				S. Carolina; power plant cooling pond
GRASSES				
Phalaris arundinacea	437			Minnesota; fertilized overland flow
Spartina alterniflora		1290		Delaware; marsh, maximum biomass
		980		Subtropical; marsh, maximum biomass
	26-177	53-112	90-289	N. Carolina; salt marsh, various fertilization rates
	11-134			N. Carolina; salt marsh
	18-60			Georgia; salt marsh
	20-100			Georgia; salt marsh, domestic waste-water sludge applied
S. patens		140		Georgia; salt marsh
		270		Delaware; salt marsh
		610		Maine; salt marsh

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[a] Source: Ref. (28).

Table 6. Nitrogen removal potential of submerged vascular plants.[a]

	Removal Potential (kg/ha)		
Species	Aboveground biomass	Total Biomass	Study Area
PONDWEED			
Potamogeton spp.		56.50	Minnesota; agricultural drainage ditches
P. pectinatus	6		Poland; eutrophic lake, area highly polluted with domestic wastewater
P. perfoliatus	6		Poland; eutrophic lake, area highly polluted with domestic wastewater
P. pulcher	19.6		New Jersey; artifical ponds, 1 months growth
ELODEA			
Elodea canadensis	39.8		New Jersey; artifical ponds, 1 months growth
COONTAIL			
Ceratophyllum demersum		4.47	Poland; eutrophic lake
	1.34-13.1		Poland; small eutrophic lake
WATERMILFOIL			
Myriophyllum excalbescens		89.66	Wisconsin
M. spicatum		8.5	Poland; small eutrophic lake
	64.94		Wisconsin; shallow, eutrophic, hardwater lake
	83.9		New Jersey; artificial ponds, 1 months growth
	56.28		Wisconsin; shallow, eutrophic, hardwater lake

[a] Source: Ref. (28).

Table 7. Nitrogen uptake rates of emergent aquatic plants.[a]

Species	Uptake Rates			Study Area
	kg/ha/day	kg/ha/year	kg/ha/month	
CATTAILS				
Typha latifolia	-0.9-1.6			S. Carolina; power plant cooling pond
	1.4			Czechoslovakia; marsh growing season
		689		Minnesota; marsh maximum aboveground productivity
		2630		Temperate climate; total plant mass at maximum possible productivity
T. augustifolia			5.9-129.8	England; marsh
REEDS AND RUSHES				
Phragmites communis		270 160		The Netherlands wastewater ponds aboveground/ belowground plant mass
		437		The Netherlands; maximum aboveground plant mass
			0.4-378	England; marsh
SEDGES				
Carex lacustris	1			New York; wetlands, growing season
Scirpus americanus	-0.32-0.34			S. Carolina; power plant cooling pond
S. fluviatilis		208		Wisconsin; marsh
S. lacustris		260 320		The Netherlands; wastewater ponds, aboveground/ belowground plant mass
GRASSES				
Phalaris arundinacea		124-272		Alberta, Canada; overland flow, wastewater
		109-299		W. Canada; overland flow, wastewater
Spartina alterniflora		186		Louisiana; salt marsh

[a] Source: Ref. (29).

Table 8. Phosphorus removal potential of emergent aquatic vegetation.[a]

Species	Removal Potential (kg/ha) Aboveground	Belowground	Total Biomass	Study Area
CATTAILS				
Typha spp.	0.419-0.481			Poland; acid lakes
T. augustifolia	7.9 5.0 4.0			Wisconsin wastewater pond, seasonal totals of biweekly/monthly/ seasonal harvesting schemes
	6-10			Wisconsin; wastewater pond, multiple harvests
	31.7			N. Europe; wastewater pond
	45-65			Czechoslovakia; fishpond
	32-46			Wisconsin; wetlands
T. glauca	2.7	39	42	New York; wetlands, winter biomass
T. latifolia	43.9	28.6	42.5	Wisconsin, marsh
	77			Czechoslovakia; fishpond
	6.8-32			Wisconsin; wetlands
	24 43			Wisconsin; wetlands, winter/ summer plant mass
REEDS				
Phragmites communis	0.126			Poland; acid lake
	0.39-1.16			Poland; eutrophic lakes
	32-53	38-74		Czechoslovakia; fishpond
	0.4			Poland; lake, 3 month growing season
	14-63.5			Sweden; lake
	62.7			N. Europe; wastewater pond
	14-53	38-74		Czechoslovakia; fishpond
	80			N. Europe; marshes, maximum productivity
	10.6-26.7			Poland; marsh
RUSHES				
Juncus effusus			10-30	S. Carolina; power plant cooling pond
SEDGES				
Carex spp.	0.96-3.48			Michigan; wetlands
Carex lacustris	5	5.5	11	New York; wetlands
	2.4	19.7	22	Wisconsin; wetlands

Table 8 (continued)

Species	Removal Potential (kg/ha)			Study Area
	Aboveground	Belowground	Total Biomass	
C. rostrata	5	5.5	11	New York; wetlands
C. languinosa	1.2	37	38	New York; wetlands
C. stricta			59.3	N. Europe; wastewater pond
Scirpus fluviatilis	20	32	34	Wisconsin; marsh
	11.3			Wisconsin; wastewater pond, total of 4 harvests
S. validus	35.1-38.3			Wisconsin; wastewater pond, total of 4 harvests
S. lacustris			67.2	N. Europe; wastewater pond
GRASSES				
Phalaris arundinacea	43.71			Minnesota; marsh maximum production
	33-56			Pennsylvania; overland flow, wastewater, totals of 3 harvests/season
Spartina alterniflora	6			Georgia; salt marsh
	1.1-14.9			N. Carolina; salt marsh

[a] Source: Ref. (29).

Table 9. Phosphorus removal potential of submerged vascular plants.[a]

Species	Removal Potential (kg/ha)		Study Area
	Aboveground Biomass	Total Biomass	
PONDWEED			
Potamogeton spp.		12.9	Minnesota; agricultural drainage ditch
P. natans		3.6-11.6	Sweden; small stream polluted with domestic wastewater
P. pectinatus	0.6		Poland; lake, site heavily polluted with domestic wastewater
P. perfoliatus	0.6		Poland; lake, site heavily polluted with domestic wastewater
P. pulcher	3.5		New Jersey; artificial ponds, 1 months growth
ELODEA			
Elodea canadensis		0.03-0.93	Poland; eutrophic lake
	12.1		New Jersey; artificial ponds, 1 months growth
COONTAIL			
Ceratophyllum demersum		0.58-0.99	Poland; eutrophic lake
	0.62-6.08		Poland; eutrophic lake
WATERMILFOIL			
Myriophyllum excalbescens		8.97	Wisconsin
M. spicatum		0.015-0.078	Poland; eutrophic lake
	12.55		Wisconsin; shallow, euthrophic, hardwater lake
	2.90-17.70		Wisconsin; lake
	2.20-12.30		S. Carolina; power plant cooling pond
	20.3		New Jersey; artificial ponds, 1 months growth
	1.13-5.06		Wisconsin; highly alkaline lake
	12.99		Wisconsin; shallow, eutrophic, hardwater lake

[a] Source: Ref. (28).

Table 10. Phosphorus uptake rates of emergent aquatic plants.[a]

Species	Uptake Rates			Study Area
	kg/ha/day	kg/ha/year	kg/ha/month	
CATTAILS				
Typha augustifolia			0.7-32.1	Temperate marsh
T. latifolia	-0.03-0.19			S. Carolina; power plant cooling pond
	0.08			Czechoslovakia; marsh, growing season
	0.95	31		Wisconsin; marsh, growing season total biomass
		74		Minnesota; maximum productivity
		403		Temperate climate; maximum productivity, total biomass
REEDS AND RUSHES				
Phragmites communis		35 20		Temperate climate; wastewater ponds aboveground/ belowground
			0.13-19.6	England; marsh
SEDGES				
Carex lacustris	0.06			New York; wetlands, growing season
Scirpus americanus	-0.04-0.05			S. Carolina; power plant cooling pond
S. lacustris		50 55		The Netherlands; wastewater ponds aboveground/ belowground
S. fluviatilis		53.3		Wisconsin; marsh
GRASSES				
Phalaris arundinacea		70.14		Temperate climate; wastewater irrigation
Spartina alterniflora	0.06			Georgia; salt marsh

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[a] Source: Ref. (29).

Table 11. Heavy metal removal potentials of emergent aquatic plants (Cd, Co, Cu Fe, Hg).[a]

Species	Removal Potential (kg/ha)					Study Area
	Cd	Co	Cu	Fe	Hg	
CATTAILS						
<u>Typha augustifolia</u>		0.006	0.068	15.80		W. Europe; wastewater ponds
<u>T. latifolia</u>		0.010	0.360			Ukraine; reservoir
REEDS AND RUSHES						
<u>Phragmites communis</u>		0.028	0.188	41.20		W. Europe; wastewater ponds
		0.004	0.350			Ukraine; reservoir
SEDGES						
<u>Carex stricta</u>		0.020	0.152	103.40		W. Europe; wastewater pond
<u>Scirpus lacustris</u>		0.023	0.161	26.20		W. Europe; wastewater pond
GRASSES						
<u>Phararis arundinacea</u>	0.001-0.005					Pennsylvania; overland wastewater disposal; varied rates
<u>Spartina alterniflora</u>				0.19-9.90		N. Carolina; salt marsh
				3.84		N. Carolina; salt marsh
	0.004	0.026		5.25	0.001	S. Carolina; salt marsh
<u>S. alterniflora and S. patens</u>	0.0003-0.0050					Massachusetts; salt marsh, wastewater sludge applied at various rates to a mixed stand
OTHERS						
<u>Justica americana</u>			0.30-0.80	9.8-38		Alabama; lake
<u>Salicornia pacifica</u>	0.08-0.38		0.42-1.58			California; brackish marsh receiving urban runoff

[a] Source: Refs. <u>(29, 30)</u>.

Table 12. Heavy metal removal potentials of emergent aquatic plants (Mn, Mo, Ni, Pb, Zn).[a]

Species	Removal Potential (kg/ha) Mn	Mo	Ni	Pb	Zn	Study Area
CATTAILS						
Typha augustifolia	11.22	0.004	0.027		0.629	W. Europe; wastewater ponds
T. latifolia	13.66				0.600	Ukraine; reservoir
REEDS AND RUSHES						
Phragmites communis	7.44	0.012	0.068		1.658	W. Europe; wastewater pond
	15.60		0.068		0.500	Ukraine; reservoir
SEDGES						
Carex stricta	26.38	0.008	0.067		1.714	W. Europe; wastewater pond
Scirpus lacustris	40.32	0.018	0.058		1.680	W. Europe; wastewater pond
GRASSES						
Phalaris arundinacea				0.106-0.437		Pennsylvania; overland wastewater disposal; varied rates
Spartina alterniflora	0.02-0.42					N. Carolina; salt marsh
S. alterniflora				0.028-0.116		Massachusetts; salt marsh, wastewater sludge applied at various rates
	0.32				0.06	N. Carolina; salt marsh
	0.35					S. Carolina; salt marsh
S. alterniflora S. patens					0.048-0.301	Massachusetts; salt marsh, wastewater sludge applied to a mixed stand at various rates
OTHERS						
Justicia americana	1.3-2.5				2.6-5.8	Alabama; lake
Salicornia pacifica				0.026-1.01	0.43-0.68	California; brackish marsh receiving urban runoff

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[a] Source: Refs. (29, 31).

Table 13. Heavy metal content of floating aquatic vegetation.[a]

Species	Al	Cd	Gr	Co	Cu	Fe	Pb	Hg	Ni	Ag	Sr	Zn	Comments
	Dry Weight, mg/g												
Water hyacinth		300					3200						96 hrs. in 0.1 ppm Cd and 10 ppm Pb solutions
				0.5-2.9	0.4-2.6	15-70							Plants of different sizes from natural populations
		200-670							300-500				24 hrs. in 0.6-2 ppm solutions
		<0.001		<0.007	<0.01		0.063	<0.001	<0.05	<0.02	<0.01	0.58	2 wks. in sewage effluent; measurements made on roots only
				89-568						140-650	102-544		24 hrs. in 0.6-2.4 ppm solutions. Uptake measured as difference in metal content of substrate
		2-164	4-286		15-570		25-257			4-77			6 wks. in chemical waste system. Lowest concentrations in leaves and stems; highest in roots
		<0.2-281											24 hrs. in 0.001-0.1 ppm solutions. Lowest concentrations in plant tops; highest in roots.
Duckweed					3-110								Naturally-occurring population, England
	468	17.4	65	19.2	101.1	13.9		5.6			679	58	Plants growing in drainage system of coal-fueled power plant, S. Carolina
	1980			26	79				1840				American River, California

[a] Source: Ref. (29).

Table 14. Heavy metal removal potentials of submerged vascular plants.[a]

Species	Removal Potential (kg/ha)							Comments
	Al	Cd	Co	Cu	Fe	Mn	Zn	
PONDWEED								
Potamogeton crispus		0.001-0.114						Indiana; shallow eutrophic lake; soil Cd concentrations 0.66-44.8 ppm
P. lucens			0.024	0.087		4.250	0.400	Ukraine; shallow eutrophic reservoir.
P. pectinatus			0.010	0.030		2.500	0.210	Ukraine; shallow eutrophic reservoir.
					0.140	0.040	0.001	Poland; eutrophic lake, site heavily polluted with domestic wastewater, reduced growth.
P. perfoliatus					0.140	0.040	0.001	Poland; eutrophic lake, site heavily polluted with domestic wastewater, reduced growth.
WATERMILFOIL								
Myriophyllum spicatum	0.109			0.007	0.130	0.109	0.002	Wisconsin; shallow eutrophic hardwater lake.

[a] Source: Ref. (28).

Table 15. Summary of pollutant removal effectiveness in wetland treatment systems for various types (exclusive of aquaculture systems).

Geographic Location	Type of Wetland	General Description	Pollutant Removal Effectiveness	Comments	Reference
I. Highway and Urban Stormwater Runoff					
City of Wildwood, Florida	Hardwood swamp	Receives combination municipal wastewater and urban runoff			(32)
Florida Technical University	Cypress stand	9.75 ha watershed, with 67% impervious area	Total-N 95% Total-P 97% SS 99% BOD_5 89%		(15, 33, 34)
Wayzata, Minnesota	Peatland	2.8 ha wetland receives urban runoff from 28.3 ha watershed	NH_3-N Net increase Total-P 78% SS 94% Cd 25-80% Cu 73-83% Pb 90-97% Zn 78-86%		(15, 35)
Roseville, Minnesota	Freshwater wetland	11.7 ha wetland receives urban runoff from 90 ha watershed	TKN 31% NO_2-N 70% NO_3-N 97% Ortho-P 62% Total-P 61% SS 80%	Hydraulic retention time (HRT) 45 days	(36)
Lake Tahoe, California	High altitude meadows overland flow hydraulic mode	Several watersheds and meadows studied, meadow slopes ranged from 2-7%	NH_3-N ≤67% NO_3-N ≤96% TKN ≤76% Total-P ≤93% SS ≤99%		(15, 37)
Palo Alto, California	Brackish tidal marsh	243 ha marsh receives urban runoff from 7130 ha watershed	Total-N 37% Total-P Net increase SS 87% VSS 85% BOD 54%		(15, 30)
Montgomery County, Maryland	Wetland detention basin, 0.9 - 4 m deep	2.4 ha pond receiving urban runoff from 60 ha watershed	NH_3-N 99% Total-P 99% Ortho-P 93% BOD_5 97% Cd 98% Fe 96% Pb 96% Zn 99%		(15, 34, 38)
Central Florida	Roadside ditches along Florida interstate and state highways	11 sites were used to demonstrate variability between aerobic, partly anaerobic (1-3 m depth) and different soil conditions	Petroleum hydrocarbon degradation and metals (ie., Pb, Zn, Cu, Cd, Cr and Ni) deposition and interaction with soil, plant and animal components was studied in depth, pollutant mass balance calculations not possible due to lack of detailed runoff data		(39)
II. Municipal Wastewaters					
City of Clermont, Florida	Freshwater marsh, emergent species	Four 2000 m^2 experimental plots	Total P 97% inorganic-N 95%	Recommend loading rate of 1.5 in./wk	(40)
Northern Wisconsin	Sphagnum peat bog	10 ha bog	Conductivity 70% Chloride 60% COD +204% BOD_5 21% Total-P 80% Ortho-P 79% TKN 21% NH_3-N 67% Suspended solids 95%	First year results, system not subjected to extreme storm events in that time	(41)

Table 15 (continued)

Geographic Location	Type of Wetland	General Description	Pollutant Removal Effectiveness	Comments	Reference
East Lansing, Michigan MSU Water Quality Management Facility (WQMF)	Series of ponds w/mean depth of 1.8 m, dominant macrophytes - Cladophora fracta and Elodea canadensis	200 ha system	Total-N 95%	Includes macrophyte harvesting	(42)
Eastern, Pennsylvania	Tinicum marsh	3 WWTP's discharging into tidal marsh	Reductions in BOD, PO_4-P, NH_3-N, and NO_3-N evident in majority of analyses	Quantitative removals not computed due to hydrologic complexity	(43)
Gainsville, Florida	Cypress domes	Four domes; 2 are 0.5 and 1.1 ha domes receiving secondary effluent while the other two serve as control	BOD, Total-P, Total-N and inorganic-N, 90-95% lower in groundwater than standing water in domes	No quantitative removal data	(44)
Suisin Marsh, Fairfield, California	1.2 ha irrigated pasture; four 0.2 ha marsh ponds (algae); two 0.6 ha irrigated marsh ponds, one with bulrush and one with watergrass	Wastewater fed to marsh pond first and then to each of the other systems, pasture also fed tile drainage from nearby agricultural plot	Irrigated marsh pond; provided roughly 25% Total-P removal; Total-N effluent <3 mg/l, with dissolved inorganic fraction <2 mg/l	Were some limitations due to wastewater feed availability and other hydraulic factors	(45)
Bellaire, Michigan	Freshwater marsh forest canopy	20.5 ha wetland	(NH_4+NO_3)-N 91% Total P 97%		(15, 46, 47)
Great Meadows National Wildlife Refuge, Massachusetts	Freshwater marsh, mostly deep water with 2.4 ha of shallow marsh and shrub swamp	19 ha wetland	TKN 35% NH_4-N 58% NO_3-N 20% Total-P 47% Ortho-P 49%	HRT = 57 days	(48)
Vermontville, Michigan	Volunteer freshwater seepage wetland, dominant vegetation: cattail, duckweed and willow	4.6 ha diked irrigation fields	Total-P 97% NO_3-N 60%	P removal largely (95%) through soil adsorption	(49)
Cootes Paradise, Ontario, Canada	Lacrustrine marsh	5.2 km^2 wetland, mean depth = 0.5 m	Total-N 41% Total-P 33%	HRT = 2-12 days, metals uptake in plants also documented	(50)
Hay River Northwest Territories, (Canada)	Northern swampland	32 ha wetland	NH_4-N 96% Total-P 97% PO_4-P 98% BOD_5 98%	Ecosystem stress evident in initial impact areas	(15, 51)
Martinez, California	Artificial marsh (wildlife enhancement)	6.1 ha plot	NH_3-N 24% NO_3-N 56% NO_2-N Net increase Organic-N 12% PO_4-P 13% BOD 37%		(52)
Brookhaven National Lab, New York	Freshwater meadow - marsh - pond system in series	0.2 and 0.4 ha systems, 0.5 1.0 m deep	Total-N 79% NH_3-N 86% TKN 81% NO_2+NO_3 73% Total P 77% PO_4-P 77% Cr 60% Cu 94% Fe 58% Mg 23% Zn 85% BOD_5 88-92% SS 92%	Total system removals	(53)

Table 15 (continued)

Geographic Location	Type of Wetland	General Description	Pollutant Removal Effectiveness	Comments	Reference
Upper Basin Swamp City of Jasper, Florida	Part forested wetland, part flood plain forests with defined streams; flow through fresh water wetland	Raw and primary effluent and urban runoff formerly discharged to swamp; now mostly secondary effluent discharged (35% of water source) with some urban runoff (8%).	Total-P - increase of 50% Total-N - decrease of 60% NO_2/NO_3 - decrease of 96% Metals concentrations too low in secondary effluent to document removal	No significant impact to wetland flora caused by application of secondary effluent	(54)
Hamilton Marshes, Hamilton Township, New Jersey (near Trenton)	Tidal and nontidal meander of Delaware River estuary	500 ha freshwater tidal marsh to receive secondary effluent	Did not perform complete nutrient mass balance, estimated nutrient uptake by dominant marsh macrophyte communities		(55)
Brillion, Wisconsin	Freshwater cattail marsh	156 ha marsh, mean depth 0.5 m	BOD 80.1 COD 43.7 Ortho-P 6.4 Total-P 13.4 Turbidity (JTU) 43.5 Nitrate 51.3 Coliform 86.2 Total Solids -8.5 Suspended Solids 29.1 Dissolved Solids -16.7	Also conducted macrophyte harvesting to evaluate plant uptake versus sediment precipitation	(56)
Tinicum Marsh, Delaware & Philadelphia Counties, Pennsylvania	Tidal freshwater marsh	Darby Creek, which receives effluent from three sewage treatment plants, flows into and out of Tinicum Marsh	Due to inadequate flow data, actual mass reductions could not be calculated; reductions in concentration were observed the following percentages of time: BOD 57% PO_4-P 57% NH_3-N 66% NH_3-N 63%	Biological and bacteriological surveys also made, the organic load had caused severe injury to biota	(43)
City of Wildwood, Florida	Hardwood swamp	202 ha swamp receiving combination of municipal wastewater and urban runoff.	Total-N 90% Total-P 98% Cu no change Fe 85% Mg net increase Pb 60% Zn 75%	Insignificant deleterious ecosystem impact	(32)
Houghton Lake, Michigan	Freshwater peatland	710 ha wetland (6.5 ha pilot site)	NH_4-N 77% (NO_2+NO_3)-N 99% Total dissolved P 95%	Pollutant removal documented for 1 ha subarea macrophyte biomass and nutrient uptake also documented	(57)
III. Industrial Wastewater					
Dulac, Louisiana	6% slope overland flow site dominated by Rouseau cane (Phragmites) upstream of enclosed marsh	0.6 ha overland flow site receiving fish meal production plant waste	TOC 58% Total-N 51% PO_4-P 53%		(58)

CHAPTER THREE

WETLAND CREATION AND MAINTENANCE

INTRODUCTION

To contain highway runoff and trap pollutants, it may often be necessary to modify an existing wetland or create a new wetland adjacent to the roadway. Generalizations concerning an appropriate technique for wetland development are risky; each site has a unique combination of topographic, edaphic, and climatic characteristics. However, in any development four areas must be considered: (1) site selection and development, (2) choice of appropriate wetland species, (3) selection of planting methods, and (4) maintenance practices. Knowledge of the physical conditions of the region and the biology of locally common wetland plant species should enable the planner to choose appropriate techniques. Detailed planning is required if wetland creation is to be successful. Poor site location, morphometry, and site preparation will result in a wetland with low productivity and treatment ability, and poor aesthetic and recreational value.

The advantages and disadvantages of natural vs. constructed wetlands have been discussed by Chan et al. (*15*) and are summarized as follows:

Advantages of Natural Wetlands
- Immediate availability (no extended construction or vegetation establishment period should be necessary).
- No new land requirements.

Disadvantages of Natural Wetlands
- Inconvenient location.
- Connection to critically sensitive water bodies.
- Inadequate size to assimilate waste load.
- Discharges to natural wetlands may be required by regulatory authorities to meet most stringent, already "polished" influent criteria.
- Operation of a managed wetland may alter ecosystem balance and relationships.

Advantages of Constructed Wetlands
- Flexibility in site location.
- Optimum size for projected waste load.
- Construction of topographic features such as channels, shallow bars, islands and levees to improve pollutant removals and facilitate maintenance.
- May be exempt from rigorous influent criteria if wetland is considered part of a treatment system.
- Would supplement existing wetlands.
- Ecosystem construction of a managed wetland could not be judged an alteration of a previous wetland ecosystem.

Disadvantages of Constructed Wetlands
- Cost and availability of suitable land.
- Construction costs for grading and planting the site.
- Unavailability of the system during the construction period.
- Possibly reduced performance during vegetation establishment period.
- Secondary problems can be produced including disease carrying mosquitos, odor, and fog. The first two problems can be managed through proper design, while little is known about control of fog generation. Benefits of wetlands include alleviating water stress (retaining water during dry periods and storing water during wet periods), providing wildlife habitat, and providing recreational, economical, and aesthetic benefits to man.

SITE CONSIDERATIONS

Sites should be chosen that will, in fact, have enough water to support aquatic plants during dry periods and receive and hold a substantial proportion of runoff water from the desired length of roadway. In locating the wetland, observation (and, if necessary, measurement) of the drainage from the highway will indicate how much and where water is moving (*63*). Wharton et al. (*64*) review the hydrodynamics of forested wetlands of Florida and suggest ways in which these natural patterns may be used in water treatment. Boelter and Verry (*65*) discuss the hydrology of peatlands. Appropriate measures should be taken to ensure that incoming water is detained in the wetland; ditches or shallow depressions may be used as sites for the new wetland, and dikes can be employed to prevent water from moving out of the system too quickly (*63, 66, 67, 68*).

Where substrates are porous, a layer of clay or other fine material should be added to slow percolation; where the slope is great, the site may require leveling to slow the outflow. Flat impoundments (gradient less than 0.01) are generally recommended (*63*). Size, shape, and orientation (with respect to the roadway) affect the amount of water the wetland can receive. Wile et al. (*69*) recommend a large length-to-width ratio to encourage efficient distribution of water. Outflows should be carefully monitored to determine the nutrient and pollutant discharge pattern (*69*). The desired water level and possible fluctuations, caused by tides or storms, must be anticipated (*70*). Standing, stagnant water will become anaerobic; these conditions may lead to release of various substances from sediments. A very shallow and fluctuating layer of water that may periodically fall below the sediment surface and that increases in depth only slightly following heavy rain may be most desirable. Ditching may have drawbacks; lowering the level of a salt marsh site may cause accumulation of salt in shalow water. Dredge spoil from ditches deposited in the wetland site may cause the formation of "cat clays"—acidic clays which inhibit plant growth(*71*). Periodic draining of shallow lakes is a management technique that has been used to discourage algae and encourage certain submerged aquatic plants (*Chara* spp.) (*72*); this method may be useful in aerating the surface sediment and in stabilization of pollutant complexes. If an existing wetland is to be modified, the hydrologic regime should be monitored to determine the wetland retention time. Wetlands should be sufficiently large to retain water for a long enough time to permit pollutant removal. Unfortunately, there are few data available in the literature on necessary wetland retention time for specific pollutants. With existing wetlands, it is sometimes possible to predict the hydrologic regime from the vegetation community present. The water depths of shallow depressions, such as the sloughs or potholes of northcentral North America, are relatively unstable; Millar (*73*) found certain wetland plant communities to indicate the relative stability of such marshes. Certain submergent species seem to be reliable indicators of year-round flooded conditions, while other species seem to be "disturbance-related" and occur where the water level fluctuates frequently. Given the anticipated inflow during and following a heavy rainfall and the extent and duration of flooding, and knowing the tolerance of the particular wetland community to flooding, the planner should attempt to predict the size wetland needed to withstand a specific design flood and to retain a substantial proportion of pollutants. Because few specific design data are available, conservative estimates should be employed.

Local zoning codes and regulations on wetland use must be observed. If an existing wetland is to be used, it should be realized that, under such use, a wetland will not remain "pristine" or "natural." For this reason, recognized "natural wetland areas," such as public or private nature sanctuaries or game reserves, are usually not appropriate disposal areas. Wetlands actively used by people or those specifically used to attract wildlife should be avoided unless it can be proved that the anticipated pollutant loads will not endanger uses. Because wetlands may attract waterfowl or certain mammals, the type, location, and form of the wetland being created or restored must be considered a potential hazard to both wildlife and highway user. These potential hazards should be monitored. Chapters Seven and Eight discuss some general assessment guidelines. A summary of current water quality criteria for possible constituents of highway runoff is provided in Table 19. Appropriate local agencies, such as Departments of Natural Resources and Health Agencies, should be consulted.

Carlozzi et al. (*12*) discuss the enhancement of ecologic and aesthetic values of wetlands associated with Interstate highways. Wetland creation and maintenance are discussed from the viewpoint of visual enhancement for driver-viewer, recreational value, and wildlife management.

WETLAND PLANT SELECTION

The choice of appropriate plant species for wetland development is largely dependent on the site. Species native to the region should be selected, if at all possible (*70*). Examination of nearby natural wetland communities in similar hydrologic settings will provide an array of possible species. Plant types that are known to take up nutrients and other materials efficiently and enhance filtration should be sought. Gallagher (*74*) suggests certain salt marsh species for particular rooting conditions and functions. *Salicornia virginica* and *Sporobolus virginicus* are typically shallow-rooted, while high marsh species, such as *Spartina patens* and *Distichlis spicata,* grow to intermediate depths. *Juncus roemerianus* and *Phragmites communis* grow more deeply rooted. Relatively rapid substrate stabilization is attained with *D. spicata* and *Spartina patens,* with high root:shoot biomass ratios. The dominant species of local natural communities are generally relatively fast-growing and competitive. In freshwater marshes, such species as cattail (*Typha* spp.), reed grass (*Phragmites communis*), burreed (*Sparganium* spp.), rushes (*Eleocharis* spp. and *Juncus* spp.), bulrush (*Scirpus* spp.), and perennial species of sedges (*Carex* spp.) are such competitors (*63, 67*). Woody species include certain willows (*Salix* spp.), buttonbush (*Cephalanthus occidentalis*), alder (*Alnus* spp.), and red osier dogwood (*Cornus stolonifera*). Species of choice in tidal brackish and marine systems include species of cordgrass (*Spartina* spp.), *Distichlis spicata,* mangroves (*Rhizophora* spp. and *Lagunclularia* spp.), and needlerush (*Juncus roemerianus*) (*75, 76, 77*).

The anticipated water level at the site should be considered. Generally, species tolerant of a range of water levels (from saturated below the substrate surface to several inches of standing water) are preferred. The natural habitats of plant species dictate whether they will grow well in a particular site. Mangroves, for instance, require tidal flushing, but cannot withstand wave action (*78*). Most wetland species have a preferred habitat; such information is available from published descriptions of each species (such as those described below) and from local experts (universities, Departments of Natural Resources, Fish and Wildlife Service, etc.). Ease of propagation or transfer is an important consideration in species choice. Seeds must be collected when they are ripe and may require stratification, scarification, or specific light and/or temperature conditions for germination. Root stocks or rhizomes require protection from damage in digging,planting, and transport. Knowledge of the biology of potential species is essential. Linde et al. (*63*) provide a detailed description of the natural history and management of cattail (*Typha* spp.); Sculthorpe (*79*), Fassett (*80*), Gleason (*81*), Godfrey and Wooten (*82, 83*), Hitchcock et al. (*84*), and others are references on the life form and habitat of other aquatic plants. Chan et al. (*15*) have summarized characteristics and environmental tolerances for the common emergent (Table 16), floating (Table 17), and submergent (Table 18) vegetation types.

A measure of diversity in species planted is often desirable for aesthetic and practical reasons. Monocultures are inherently unstable; herbivore activity or sudden hydrologic change may devastate the population of a particular species. It is extremely important to observe adjacent areas because these natural wetlands will suggest to the planner species combinations appropriate for particular hydrological conditions.

PLANTING METHODS

Plants may be introduced to a site in several ways. Litter and surface sediment taken from a nearby wetland may provide a diversity of propagules, some of which will germinate in the hydrologic setting of a marsh development. Although collection of such material may prove difficult and costly, this technique has the advantage of providing a diverse array of (most likely) native species and an organic substrate for growth and nutrition. Special treatment of seeds is not necessary (*200, 201*). One disadvantage in the use of seeds is the element of chance in germination. The seedbank of wetlands will include seeds that vary in viability or that germinate in different hydrological conditions from that in which they were deposited. The distri-

Table 16. Emergent vegetation types, characteristics, and environmental tolerances (*15*).

			Plant Occurrences or Tolerances					
Vegetation Type	Aboveground Height	Belowground Characteristics	Soil	pH (water)	Salinity	Water Depth	Air Temp.*	Comments and References
Cattails (Typha spp.)	0.7-2.7 m spreading mats & thick stands	Woody rhizomes comprise 45-60% of plant biomass lives 1.5-2 yrs, growth up to 100 cm/yr	Mud & silt w/25 cm detrital & humic layers organic content up to 32%	Wide range 4.7-10.0	0.15 ppt (up to 25 ppt some spp.)	0.2-1 m	9-31°C seed germ. @ 18-24°C	T. domingensis (coastal & inland growth inhibited @ 26 ppt salinity. California population stunted @ 12 ppt; T. augustifolia ranges from 0.2-25.5 ppt, optimum growth at 16.2 ppt, cannot tolerate prolonged salinity (22.5 ppt); T. latifolia does not occur in coastal bays - probably less salt tolerant than T. augustifolia (85, 86,87,88,89,90,91,92,93).
Reeds (Phragmites spp.)	3-4 m open stands	Dense rhizomes live 3-6 yrs - viable to 9 yrs in dry soils; leafy stolons up to 9 m long	Clay, sand or silt under swampy conditions; organic content 6-54%	Wide range 2.0-8.5	0-10 ppt optimum; up to 40 ppt some spp.	60-80 cm optimum; ranges from -.3 m to 4 m	11-32°C seed germ. at 10-30°C	P. communis of widest distribution and most studied; pioneer in early plant succession, but competes poorly; tolerates little water movement; roots can metabolize anaerobically, so reeds can grow in highly reduced muds. (86,87, 88,94,95,96,97,98,99,100,101).
Rushes (Juncus spp.) (over 200 spp.)	0.02-1.5 m dense clumps	Creeping rhizomes	Organic soils (no data on content)	No data	0-14 ppt (up to 35 ppt some spp.)	At or just below soil surface.	16-26°C	Can withstand wave action; found in fresh, brackish & salt marshes J. balticus tolerates salinities of 16-24 ppt; limitations for coastal spp: J. maritimus 14 ppt; J. balticus and J. gerardii 16-17 ppt; J. maritimus requires 7 ppt for germination (93,102,103,104, 105).
Sedges (Carex spp.)	0.1-1 m in clumps	Creeping rhizomes	Muck or clay with up to 10 cm detrital layer; up to 45% organic content	4.9-7.4	0-.4 ppt (fresh-water only)	-.05 to .95 m	15-21°C (range of 14-32°C)	Carex reproduces almost entirely by vegetative propagation. Unlike other emergents, Carex buds form and shoots emerge year-round. Carex competes poorly w/other species (86,106,107, 108,109,110,111,112,113).
Sedges - nutsedges (Cyperus spp.)	8-50 cm	Creeping rhizomes reproduction from tubers and bulbs	Refer to Carex	7.1 optimum, range of 3-8	0-.4 ppt (fresh-water only)	At or just above ground surface (-.05 to .3 m)	32°C optimum (range of 16-45°C)	Nutsedge roots enhance denitryfying bacteria activity - decreasing nitrogen availability to other plants; thrives in temperate climates (114,115,116).

Table 16 (continued)

Vegetation Type	Aboveground Height	Belowground Characteristics	Plant Occurrences or Tolerances					Comments and References
			Soil	pH (water)	Salinity	Water Depth	Air Temp.*	
Sedges-bulrushes (*Scirpus* spp.)	0.3-3 m	Thick, creeping rhizomes	Refer to *Carex*	4-9	4-20 ppt optimum, 0-32 ppt range	Minimum 5-10 cm, maximum depth variable w/ species	17-28°C varies w/ geographical location	Water level is critical for *Scirpus* success; *S. olneyi* -.75 cm to 6 m; *S. acutus* and *S. validus* 1 m; *Scirpus* spp. at Suisun Marsh, CA. 0.75-25 cm. All *Scirpus* require freshwater for germination; *S. acutus* tolerates salinities to 32 ppt; *S. validus* & *S. Heterochaetus* restricted to lower salinities; *S. olneyi* inhibited by 20 ppt; *S. robustus* thrives below 22 ppt. (86,87,88,92,116,117,118).
Canarygrasses (*Phalaris* spp.)	30 cm flower spikes 0.6-2 m	Creeping rhizomes	Silt loam (no data on content)	6.1-7.5	No data, but generally freshwater only	At or just below soil surface	15-25°C (up to 30°C some spp.) Seed germ. @ 18-35°C	Generally an upland grass that tolerates high moisture, high water tables & occasional innundation. *P. arundinacea* (reed canarygrass) is most commonly found & subject to study (118,119,120,121,122,123,124,125).
Cordgrasses (*Spartina* spp.)	Short forms; 0.3-0.4 m; tail forms: 1.2-2 m	Scaley rhizomes	Sandy substrate	4.7-7.8	9-34 ppt	-.15 to .7 m	12-29°C . Seed germ. @ 18-35°C	*S. alterniflora* tolerates salinities to 32 ppt; *S. foliosa* and *S. pagens* only to 18 ppt; most *Spartina* require low salinity (4-8 ppt) for germination. *Spartina* grows best in freshwater, but cannot compete w/cattails and rushes; common in salt marshes (126,127,128,129,130,131,132,133,134,135).
Pickleweed (*Salicornia* spp.)	0.2-0.6 m dense, erect clumps	Thick spreading roots 2-5 mm thick	Mud, clay w/low organic content	3.9-8.0	.4-34 ppt (tolerates up to 80 ppt)	-.15 to .3 m	11-32°C	Found in brackish & saltwater marshes; requires saline conditions for growth; can withstand seasonal drying & alkaline conditions (136).

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* During growing season

Table 17. Floating vegetation types, characteristics, and environmental tolerances (*15*).

Vegetation Type	Morphology	Plant Occurrences or Tolerances				Comments and References
		pH	Air Temp.	Water Temp.	Salinity	
Water hyacinth (*Eichhornia crassipes*	Spongy, multi-leaved plant 8 to 127 cm; lavender flowers; underwater rhizomes w/long fine roots	7-optimal; occurs over a wide range	20-30°C optimal; inhibited at 8-15°C; lethal under -5°C	28-30°C optimal	0-.75 ppt; lethal over 2.5 ppt	Tropical plant that will not overwinter in colder temperature climates. Extensive root system serves as a mechanical filter & support structure for bacteria (138,139,140,141,142, 143,144,145,146,147)
Duckweed (*Lemna* spp., *Spirodela* spp., *Wilffia* spp., *Wolffiella* spp.)	Small plants, each with one flat, oval frond 1 cm in length; without roots or with 2 or more threadlike roots on each frond	4.5-7.5 optimal; tolerates wide range	20-30°C optimal.	17.5-30°C optimal; inhibited over 35°C	.75-3.25 ppt optimal; serious effect over 6.5 ppt	Duckweed grows in dense mats in still water, effectively restricting gas transfer and attenuating light; can overwinter in milder temperate climates. Mats of duckweed can raise water temperature up to 12°C above air temperature (144,148,149,150,151,152, 153,154,155,156,157,158,159,160,161)
Water fern (Azolla spp.)	Small fernlike plant 1 cm in diameter with simple roots	3.5-11	27.5°C optimal; range 5-45°C	27.5°C optimal	Probably similar to duckweed but can tolerate high salinity	Nitrogen-fixing blue-green algal symbiont (*Anabaena*) grows within *Azolla*, enabling it to colonize nitrogen-deficient waters. Poor growth in open waters with wind/wave action (144,162,163)

Table 18. Submerged vegetation types, characteristics, and environmental tolerances (*15*).

Vegetation Type	Morphology	Plant Occurrences or Tolerances				Comments and References
		pH	Water Temp.	Water Depth.	Salinity	
Pondweed (*Potamogeton* spp.) 90-100 species	Plants w/thread-like to ribbon-like leaves scattered singly on flexible underwater stems; well-developed root system comprises up to 49% of plant mass.	6.3-10	10-35°C; 45°lethal 23-26° req. for seed germination	1-7 m; max. 10 m *P. pectinatus* opt.=30-46 cm	0-15 ppt max. 19 ppt	Reproduces by seeds, winter buds, rhizomes or tubers; tubers are a major waterfowl food; cosmopolitan 90-100 species; *P. pectinatus* most brackish water & pollutant tolerant; *P. crispus* , *P. pusillus*, *P. perfoliatus* & *P. natans* also tolerate brackish water and polluted habitats. (164,165,166,167,168,169, 170,171,172,173,174,175,176,177,178, 179,180,181)
Elodea (*Elodea canadensis*, *E. densa* *E. occidentalis*	Branched stems 5-15 cm; covered thickely w/.5-1.5 cm long leaves; found in groups of 2-6 depending on spp.; well developed root system.	6.5-10	10-25°C; 2-18° optimum for P uptake	1-7 m; max. 12 m	0.2-3.6 ppt (*E. canadensis* 9.2-14.4 ppt (*E. nuttallii*	Reproduces by fragmentation; over winters as winter buds; best adapted for calcareous inland lakes, ponds, slow-moving streams & slightly brackish coastal waters; good water oxygenator; marl deposits are common (79,164,166,170,172,175, 182,183,184,185)
Coontail (*Ceratophyllum demersum*, *C. echinatum*)	Many-branched bare stalk 1-2 m long; brittle, forked leaves with small thorns; found in clusters of 5-12 from central nodes.	4.0-8.7; optimum 7.1-8.0	10-20°C; optimum 18°; min. 5.5° (for one species)	No data, probably similar to Elodea	0-3.8 ppt	Reproduces by winter buds and fragmentation; requires still or very slow moving water; aquatic birds eat fruits; upright growth in spring; broad floating habit in summer/fall. (164,172,175,185,186,187,188,189)
Watermilfoil (*Myriophyllum* spp.)	Slender stems & few branches; divided leaves grouped in whorls	5-10	0.2-30°C; optimum 15 to 25°	1-3 m; max. 5 m min. 50-80 cm	0-15 ppt optimum 0.83-3.33 ppt	Reproduces by fragmentation and/or formation of winter buds; cosmopolitan-45 species (164,166,168,169, 172,189,190,191,192,193,194,195,196, 197,198,199)

bution of seeds in the sediment is not even; thus, the resulting community may be patchy and unpredictable.

Another planting method is to introduce seeds and vegetative propagules collected from nearby wetlands. In this technique, it is recommended that a suitable substrate (usually containing organic matter) be provided and that propagules be distributed at the time of year when they would normally fall (*202, 203, 204, 205, 206*); in this way, seed stratification and other treatments occur in situ. Many seeds germinate best in shallow water or on saturated mudflats; chances of seeds being washed out are also diminished in these conditions. Seneca et al. (*207*) stratified seeds of *Spartina alterniflora* at 2°C to 3°C for 3 months; germination above 45 percent was obtained with a planting density of 100 seeds/m^2. They recommend using seeds collected from local populations, which are adapted to local environmental conditions (*208*). Seeds collected and stored away from the marsh should be maintained in moist, cold conditions. Most salt marsh plant seeds should be kept in saline water (*208*).

A more predictable technique involves planting sprigs of young plants in regular or fixed density patterns. These "individuals" may be plugs taken from field populations, including roots and rhizomes and sediment, or plants that have been propagated artificially (*75, 76, 77, 205, 207, 209*). Mangroves have been transplanted as seedlings and saplings (*210, 211*). Gilbert et al. (*212*) successfully transplanted several species of trees as well as herbs into a constructed wetland in the Peace River floodplain, Florida. Transplant techniques are most successful with perennial plants and those species that inhabit standing water. This operation is relatively labor-intensive, but the chance of successful establishment is high. In coastal salt marshes, plugs taken from nearby sites and individuals grown in large peat pots have been generally most successful in producing spreading populations (*75, 213*). Plugs may be stored for a few days before planting, "heeled" into trenches near the marsh site. Ternyik (*214*) recommends that salt marsh species should be planted within 24 hours of removal; if they must be stored, they may be heeled into intertidal trenches or stored in pots in the intertidal zone, where tidal flushing will prevent dessication. Phillips (*215*) successfully propagated seagrasses as sods—plants with intact sediment placed on the surface of the new site and anchored with spikes. The drainage conditions at the transplant site seem critical to success (*77*). Hasted (*75*) recommends that plugs of emergent species should be taken from sites as well-drained as, or less well-drained than, the new site. She also suggests that hydroponically propagated stock may be best acclimated to saturated field conditions and that the technique should not be ruled out as a propagation method.

Tidal mud flats often contain flocculant, fine sediment and may be too unstable for establishment of transplants; however, those areas that drain between tides have been found to be good seed beds, especially when the perimeter is planted for protection and as a seed source.

At first, newly transplanted sprouts may require protection from wind and waves; dikes and berms have been used to ensure establishment. Fences may be needed to protect young shoots from herbivorous animals (*77, 216*).

Planting denisty is dependent on the site and species selected. Plantings of herbaceous perennials at intervals between 0.5 m and 1.0 m have been found successful for filling areas within a short period (1 to 2 growing seasons) (*69, 75, 77*).

Fertilization of young plants is usually not recommended, except where the substrate is very infertile (e.g., sand). When fertilizer is used, low levels of a slow-release form are recommended. Fertilizer should be incorporated into the substrate around the roots (*75*).

WETLAND MAINTENANCE

A planted or modified wetland will require considerable time to attain maximum coverage and function. Seneca (*208*) suggests that at least two full growing seasons are needed for the development of substrate stabilization in a planted salt marsh. This time frame seems reasonable for most wetland types; forested wetlands will require more time.

Water level control may be the most difficult and costly area of wetland maintenance. Natural wetlands are susceptible to flooding or drought; such disturbance is to be expected with managed wetlands as well. Although artificial drawdown to oxidize surface sediments was found to improve conditions for aerobic microbes, Hickok (*217*) found no improvement in the chemical load of the discharge from a shallow Minnesota wetland. Tolerant species can withstand considerable variation in conditions; however, there may be situations that require water level maintenance (*66*). Linde (*63*) discusses in detail methods of water level management.

The development of wildlife populations should be expected in any wetland. Animals play an integral role in the functioning of wetlands and certainly enhance the aesthetic qualities of a site; however, potential problems with wildlife should be anticipated. Herbivores, such as muskrat and nutria, may remove large portions of the emergent plant population. This may be critical especially in early stages in wetland creation, when plants are tender and sparce. Animal trails may channel surface flow such that it is not detained for filtration. Animal feces (particularly of water-fowl) may be an important source of nitrogen and other nutrients; such additions may cause changes in the plant community.

Animals chiefly serve to cycle the material of plants and sediments. Invertebrates may bring buried pollutants to the sediment surface and fragment plant parts into smaller particles more likely to flush from the system. Large animals feeding in the wetland may concentrate toxic substances from plants or their animal prey and thus carry them away from the site. This may pose a particular threat to game animals, such as muskrat, fish, ducks, crayfish, and oysters (*218*). Such potential effluxes should be monitored.

Insect pests, such as mosquitos, may present problems, particularly where insect-borne diseases are present or where residential areas are located near the developed wetlands (*69*). Chan et al. (*15*) reviewed the standard recommendations of the Alameda County, California, Mosquito Abatement District which included recommendations for the design of new wetlands or modifications of existing wetlands and for marsh operation and long-term management. Important recommendations included:

1. Provisions for deep water areas to maintain fish populations that will provide the primary natural predator control for mosquito populations.
2. Management of vegetation, such as thinning or removal, to allow greater access for predator fish.
3. Establishment of water control structures to manage water levels so that water may be drawn down to concentrate mos-

quitos and fish in deep water areas or to raise water levels to allow fish to enter into previously shallow inaccessible areas for predation.

Vigorous and productive wetland systems inevitably accumulate organic material and fill; runoff also contributes sediment. Such filling should be anticipated as a normal wetland function, and the rate should be monitored for future management. Recommendations on management strategies can probably be obtained from local universities and Departments of Natural Resources. Surrounding slopes, such as the road bed, spoil banks, or dikes, should be stabilized by planting; this vegetation will also intercept some runoff pollutants and serve as a prefilter for the wetland. Accumulation of sediment will result in a decrease in the level of standing water. Invasion of plant species accustomed to drier conditions will follow. The manager should not expect the planted community to remain without change; planted species will spread and other species will invade the site, even without a water level change. Plugs of *Spartina patens,* an upper salt marsh species, did not spread well in standing water at the Harrington Experimental Marsh (*219*). Vadas concluded that more limnetic species, such as *S. alterniflora,* might have been a better choice. Several species invaded the marsh after planting and sorted out into the various soil moisture conditions; surrounding wetlands served as sources for propagules. If chosen properly, the planted species will probably become dominant; however, competition between plant populations, chance invasion, soil differences, and animal activity may result in a plant community with a species composition different from that originally planted.

It may be desirable to remove contaminated bottom sediments (*220*) or to harvest above-ground biomass and remove it from the wetland. Although often a costly procedure, harvesting serves to remove some pollutants from the system permanently. This effect may be enhanced when harvesting increases productivity (and uptake of pollutants); Stout et al. (*220*) found increased growth in some (but not all) salt marsh species studied in Mississippi but not in Alabama. Thus, the effect of harvesting on plant growth seems to depend on site characteristics and species. Harvesting may also slow the process of wetland filling to a degree. Care should be taken that viable propagules (seeds, corms, rhizomes) are left. The season of harvest is critical to the ease and cost of using appropriate equipment and to the effectiveness of material removal, as well as the survival of the wetland (*69*). In shallow marshes, harvest may be easiest in winter when the substrate is frozen (*221*). Harvesting in deep water may result in leakage back to the wetland of soluble compounds, including some pollutants, from plant fragments. Information on harvesting methods and equipment to be used in a specific area can be obtained from local universities and Departments of Natural Resources. An example of the type of information available can be found in Nichols (*222*).

CHAPTER FOUR

WILDLIFE CONSIDERATIONS IN WETLANDS

INTRODUCTION

Wetlands provide habitat for a great variety of wildlife. The species comprising these wildlife populations vary by region, and within any region, with the nature of the wetland. The plant communities that are present, the proportion of vegetation to open water, size, connection to other wetlands or water bodies, degree of water level fluctuation as well as highway design and maintenance techniques are all important. This report suggests the development of wetlands for retention and treatment of highway runoff, and by implication, the development of wildlife habitat. The remainder of this chapter is composed of four sections discussing the nature of wetland wildlife and highway-wildlife interactions including the effects of runoff from highways on these organisms, as well as other wildlife management considerations in developing wetlands including water quality criteria and habitat preferences. The discussion of wildlife considerations is limited primarily to vertebrates including a great diversity of forms: birds, mammals, reptiles, amphibians, and fish. However, the influence of highway runoff on the plant and invertebrate components of the several wetland food webs cannot be ignored.

WETLAND WILDLIFE

Extensive invertebrate populations occur in most wetlands; in general, these organisms have their primary importance as a link in the food chain web of wetland vertebrates. Crayfish are an exception because their burrows may cause leaks in dikes and embankments. Other large groups include the snails, clams, mussels, limpets, scallops, barnacles, and crabs. These organisms may be affected by highway runoff, although in salt water wetlands, the tidal flux helps to limit some potential contaminants. The accidental release of a large quantity of oil or other hydrocarbons may cause a major disaster.

Fish are often present and can have both beneficial and detrimental effects on wetland systems. In general, fish require relatively deep water and are found where the wetland is large and/or connected with other water bodies. Various pan fish, e.g., bluegill and perch, may be stocked in borrow pits to provide recreational fishing, especially in urban areas. Bottom feeding fish, such as carp, when present, may produce high turbidity, destroy emergent vegetation, promote erosion, and cause algal blooms.

Reptile and amphibian populations differ with the type and size of the wetland. Larger forested wetlands in southern states provide habitat for water snakes such as cottonmouth. Northern and southern wetlands are frequented by several species of turtles. The species present and the number and size of these animals depend on the condition of the wetland and its relationship to other terrain features, as well as to the highway. For many reptiles and amphibians, highway mortality is high. Amphibians, primarily frogs, are common in both large and small wetlands associated with highways. Frogs provide a food supply for birds and large mammals, as well as for some of the reptiles, and any detrimental effect of highway runoff on frog population may decrease food availability.

The avian wetland wildlife component is extremely varied, including numerous waterfowl, dabbling and diving ducks, geese and loons, as well as wading and shorebirds such as herons, sandpipers, and egrets. Among avian predators, osprey, eagles, hawks, and insect feeders utilize production of the wetland food chain, although with limited direct contact with the water. The Redwing Blackbird is a conspicuous example of a species nesting chiefly in wetland vegetation.

The mammals of wetland systems are fewer in number than the birds, but similarly diverse. The most common, conspicuous, and widespread include muskrat and beaver, both rodents that may have a considerable direct impact on wetland plant communities. Muskrat and beaver, although valuable and generally desirable, may damage the highway as well as the wetland. Muskrat may burrow into road fill for dry dens, causing collapse of the berm or road surface (*223*). Beaver may show their engineering skill by building dams or plugging a culvert, flooding the road and wetland (*224*). Predatory mammals, such as mink and otter, are widespread in different wetlands, while herbivores, such as the whitetailed deer and snow-shoe hare, are occasional inhabitants of the northern cedar swamps.

HIGHWAY RUNOFF AND ITS EFFECTS ON WILDLIFE

The impacts on wildlife of certain materials, notably lead, road salt, oil, and certain organic pesticides, are reasonably well documented, particularly for birds. However, although there are data on the effects of leadshot ingestion by waterfowl or fish, little is known of the sublethel effects that may be produced by amounts normally found in highway runoff. Likewise, there is no substantial and quantitative body of knowledge of the effects on most wildlife species (*225*). This gap is being filled slowly as the field of wildlife toxicology is developed. In any event, wetlands developed to retain highway runoff should seek to minimize pollutant inflows, or failing this, should be designed against extensive wildlife use especially where pollutant loads are heavy. The following sections highlight some wildlife-highway runoff interactions.

Deicing Salts

Deicing salts form a major component of highway runoff in northern states and may affect wildlife populations directly and indirectly. Save where concentrations are exceptionally high, the major effect of sodium chloride is damage to the vegetation that provides food, nesting cover, and shelter. Such damage has been documented extensively for woody plants and grasses (*226, 227, 228*) but not for wetland species. Increased salt concentrations in streams and lakes near highways are readily demonstrated, but apparently they do not often reach levels toxic to fish. Sharp (*229*) suggests that blue gills will tolerate about 10,000 ppm NaC1, while rainbow trout begin to show mortality near 12,000 ppm. Ferrocyanides are often added to road salt and their effect is not known, although under certain conditions ferrocyanide may be converted to cyanide with a high potential for damage (*230, 231*).

Salt poisoning of mammals and birds, rabbit, pheasant, and quail has been shown only infrequently (*232, 233*) and usually in special circumstances. Reports of effects of deicing salts on waterfowl and wetland mammals are lacking. Feick, Horne, and Yeaple (*234*) suggest that sodium chloride may act to release mercury from sediments, increasing its concentration by several orders of magnitude. In areas where mercury is abundant in wetland sediments, this increase could have a serious impact.

Wetlands in urban areas are sometimes used as snow dumps. This practice may be especially deleterious because both deicing salts and lead (*235*) (discussed later) accumulate in the snow. Lead accumulations build up from year to year.

Particulates

Fine particles of sediment in highway runoff may affect wildlife indirectly through damage to plants and invertebrates in the food web, and directly by influencing reproduction of egg-laying animals. If the particulates are of inert and nontoxic materials, these effects are limited. However, organic pollutants and heavy metals are often associated with, or adhere to, the sediment. Sediment particles may affect survival and hatching of fish and amphibian eggs. For example, concentrations as low as 1,000 mg/1 may affect hatching of yellow perch (*236*). Sediment deposition probably influences survival of amphibian eggs. The suspended sediment load will also affect mollusks and crustacea (*237*). Stream sediments have been shown to reduce survival of fish eggs, affect aquatic insect production, and alter substrates needed for food plants. Fine sediments are especially deleterious, and their presence in highway runoff implies that a sediment trap should be provided to catch the material run off as it enters the outflow stream (*238*).

Lead

The toxicity of lead as a systemic poison for man has been recognized for centuries (*239*). Lead has been used in the manufacture of gasoline in large quantities and, particularly in recent years, has been a component of airborne exhaust compounds (*240*) (i.e., the lead alkyls, tetraethyl and tetramethyl lead, used in gasoline). The most conspicuous source of lead poisoning in wildlife has been leadshot pellets from which serious die-offs in goose and duck populations have resulted. Lead reaching wetlands through highway runoff may be of less importance to most wildlife than that in the air; at least 30 to 50 percent of the human lead burden has been inhaled. In wetlands, most lead will be found in the sediment where it is available to benthic organisms and may reach vertebrates in small amounts. However, since lead is usually eliminated readily from vertebrate systems, accumulations in mammals appear relatively low. Because leadshot is retained in the gizzard of waterfowl, toxic and lethal amounts are common.

In a study on canvasback ducks, Fleming (*241*) found lead levels in adults (wingbone) to average 5.97 ppm; and in immature birds, 0.84 ppm. A concentration in wingbones of 20 ppm indicates exposure to high lead levels (although not necessarily to leadshot) for adults. Fleming concluded that the amount of lead found represented a significant exposure but that "it appears that mercury, lead, cadmium and nickel are not having a serious impact on continental populations of canvasbacks. . . ." The prevalence of leadshot poisoning in waterfowl has resulted in numerous studies. However, Bellrose (*242*) points out that the importance of lead poisoning is not so much in the dramatic die-offs as the daily losses. Sublethal doses of lead (1 to 25 ppm) produced no mortality, but changes in enzyme activity were demonstrated (reduction in ALAD, an enzyme involved in heme synthesis).

If, as Dieter and Finley (*243*) calculate, 7 percent of all waterfowl ingest at least one pellet and of these 2 percent die, 5 percent are left suffering sublethal effects. Presumably, sublethal effects caused by leadhsot might be augmented by lower lead levels from food material that had absorbed lead from the sediment. Cook and Trainer (*244*) also note the importance of nonlethal dosages and suggest that low lead levels may cause increased offspring mortality and reduce reproductive success.

Various bivalves (*245*) and benthic invertebrates, particularly the Tubificidae (McNuryney) and Oligocheates, have also been shown to accumulate lead. Lead levels in bottom feeders ranged from 5.3 to 160 ppm, in contrast to levels in fish of 1.4 to 4.1 ppm. The work demonstrated the absence of appreciable accumulation of lead in higher trophic levels.

There is little data on lead poisoning in mammals other than man. Bats and small terrestrial mammals were found to show differences in lead levels, depending on the relationship of the trapping location to highway traffic. Levels in bats were sufficient to suggest sublethal effects on reproduction (big brown bat: male 145 ppm, female 105 ppm; little brown bat: 48.7 ppm) (*246*). Wetland mammals may obtain lead by eating fish or waterfowl poisoned by leadshot.

Lead in sublethal doses may impair reproduction and cause renal abnormalities. Among the small mammals, herbivores (e.g., prairie voles) will usually carry the highest loads. Small mammals serve as food for predatory animals and raptors, thus the lead ingested by small mammals may present problems higher in the food chain. Lead content in vegetation and soil is generally correlated with traffic volume, and areas where traffic volume is greater than 5 to 7,000 vehicles per day should not be developed for wildlife habitat (*247*). If hunting is to take place, highway wetland managers should prohibit use of leadshot that, in combination with highway lead, might produce mortality or sublethal effects.

The toxicity of other elements, notably cadmium, arsenic, mercury, vanadium, zinc, and copper, has been well recognized in relationship to human health. However, save for mercury uptake by fish and shellfish, the wildlife impacts and permissible levels are not well documented.

Mercury

As with lead, indirect impacts of mercury come through the food chain. Some aerobic organic decomposing bacteria, as well as certain flagellates, show lethal effects of lead (0.1 to 1.0 ppm) at extremely low levels. This suggests that decomposition and organic processing in some wetlands could be retarded, or that the wetland might become anaerobic. Mercury present in such wetlands could then be converted to methyl mercury and, thus, readily accumulated by the biota.

Mercury is highly toxic and is readily transferred from prey to predator with biomagnification occurring as it moves up the food chain (*248*). Variation in mercury (and other metals) is usually a function of feeding behavior and aerial distribution of mercury. For this reason, permissible levels of mercury are set by EPA at 0.05 ppm in body tissue. Work to date has concentrated on fish and waterfowl and has demonstrated sublethal as well as lethal effects (*249*). A methylmercury concentration, estimated as 0.1 ppm, in the diet of a mallard duck, reduced the number of eggs laid and hatching success and caused the young to be less responsive to the mother and more readily frightened (*250*). Similar symptoms and effects have been shown for other ducks. Mercury accumulates in brain, liver, and kidney tissue, and one may assume that ducks with a mercury load will pass it to predators and scavengers. Mercury content of wetlands from sources other than highway runoff should be considered when designing wetlands for use by wildlife. If mercury is present, fish should not be introduced because they provide a direct link to predators (and humans). Concentrations above 0.1 ppm should not be exceeded (*251*).

Recent surveys of mercury burdens in Wisconsin wetland species indicated elevated body levels ranging from 0.05 to 2.49 ppm in wading birds and fish eating ducks (*252*); in wetland mammals mean levels ranged from 0.04 to 3.34 ppm for liver content and 0.09 to 8.47 ppm in the kidneys. The lowest levels were found in muskrat and beaver, while the highest levels occurred in mink and otter (both of which depend heavily on fish) (*253*). Levels in mammals paralleled those in crayfish, fish, and sediments. Maximum levels found in mink and otter approximate those causing mercury intoxification in cats and may well pose a physiologic burden.

Mercury contamination of fish has been linked to industrial processes (*254*) or to mining adjacent to streams (*255*), and in one case has been blamed for the decline in fish-eating mammals. Although levels of contamination may be considerably higher than those in highway runoff, the implication remains; *wetlands should be kept free of mercury.*

Mercury levels in waterfowl have been related directly to mercury levels in their food. In an Ontario study (*256*), high mercury levels in hooded mergansers resulted from mercury found in the crayfish that were a substantial part of the birds' diet. Similarly, elevated levels in sea ducks apparently were related to their feeding on contaminated mussels.

Information on mercury contamination, available in 1970, was tabulated by the U.S. Department of the Interior in a 32-page bibliography (*251*). The NAS/NAE Report on Water Quality Criteria (*257*) also provides a useful source of information on all pollutants harmful to wildlife.

Earthworms found along the edges of wetlands, like benthic organisms, have been shown to accumulate concentrations that could produce lethal or sublethal effects in birds, reptiles, amphibians, and mammals that consume them (*258*).

Cadmium and Vanadium

Cadmium, another component of runoff, appears to vary in toxicity with pH of the water (*259*). Certain invertebrates and fish are particularly sensitive, and sensitivity varies with the stage in the life cycle. In water with a low pH, the EPA criterion for sensitive species varies from 0.0004 to 0.004 ppm, while in harder water, it ranges from 0.0012 to 0.012 ppm. Work on ducks indicates sublethal effects on reproductive functions, with cadmium accumulating in the liver, kidneys, and testes (*260*). Presumably, effects on reproduction in waterfowl will be noted at levels above 20 ppm but, at least on canvasback ducks and by extrapolation, other waterfowl (*261*) cadmium levels are not yet affecting waterfowl production appreciably.

Caution should be exercised in wetland development, or in existing wetlands, in areas that receive sewage sludge known to contain cadmium. The potential for accumulation may result in impacts through the food chain.

Similarly, vanadium at concentrations of 200 to 300 ppm has been shown to affect the reproductive process in birds. Save for one report (*262*) indicating that concentrations lower than 100 ppm have little impact on waterfowl, information on wildlife effects is lacking.

Petroleum

Like inorganic elements, petroleum products as common constituents in highway runoff also impact wildlife directly and indirectly.

Initially, most attention was given the direct effects of oil spills and similar catastrophes on birds, because high mortality often results. Burns and Teal (*263*) demonstrated the impact of a spill, such as the 1969 West Falmouth incident, on a variety of marsh organisms, including algae, higher plants, mussels, eel, fiddler crab, and marsh minnows. All organisms tested contained oil in their tissues after one year. Much of the oil was adsorbed into the anaerobic marsh sediment, where it has shown gradual degradation and change in composition with time. The authors indicate that after eight years recovery was not yet complete, and anticipate that the naphthalene and heavy aromatic components of the oil will persist for many years. Other studies (*264*) report that crude oil has low toxicity when ingested by cranes or kestrels, and the external effect of feather oiling is more serious. Refined oils appear to be more toxic. Thus, a highway spill of diesel, gasoline or motor oil, flushed into a wetland, may have a more serious effect than a crude oil spill.

Ducks fed small quantities of various cutting, fuel, and lubricating oils developed pathological and physiological effects, varying with the type of oil (*265*). Symptoms included intestinal tract problems, diarrhea, pathological symptoms in liver, pancreas, and kidneys, and adrenal enlargement. Most birds also exhibited lipid pneumonia. Doses given ranged from 2 to 3 g/kg and were believed comparable to the amounts ingested in several days during feather preening.

In ducks under temperature stress, LD-50 levels for ingested oils ranged from 3 to 4 g/kg for cutting and diesel oil, respectively.

Pesticides

Pesticide effects on waterfowl and other birds have been examined extensively. In addition to the well-known effects of chlorinated hydrocarbons, the less persistent organophosphates are also implicated in poisoning. Fenthion, used widely in mosquito control, has been shown to cause mortality in a variety of birds, including shore and wading species (*266, 267*). Weather conditions concentrating pesticide-laden water in on-shore areas may be involved. A specific case of poisoning by another organophosphorus compound, parathion, was noted in geese (*268*) that consumed wheat from a recently sprayed field.

For wildlife protection, wetlands receiving highway runoff and adjacent areas should not be sprayed with insecticides. Likewise, pesticides should not be used on road shoulders and ditches. If mosquito control becomes necessary in such wetlands, means of management other than oil or pesticides should be attempted. If not feasible, materials less toxic to wetland birds and mammals should be investigated.

Little is known of the impact of oils or pesticides on amphibians or reptiles, although toxic reactions would be anticipated.

AQUATIC LIFE CRITERIA

Table 19 summarizes the Environmental Protection Agency water quality criteria for possible constituents found in highway runoff. Detailed discussion of these quality criteria can be found in two publications: "Quality Criteria for Water" (*60*) and "Water Quality Criteria Documents"(*259*).

HABITAT SELECTION AND EVALUATION

No easy method has been devised to determine the wildlife value of a particular wetland. The most direct approach is to observe which species find the area of value and maintain or increase their numbers. However, for many purposes, including the selection of wetlands for highway runoff disposal, a quantitative measure would be useful. Some attempts have been made, such as the Canadian Wildlife Service classification, that depend on the suitability of the wetland to produce a sustained yield of waterfowl, while others utilize a mixture of environmental parameters to estimate productivity. An early approach was the man-day-use method for evaluating the effects of water development projects on wildlife. This approach evaluated human use of the wildlife resource (hunting, fishing, trapping, etc.) rather than actual wildlife habitat values. Another technique involved estimation of habitat units lost or gained; it combined habitat area and subjective values for each habitat type (*269*). The Fish and Wildlife Service recently developed Habitat Evaluation Procedures that can be used for a single species or a group of species (*270*). These procedures determine values for food, aquatic habitat, cover, and reproductive value, and the lowest of the foregoing values becomes the Habitat Suitability Index. This analysis is complex and expensive and seems ap-

Table 19. Summary of water quality criteria for possible constituents of highway runoff.

Constituent	Description of Critical Level	Year of Criteria Issuance	Basis for Criteria or Water Use
Suspended solids	Should not reduce the depth of the compensation point for photosynthetic activity by more than 10% from the seasonally established norm for aquatic life	1976	Freshwater fish and other aquatic life
Ammonia	0.02 mg/l (un-ionized as NH_3-N)	1976	Freshwater aquatic life
Dissolved oxygen	Greater than or equal to 5.0 mg/l	1976	Freshwater aquatic life
Phosphorus	0.10 g/l (elemental)	1976	Marine or estuarine waters
Nitrate	10 mg/l (as N)	1976	Domestic water supply (health)
Chlorides	250 mg/l	1976	Domestic water supply (welfare)
Sulfates	250 mg/l	1976	Domestic water supply (welfare)
Lead, g/l (total recoverable)	$e^{(2.35[\ln(\text{hardness})]-9.24)}$ 24-hour average	1980	Freshwater aquatic life
	$e^{(1.22[\ln(\text{hardness})-0.47)}$ (not to exceed)	1980	Freshwater aquatic life
	668 g/l (acute toxicity*)	1980	Saltwater aquatic life
	25 g/l (chronic toxicity*)	1980	
	50 g/l	1980	Human health
Cadmium (total recoverable)	$e^{(1.05[\ln(\text{hardness})]-3.73)}$ (not to exceed)	1980	Freshwater aquatic life
	4.5 g/l (24-hr average)	1980	Saltwater aquatic life
	59 g/l (not to exceed)	1980	
Chromium (total recoverable hexavalent)	0.29 g/l (24-hr average)	1980	Freshwater aquatic life
	21 g/l (not to exceed)	1980	
	18 g/l (24-hr average)	1980	Saltwater aquatic life
	1,260 g/l (not to exceed)	1980	
	50 g/l	1980	Human health
Chromium (total recoverable trivalent)	$e^{(1.08[\ln(\text{hardness})]+3.48)}$ (not to exceed)	1980	Freshwater aquatic life
	44 g/l (chronic toxicity*)	1980	
	10,300 g/l (acute toxicity*)	1980	Saltwater aquatic life
	170 mg/l (ingestion of water and contaminated organisms)	1980	Human health
	3,433 mg/l (ingestion of contaminated organisms alone)	1980	Human health
Copper (total recoverable)	5.6 g/l (24-hour average)	1980	Freshwater aquatic life
	$e^{(0.94[\ln(\text{hardness})]-1.23)}$ (not to exceed)	1980	Freshwater aquatic life
	4.0 g/l (24-hr average)	1980	Saltwater aquatic life
	23 g/l (not to exceed)	1980	
	1 mg/l	1980	Taste & odor
Nickel (total recoverable)	$e^{(0.76[\ln(\text{hardness})] + 1.06)}$ (24-hr average)	1980	Freshwater aquatic life
	$e^{(0.76[\ln(\text{hardness})]+4.02)}$ (not to exceed)	1980	Freshwater aquatic life
Nickel (cont.)	7.1 g/l (24-hr average)	1980	Saltwater aquatic life
	140 g/l (not to exceed)	1980	
	13.4 g/l (ingestion of water of water & contaminated organisms)	1980	Human health
	100 g/l (ingestion of contaminated organisms alone)	1980	Human health
Zinc (total) recoverable)	47 g/l (24-hr average)	1980	Freshwater aquatic life
	$e^{(0.83[\ln(\text{hardness})] + 1.95)}$ (not to exceed)	1980	Freshwater aquatic life
	58 g/l (24-hr average)	1980	Saltwater aquatic life
	170 g/l (not to exceed)	1980	
	5 mg/l	1980	Taste & odor
Mercury (total recoverable)	0.00057 g/l (24-hr average)	1980	Freshwater aquatic life
	0.0017 g/l (not to exceed)	1980	
	0.025 g/l (24-hr average)	1980	Saltwater aquatic life
	3.7 g/l (not to exceed)	1980	
	144 ng/l (ingestion of water and contaminated organisms)	1980	Human health
	146 ng/l (ingestion of contaminated organisms alone)	1980	Human health
Iron	0.3 mg/l	1976	Domestic water supply(welfare)
	1.0 mg/l	1976	Freshwater aquatic life
Manganese	50 g/l	1976	Domestic water supply(welfare)
	100 g/l	1976	Ingestion of marine mollusks
Arsenic	440 mg/l (not to exceed)	1980	Freshwater aquatic life
	508 g/l (acute toxicity*)	1980	Saltwater aquatic life
	Zero (cancer risk levels also specified)	1980	Human health
Cyanides (free cyanide)	3.5 g/l (24-hr average)	1980	Freshwater aquatic life
	52 g/l (not to exceed)	1980	
	30 g/l (acute toxicity*)	1980	Saltwater aquatic life
	2.0 g/l (chronic toxicity*)	1980	
	200 g/l (ingestion of water and contaminated organisms)	1980	Human health
Asbestos	No toxicity date available for aquatic organisms	1980	Aquatic life
	Zero (cancer risk levels also specified)	1980	Human health
PCB	0.014 g/l (24-hr average)	1980	Freshwater aquatic life
	0.030 g/l (24-hr average)	1980	Saltwater aquatic life
	Zero (cancer risk levels also specified)	1980	Human health
Oil & Grease	0.01 times lowest continuous flow 96-hr LC_{50} for several important freshwater species; minimize sediment levels; surface waters free from floating oils	1976	Freshwater aquatic life

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* Specified as the lowest level that toxicity has been measured for certain organisms; other organisms could be affected at lower levels.

* Specified as the lowest level that toxicity has been measured for certain organisms; other organisms could be affected at lower levels.

Source: Refs. (60,259).

propriate only for large wetland areas. Subjective estimates of wildlife values, based on vegetation types and water area, evaluated by local wildlife specialists seem suitable for most highway wetland development.

Waterfowl selection of habitat has been studied extensively. In general, waterfowl prefer areas with some open and surface water, but edge cover is also important. For example, in Maine, female black ducks rearing broods favored ponds with emergent vegetation and were often found in brushy areas flooded by beaver (*271*). In addition to glacial ponds and lakes, ducks in North Dakota have been found to use stock ponds and other dugouts extensively (*272*). Habitat preferences vary greatly with species; however, ponds with greater open water area are favored, as are stock ponds with some emergent vegetation or those with nearby wetlands. Some species favor ponds with fringing emergents, and others prefer areas where emergents have been grazed. Height of emergent vegetation is important, as is the presence of nearby nesting cover. Many wading and shore birds tend to favor semipermanent or seasonal ponds; species such as the Redwing Blackbird requires strong emergent cover (*272*). Wood ducks use nesting cavities in trees, while herons roost in colonies in wetland forests.

Landrin (*273*) indicated favored wetland types for many nongame species. She suggested that, as a general rule, woody vegetation along the wetland edge improves nesting habitat. As with waterfowl, habitat selection by other wetland wildlife species depends on a suitable and specific mix of food and cover. This mix differs between species, but the community is favored by diversity in habitat types.

Techniques for roadside vegetation management are shifting from reliance on herbicides to the planting of low maintenance cover types, and are depending on natural controls. In designing highway wetlands for wildlife, considerations involved include: (1) the possible impact of vegetation control methods on wildlife or the wildlife food chain, and (2) the need to restrict the type of vegetation development that is in close proximity to the highway to avoid direct contact between wildlife and passing vehicles that often results in damage or mortality. Control of plant nutrient loading may be critical; high nutrient levels favor algal growth and often result in development of heavy blooms of bluegreen algae. These blooms reduce the light available for submergent vegetation, produce unpleasant odors, and sometimes form toxins that cause wildlife mortality. Users of existing wetlands, as well as of created wetlands, should recognize the potential for nutrient loading (from runoff and from waterfowl) and provide for adequate flushing or other methods of nutrient removal (*274*).

Most of the vertebrates found in wetlands are not restricted to these areas over their entire life cycle; they utilize terrestrial habitats or may move from one wetland area to another. The list of obligate wetland species is small compared to those that use wetlands sporadically or seasonably. The literature on wildlife management is extensive, and for specific problems or design, wildlife specialists should be consulted. Most State Departments of Natural Resources employ specialists in waterfowl and wetland wildlife and can also provide published information appropriate to the specific region.

CHAPTER FIVE

FEDERAL AND STATE REGULATIONS

INTRODUCTION

One of the most significant management aspects of wetland utilization for amelioration of highway stormwater runoff effects concerns legal constraints imposed on such utilization. These constraints accrue from both statutory and judicial law on the federal, state, and local levels. Although it is beyond the scope of these guidelines to review the common law constraints (judicial), it must be pointed out that statutory laws are very often subject to judicial review for interpretation or even superseded or bypassed on common law grounds. Similarly, local ordinances or judicial controls cannot be ignored even though these also are beyond the scope of this report.

Chapter Five briefly describes the myriad of federal statutes and programs that affect the protection and/or use of wetland activity. A state-by-state summary of specific wetland-related statutes is given in Table A-1 of Appendix A. It is not the function of this listing to serve as a legal guide to state highway agencies with respect to wetland legislation. Because of the evolving nature of the legislative process, certain statutes may no longer be in effect and most will be modified. Its function, rather, is to serve as an illustrative guide to the types and variability of regulatory schemes in these states. It is advised that the highway planner conduct an updated search of pertinent legislation for the states affected by a given transportation project.

Finally, this chapter reviews the responses by state transportation agencies to one of the questions contained in the questionnaire in Appendix A of the agency final research report (see Foreword for availability) concerning their perceptions of state policies regarding highway interactions with wetlands.

FEDERAL STATUTES

There are a number of federal statutes that have implications for wetland management. These statutes are administered by several federal agencies including the Departments of Agriculture, Commerce, Defense, Housing and Urban Development, Interior and Transportation; the Council on Environmental Quality; Environmental Protection Agency; Water Resources Council; and Tennessee Valley Authority. Pertinent legislation is described in the following sections for each of the federal agencies as well as several noteworthy Executive Orders. Except where otherwise noted, this information was derived from the *National Wetlands Newsletter* (*275*).

Department of Transportation

DOT Order 5660.1A—Preservation of the Nation's Wetlands

By virtue of this order, it has become the expressed policy of DOT to protect wetlands to the fullest extent possible during planning, construction, and operation of federal and federally financed highway projects. In cases where wetland destruction cannot be avoided, DOT might assist by acquisition or mitigation. DOT Order 5660.1A was issued in August of 1978 in response to President Carter's May 1977 Executive Order 11990, which is described later in this chapter. A copy of DOT Order 5660.1A is contained in Appendix A as is the subsequent DOT memorandum dated November 1978, which is the "Revised Guidance and Procedures" for implementation of Executive Order 11990.

General Bridge Act

This act gives the U.S. Coast Guard permit issuance authority for all bridge projects crossing navigable waters.

Department of the Interior

Bureau of Land Management

The Federal Land Policy and Management Act mandates the protection, maintenance, and enhancement of wildlife habitats on public land and requires the preparation of Habitat Management Plans.

Bureau of Reclamation

The Reclamation Act allows the Bureau to construct and operate irrigation, flood control, and power projects in certain western states. It also establishes fish and wildlife sanctuaries on reclamation land.

Fish and Wildlife Service

The following acts provide for direct involvement for the Service in wetlands-related projects:

- Fish and Wildlife Coordination Act
- Fish and Wildlife Act
- Clean Water Act
- Migratory Bird Conservation Act, Wetland Acquisition Act
- Migratory Bird Hunting Stamp Act
- Endangered Species Act
- Land and Water Conservation Fund Act
- Federal Aid to Wildlife Restoration Act
- Federal Aid to Fish Restoration Act

These acts provide the Service with responsibility in programs to classify, identify, and map wetlands; provide consultation on impacts of federal projects on fish and wildlife populations and habitat including endangered species; and, if necessary, provide financial resources (acquisitions or grants-in-aid) for wetland restoration or protection.

U.S. Geological Survey

Under the authority of a variety of legislation, the Geological Survey catalogs land-use distributions, and maps and classifies wetlands.

Department of Agriculture

The Waterbank Act of 1970 provides the Secretary of the Department authority to enter into contracts with landowners for preservation of water fowl inhabited wetlands through payment of annual fees to landowners. Similarly, the Agriculture and Consumer Protection Act, through contracts and easements with landowners, provides for protection of migratory water fowl and other wildlife habitat.

Under authority of the Rural Development Act, the Soil Conservation Service classifies, monitors, and inventories wetlands. The Renewable Resources Planning Act stipulates that the Forest Service access all renewable resources in forests and rangeland, including wetlands.

Department of Commerce

Office of Coastal Zone Management

Implementation of the Coastal Zone Management Act (CZMA) (*276*) and Estuarine and Marine Sanctuary Programs is the responsibility of the Office of Coastal Zone Management (OCZM). These programs have the potential to exert great influence on the overall direction of coastal wetland policy in the United States. The CZMA provides federal grants to states for development of coastal management and preservation programs, especially with regard to coastal energy development impacts. Management or protection of coastal wetlands should obviously be one critical concern of coastal zone management programs. Although the CZMA has had some positive benefit since its passage in 1972 (e.g., new funding sources for existing but underfunded state programs and adoption of new legislation in several states), certain critics contend that the act has been interpreted by OCZM to be a natural planning act rather than an attempt to vigorously protect coastal ecosystems, especially wetlands (*277*).

National Marine Fisheries Service

The Fish and Wildlife Coordination Act impowers the National Marine Fisheries Service to review federal activities and permits with respect to impacts on wetland fish resources.

Department of Defense—U.S. Army Corps of Engineers

In conjunction with the Environmental Protection Agency, the Corps of Engineers is given jurisdiction over discharges of dredged and fill materials into all navigable waters and their tributaries and contiguous or adjacent wetlands, by virtue of Section 404 of the Clean Water Act. The Rivers and Harbors Act of 1899 provides the Corps with power to authorize permits for structures and discharges in all navigable waters.

Environmental Protection Agency

On March 20, 1973, the EPA Administrator issued a detailed EPA policy statement on the protection of the nations wetlands, which was to apply to its authorities in conducting all program activities (*278*). EPA works together with the Army Corps of Engineers on implementation of the requirements of Section 404 of the Clean Water Act which regulates the discharge of dredged or fill materials into the nation's waterways. Section 208 of the Clean Water Act affects the management and protection of wetlands through their incorporation into Areawide Water Quality Management Plans which must be approved by EPA. The Safe Drinking Water Act gives EPA the authority to designate a given aquifer as a principal water supply source, which will then necessitate EPA review of any project that might adversely affect the quality of the water source.

Department of Housing and Urban Development

The Interstate Land Sales Full Disclosure Act requires distribution to purchasers of subdivision lots a report stating whether or not permits are required for dredge and fill operators on the land. The Community Planning and Development Act provides grants for community planning which carry the stipulation that environmental assessments be performed by the grantee.

Council on Environmental Quality (CEQ)

CEQ is responsible for receiving and reviewing Environmental Impact Statements (under authorization of the National Environmental Policy Act (NEPA), for sponsoring research, and for advising the President.

Tennessee Valley Authority

TVA is involved in management of reservoir systems that might contain wetlands and is also associated with fisheries and wildlife management.

Executive Orders 11990 and 11988

Executive Order 11990, Protection of Wetlands (*279*), issued on May 24, 1977, mandates that all federal agencies, including the military department,

> . . . provide leadership and shall take action to minimize the destruction, loss or degradation of wetlands, and to preserve and enhance the natural and beneficial values of wetlands in carrying out the agency's responsibilities for:
> 1. Acquiring, managing and disposing of Federal lands and facilities; and
> 2. Providing Federally undertaken, financed, or assisted construction and improvements; and
> 3. Conducting Federal activities and programs affecting land use, including but not limited to water and related land resources planning, regulating and licensing activities.

Furthermore, in accordance with the requirements of NEPA, such agency

> . . . shall avoid undertaking or providing assistance for new construction located in wetlands unless the head of the agency finds:
> 1. That there is no practicable alternative to such construction, and
> 2. That the proposed action includes all practicable measures to minimize harm to wetlands which may result from such use.

Factors relevant to agency consideration of wetland survival and use include public health, safety and welfare, maintenance of natural systems, and other public interest uses such as recreational, scientific, and cultural uses.

Executive Order 11988, issued on the same date as Executive Order 11990, calls for similar federal agency leadership in order to "... avoid to the extent possible the long and short term adverse impacts associated with the occupancy and modifications of floodplains and to avoid direct or indirect support of floodplain development wherever there is a practicable alternative." The term floodplain is defined in the order to include all "lowland and relatively flat areas adjoining inland and coastal waters including floodplain areas of offshore islands, including at a minimum, that area subject to a one percent or greater change of flooding in any given year."

The response of federal agencies to Executive Orders 11990 and 11988 is illustrated by policy statements issued by Department of the Interior (Bureau of Land Management (*280*)), the Department of Agriculture's general Statement on Land Use Policy (*281*), Soil Conservation Service (*282*), and DOT Order 5660.1A, described previously.

STATE REGULATIONS

State regulatory approaches to wetland protection are quite diverse, although threads of similarity run within regional areas (*283*). Often, wetland protection is provided as a component of broader regulatory efforts, such as shoreland or floodplain zoning acts (*284*), with explicit protection of wetland ecological benefits rarely specified (*285*). As mentioned earlier, a state-by-state summary of wetland-related statutes is given in Table A-1 in Appendix A. Stephen and Fernandez (*283*) suggest the following four generalizations on state wetland regulatory approaches:

1. Some states deal only with state-owned land, while others deal with both state-owned and privately held land.
2. In states where both fresh and saltwater wetlands exist, most states attempt to regulate only one or the other type. Most coastal states neglect inland freshwater wetlands while concentrating on protection of the economically critical estuarine wetlands (marine fishery protection). Some states (e.g., Connecticut and New York) have separate statutes for inland and coastal wetlands.
3. In several states, regulation of wetland use is contingent on the navigability of the system; with nonnavigable waterways often being ignored apparently because of a lesser magnitude of public interest.
4. Much variability exists from state to state with regard to the definition of wetlands and their respective boundaries. Some use classification systems based on hydrologic, soils, or vegetation characteristics, or some combination thereof.

In addressing some of the differences in state wetland regulatory practices, it is useful to separate the information into two broad categories; coastal and inland wetland protection. Much of the information described in the following was taken from Kusler (*284*).

Coastal Wetland Protection

More than a dozen coastal states now require permits granted on a case-by-case basis for any fill or structural activities in coastal wetland areas. In addition, six states authorize a state regulatory agency to enact wetland protection orders such as zoning regulations, permitting, and wetland use designations.

Most remaining coastal states effect coastal wetland protection as part of a broader regulatory scheme. Most common are conservancy provisions in shoreland zoning programs, dredge and fill regulations, coastal zone management programs, and broader critical area protection programs.

Inland Wetland Protection

Again, explicit inland wetland protection statutes are not as prevalent as wetland programs contained within broader regulatory efforts. As of 1978, only five inland states had adopted specific wetland protection acts (see App. A) with several laws pending in other states (*277*). Some of these acts require or encourage local regulations of wetland use. Programs of a broader scope that often incorporate wetland provisions include:

1. Flood plain or floodway regulations.
2. Shoreland zoning programs.
3. Wild and scenic river programs.
4. Dredge and fill permit laws.
5. Plumbing and sanitary codes.
6. Large-scale development regulation.
7. Environmental impact review acts.

Nonregulatory approaches are also an integral part of the overall wetland protection scenario. Kusler (*284*) listed five general types of nonregulatory involvement at the state level:

1. Waterfowl and wildlife protection programs.
2. Public land management programs.
3. Flood control efforts.
4. Public education (i.e., state university acquisition of wetlands for educational or scientific purposes).
5. Tax incentive programs.

Perceptions of State Highway Agencies Concerning State Wetland Protection Policies

As described in the agency research report for NCHRP Project 25-1, a questionnaire was sent to all state highway agencies concerning their state activities in the wetland/highway interaction area. One of the questions read "Does your state have any specific policy regarding construction of highways through wetlands, i.e., attempt to preserve the character of wetlands." The responses can be summarized as follows.

Many state highway agencies indicated they had no specific state wetland policy. A large percentage of these had no state policy but followed DOT Order 5660.1A/Executive Order 11990. Several states also mentioned compliance with Section 404 of the Clean Water Act (dredge and fill permits), the Coastal Zone Management Act, and the Fish and Wildlife Coordination Act. Seven states replied that they coordinated all highway construction through wetlands with appropriate state land resource management agencies. The policy of 16 states was to avoid wetlands whenever practicable and minimize contact or adverse effects whenever wetlands cannot be avoided. Maintaining natural drainage patterns was a common approach to minimize impact. Several states noted that wetland interactions are seldom encountered because of the sparcity of wetlands within those states.

In addition to answering the question, several states provided copies of pertinent state regulations or agency policy statements. For example, the State of Vermont sent a copy of the Vermont Agency of Environmental Conservation's Interim Stormwater Management Policy (July 1980). This policy is authorized under the State wastewater discharge permit program (Title 10 V.S.A., Chapter 47). It stipulates that all stormwater runoff discharges require a permit and that runoff from paved roads with curb, gutter, or collection facilities be collected in catch basins similar to that shown in Figure 1 or use a settling pond with submerged hooded outlet.

Another example is Directive Number D 22-27(HR) of the Department of Transportation of Washington State. This directive is entitled, "Protection of Wetlands" (Effective date: November 7, 1979), and is intended to provide guidance to DOTs regarding transportation project impact on wetlands. The directive includes wetland definitions, rules, and procedures to minimize impacts. Of particular value is a "Wetland Activity Flow Chart," shown in Figure 2, which illustrates the nine basic steps required for documentation of potential environmental impacts to wetlands.

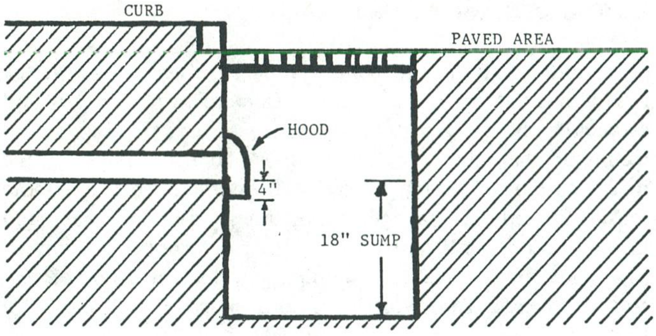
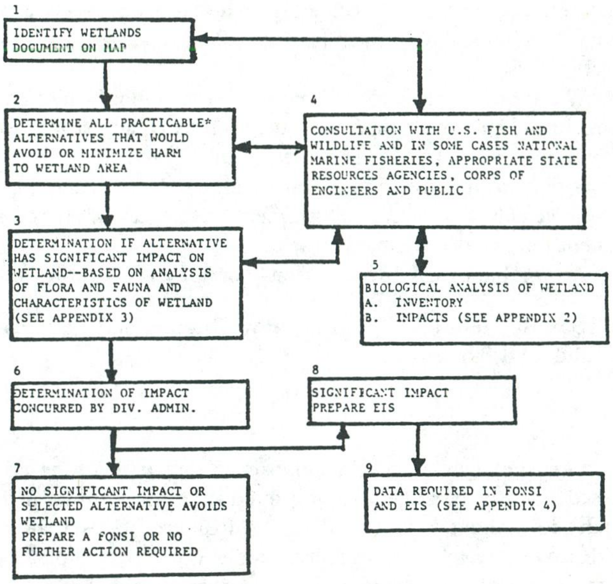


Figure 1. Typical drawing of trap catch basin required by Vermont State law (Title 10 V.S.A., Chap. 47) for all stormwater discharges from impervious surfaces with curbs, gutters, or collection facilities. (Courtesy of Vermont Agency of Transportation)



*DOT policy on floodplains (Federal Register June 22, 1978) defines "practicable" as capable of being done within feasible and reasonable natural, social, and economic constraints.

Figure 2. Wetland protection activity flow chart (as prepared by Washington State Department of Transportation after DOT Order 5660.1A).

CHAPTER SIX

WETLAND MONITORING

INTRODUCTION

There are a number of reasons for conducting wetland monitoring activities in support of proposed or existing highway projects, e.g., to obtain wetland inventory and classification data for planning purposes, to obtain baseline and highway-influenced data for potential impact assessment, and to estimate pollutant removal effectiveness in the wetland system. This chapter briefly describes methods of field data collection. Because the quantity and scope of information on field methodologies is so immense, it is the main objective of this chapter to put the user in touch with pertinent literature on field methods rather than to provide a voluminous duplication of effort. Information is presented on direct field measurement, use of remote sensing, and application of pollution indices.

DIRECT FIELD MEASUREMENT

A procedural manual for field monitoring of highway runoff (*286*) has been recently published by the Federal Highway Administration (Report No. FHWA/RD-81-043). This manual includes sections on site selection, program planning, installing and maintaining monitoring equipment, and evaluation and application of data. A more comprehensive field monitoring manual is currently being prepared for FHWA (under Contract No. DTFGH-61-80-C00001) which includes not only runoff monitoring but also methods of direct measurement of receiving water impacts from stormwater runoff. These include both the hydrological, physical, chemical, and biological components of surface water systems. Major sections of the manual will include site selection criteria, program planning, installation and maintenance of equipment, detailed field monitoring strategies, data evaluation and application for impact assessment.

Specific areas of field monitoring that will be outlined in the new FHWA manual are as follows:

1. Meteorological monitoring—precipitation, atmospheric deposition of particulates, wind speed and direction, and air temperature.
2. Quantitative and qualitative highway runoff monitoring.

3. Receiving water hydrological characterization—stage/discharge relationships, water budgets, dispersion, and time of travel studies.
4. Water quality determinations—water sampling, handling, preservation, and analyses; *in-situ* measurements; and strategies for baseline and wet weather surveys.
5. Sediment investigation—grab sampling, core sampling, suspended sediment sampling, sediment oxygen demand measurement, and use of sediment traps.
6. *In-situ* biological investigation—periphyton, benthic invertebrates, bacteria, plankton, and macrophytes.
7. Bioassay testing—laboratory flow through and static assays and field bioassays.

One pertinent area of field monitoring that will not be addressed extensively is the area of groundwater monitoring. Due in part to mandates contained in the Resource Conservation and Recovery Act pertaining to hazardous waste contamination of groundwater, a considerable amount of research effort is currently being directed to the area of groundwater pollution. Field techniques for direct monitoring of groundwater quality and hydraulic characteristics include the use of observation wells, lysimeters, infiltrometers, seepage meters, flow meters, geophysical well-logging, and tracers (*287* through *292*). Indirect methods include calculation by difference of seepage by monitoring all other components in the water budget, measurement of soil characteristics such as particle size distribution and permeability, and measurement of subsurface characteristics using surface geophysical techniques (*287, 291, 293, 294*). These surface geophysical techniques include:

1. Electrical Resistivity (*291, 293, 294*)—Resistivity measurements can provide information on aquifer limits, changes in groundwater quality, mapping freshwater-saltwater interfaces, locations of water tables, impermeable formations, and bedrock depths. Resistivity of rock formations is contingent on the resistivity of minerals contained, ratio of pore water to rock volume, resistivity of pore water, shape of pores, and temperature.
2. Seismic (*291, 293*)—This method can be used to map rock types, trace gravel deposits, and distinguish saturated and unsaturated overburden. It utilizes the theory of propagation (speed of transmission) of wave energy through various rock formations. The seismic wave is created by an explosive charge.
3. Gravimetric (*291, 293*)—These measurements can be used in locating such structures as faults, dikes, synclines, anticlines, and buried channels; such structures are bounded by rocks of significant density difference. The method employs the concept of gravitational pull on mineral and rock masses of variable density.
4. Magnetic (*291, 293*)—As a function of observed variations in magnetic intensity (caused primarily by the mineral content of a rock formation), such formations as intrusive dikes and veins of minerals and sedimentary and igneous rock formation contacts can be located with this method.
5. Thermal (*294*)—Specific heat of water versus that of dry geologic formations is used to correlate resistivity to temperature changes in order to locate shallow buried aquifers and delineate groundwater flow direction, zones of leakage, recharge and discharge zones, and groundwater contamination.

REMOTE SENSING TECHNIQUES

Remote sensing in this context can be defined simply as the use of imagery from airborne or satellite-borne devices and associated photointerpretation techniques. Several photographic techniques have been employed for wetland management, the most common of which is color infrared. The role of remote sensing in wetlands management includes wetland mapping and inventory, planning and classification, environmental impact assessment, water quality determination, discrimination of vegetative types and productivity, and pollution tracing (*295* through *302*).

The specific application of remote sensing to highway planning has been limited, although the potential is great, especially with respect to optimal corridor location to minimize deleterious environmental effects (*301*). One comprehensive study was performed by Kennard et al. (*302*) for the Joint Highway Research Advisory Council of the University of Connecticut and the Connecticut Department of Transportation. A rigorous mathematical procedure was developed which utilized data from remote sensing in conjunction with information from topographic and soils maps and field surveys. Environmental impacts of six alternative corridor locations were thereby assessed, paying special attention to wetland protection. One significant aspect of this study was performance of a detailed cost/benefit analysis of various remote sensing techniques. These included a matrix of black-and-white, color and color infrared film and low (6,000 ft), medium (27,500 ft), and high (63,500 ft) altitude imagery. The costs for aerial photograph acquisition (summarized in Fig. 3) included film, processing, printing, and aircraft (platform). Other costs included photointerpretation equipment and labor, and labor for transfer of information and drafting. A summary of all costs is given in Table 20.

The only benefit considered in this analysis included accuracy in wetland delineation to a 1/4-acre minimum mapping unit obtained by means of personal observation and quantitative modeling of sensor systems. Accuracies are summarized in Table 21. The relative cost/benefit ratios (or cost/accuracy), given in Table 22, show the optimal system to be the medium altitude color infrared imagery. The authors also note that total imagery costs can range from 8 to 24 percent of the total wetland mapping program (*302*).

POLLUTION INDICES

The development of numerical pollution indices has considerable historical precedent and relevancy. These indicators provide relative information on baseline conditions and potential degradation. Such indicators can range from a single water quality parameter, such as turbidity, to a numerical combination of a number of parameters. In general, water quality classifications are based on ranges of individual water quality parameters that have been correlated to the various types of organisms found in various degrees of polluted streams. One of the first systems is the Kolkwitz-Marson saprobien system on which many European water quality classifications are based. Several recent examples of other indices include:

1. The development of a heavy metal monitoring technique based on uptake by aquatic insects (*303*).
2. Biological Quality Index based on the type, quantity, and distributions of aquatic organisms (*304*).

3. Pollution Load Index based on metals levels in algae or other fauna compared to known background levels (*304*).
4. A Vulnerability Index based on biological effects on organisms from specific pollutants related to the presence of such organisms in a given region (*305*).

Most of these indices, although nobly conceived, have serious drawbacks. For example, an index based on the summation of a number of weighted parameters could be insensitive to acute loadings of one particular parameter. Similarly the application of the Vulnerability Index is limited by the paucity of hard data on "background" levels and incomplete use-allowable limit relationships (i.e., water use designation versus pertinent pollutant concentration limits) (*305*). Consequently, although the use of broad-based indices appears attractive, more work must be done to develop a suitable method for highway/wetland interactions.

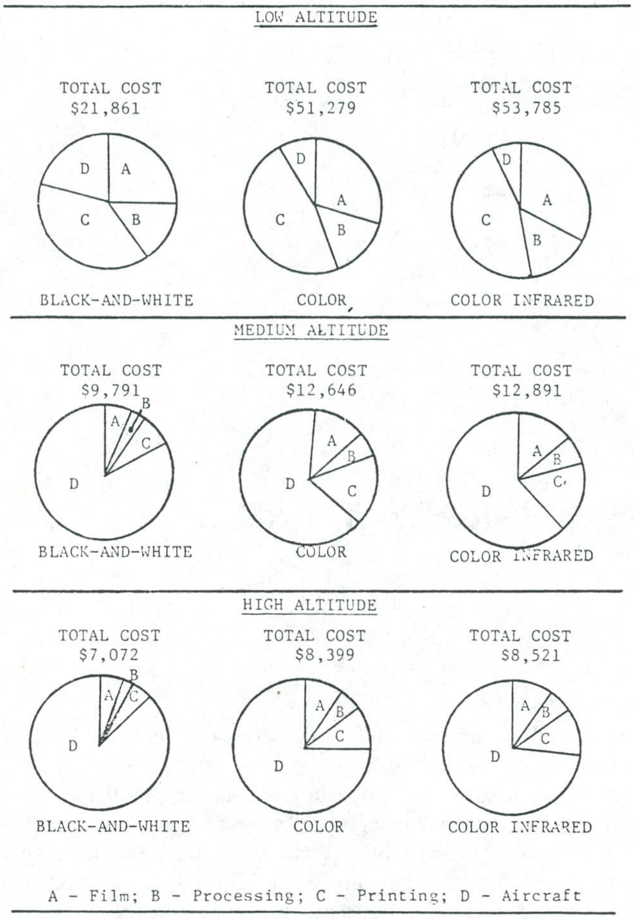


Figure 3. Total and relative costs of film, processing, printing, and aircraft.

Table 20. Summary of costs.

Wetland Inventory Parameters	Low Altitude (6,000 ft) BW	Color	CIR	Medium Altitude (27,500 ft) BW	Color	CIR	High Altitude (62,500 ft) BW	Color	CIR
Photos[a]	$17,497	$46,915	$49,421	$1,701	$4,556	$4,801	$797	$2,124	$2,246
Platform	4,364	4,364	4,364	8,090	8,090	8,090	6,275	6,275	6,275
Equipment[b]	1,550	1,550	1,550	1,650	1,650	1,650	1,700	1,700	1,700
Interpreting	80,291	69,207	69,207	17,714	12,478	12,478	13,923	10,829	10,829
Transfer	50,000	50,000	50,000	12,500	12,500	12,500	10,000	10,000	10,000
Drafting	54,000	54,000	54,000	54,000	54,000	54,000	54,000	54,000	54,000
TOTAL	207,702	226,036	228,542	95,655	93,274	93,519	86,695	84,928	85,050

[a] Includes cost of film, processing, and printing.
[b] Annual cost amortized over a 5 year period.

Table 21. Percent correct wetland delineation with a ¼-acre minimum mapping unit (*302*).

Sources of Estimates	Low Altitude (6,000 ft) BW	Color	CIR	Medium Altitude (27,500 ft) BW	Color	CIR	High Altitude (62,500 ft) BW	Color	CIR
In-House[a]	73	88	91	56	68	71	43	53	56
Commercial[b]	60-80	85-90	90	50-75	60-85	80-90	25-30	30-60	40-75

[a] The values reported by D. L. Civco for low altitude BW and CIR are statistically derived; the remaining seven were predicted by sensor system simulation.

[b] Gordon R. Derman, Avis Airmap, Inc., Braintree, Mass.

Table 22. Cost effectiveness indices.

Indices and Ranks	Low Altitude (6,000 ft)			Medium Altitude (27,500 ft)			High Altitude (62,500 ft)		
	BW	Color	CIR	BW	Color	CIR	BW	Color	CIR
CEI	3.049	2.752	2.691	1.830	1.470	1.412	2.160	1.717	1.628
Rank Order[a]	9	8	7	5	2	1	6	4	3

[a] Rank order is from most cost effective(1) to least cost effective(9).

CHAPTER SEVEN

MODELING TECHNIQUES FOR ASSESSING HIGHWAY AND WETLANDS

ASSESSMENT DATA

Assessment data may be collected to meet a wide range of objectives. Data might be required for an environmental impact statement, a permit application, an evaluation of treatment capability, or an analysis of a change in the system. The level and type of data collected are determined by specific objectives. The Federal Highway Administration has published a five-volume water quality manual which may aid the researcher in determining the type and level of data required to meet research objectives (*2, 306* through *309*). The Fish and Wildlife Service has also published a document on collecting assessment data, which should also be useful (*310*).

The most common type of assessment is the impact assessment. However, as noted earlier in Chapter One, impacts on wetlands due to highway runoff can be defined in several different contexts. The type and level of data collection, therefore, will also depend on that definition.

Heaney et al. (*311*) describe several different perspectives on stormwater impacts on receiving waters. These include "paper" impacts, such as violations of water quality standards or criteria for purposes of public health or protection of aquatic life; actual impacts, such as fish kills, changes in numerical quality indices, aesthetic considerations, and ecological assessment of impacts. The authors adopted a broad definition of impacts from stormwater discharges as effects that result in a "loss of beneficial use" of the receiving water. Three levels of these impacts were defined as follows:

1. *Policy or management planning*—loss of beneficial use is implied or considered possible.
2. *Standards or criteria violation*—loss of use is implied by violation, may be imminent, or can actually occur.
3. *Documented cases of cause effect*—actual impacts such as fish kills.

This approach to impacts definition centers on water quality, public health, and biotic effects and ignores the hydrologic effects of urbanized areas on receiving waters.

Another definition of impacts has been proposed by one of the agencies required to approve projects involving wetlands. The U.S. Army Corps of Engineers defines an impact on a wetland as anything that affects the normal functioning of a wetland (*312*). This is an ecological definition of an impact because values other than beneficial uses to mankind are inherent.

Pollutants present in highway runoff discharges may result in impacts on wetlands because of two mechanisms: (1) shock or acute loadings; and (2) long-term accumulation within the waterbody by associated sediments and biota.

Both mechanisms may result in levels of water quality impairment outside the limits of general water quality criteria for aquatic life, water supply, and recreational uses of the wetland. Wetland impacts are site specific, and the extent of the problem can depend heavily on conditions such as precipitation, point sources of pollution, land use activities, and sensitivity of the particular wetland.

Horner and Mar (*61*) suggest that both concentrations and loadings of pollutants be considered when assessing the effects of highway runoff on aquatic environments. Contaminant concentration (mass per volume) is the criteria used to assess potential acute effects to aquatic organisms. Assessment is based on the probability that the mean concentration will exceed a designated critical level during any storm event (short-term impact). Pollutant loadings (mass per unit time or mass per unit area per unit time) indicate the relative stress on biota under two contrasting conditions (e.g. before and after the placement of a highway), as well as the potential for contaminant accumulation within the system (long-term impact). Increased loadings may result in habitat changes that would displace certain species and favor colonization by others.

The wetland being assessed is likely to have many sources of runoff entering the system. To evaluate the impact of constituents in highway runoff on wetlands, constituents entering the wetland from all sources need to be quantified. Field monitoring, modeling and data from the literature, or a combination of these data sources will be required. The amount and type of data will depend on such variables as availability of existing data, time, money, and so on.

The U.S. Environmental Protection Agency has prepared several documents that will aid the researcher/planner in determining the data requirements for assessing impacts (*60, 259, 313, 314, 315*). Another EPA publication summarizes and compares 30 aquatic assessment techniques to provide appropriate information (*316*). Most methods described in this report (*316*) have greatest application in the western United States. Other documents prepared for the Federal Highway Administration may also be helpful (*317, 318*). Generally, an assessment of potential highway effects on wetlands involves the collection and reduction of baseline data, selection for study of suitable location alternatives that minimize land-use conflicts, and an estimation of the potential wetland water quality effects of highway construction and operation (*319*).

As mentioned earlier, there are essentially four ways to evaluate a highway/wetland system: (1) field monitoring data, (2) modeling data, (3) literature data, and (4) combination of the first three. The best data on which to evaluate the system are obtained from field monitoring programs. Wetland monitoring is discussed in Chapter Six of this document, and a procedural manual for monitoring highway runoff has been prepared by Gupta et al. (*320*). Data sources also include maps, photographs, satellite imagery, previously published data and wetland inventories developed by state agencies to delineate critical areas (*319*). However, in many cases, field monitoring programs to collect the required data will be prohibitive because of cost, time, or other constraints. Modeling is an alternative means of initially evaluating a particular system. Models are also excellent analytical tools for evaluating system change, i.e., effect of increased average daily traffic on runoff quality, effect of a drought year on the system, change in highway configuration, or other design aspects. An alternative to utilizing strictly field data or strictly predicted data from a model for evaluation is to implement a selected field monitoring program supplemented by modeling techniques. Field data can then also be used for model validation. This method is commonly used in evaluating environmental impacts to a particular system.

A model is an analytical tool that relates a response variable to independent variables affecting it. Several models are available that will predict highway runoff quantity and quality (response variables) from site characteristics (independent variables). Runoff from other land uses in the wetland watershed can also be evaluated using modeling techniques. Models are also available that can be used to assess wetland processes or economic values. The remainder of this chapter includes discussions of a few of the many models available that may facilitate the assessment of highway runoff and wetlands.

ECONOMIC AND CULTURAL ASSESSMENT

Many states require anyone who would alter a wetland to submit plans and environmental impact documentation to appropriate agencies for review prior to obtaining a permit. One aspect usually covered in such a review is a determination of whether the proposed project will significantly affect wetland values. Cost/benefit and risk analyses can also be used to put mitigation schemes into better perspective (*319*). However, those are difficult to make because of disagreement on wetland benefits/cost (*319*).

Models are available to systematically assess economic and cultural values of wetlands. Larson (*321*) includes a model consisting of four submodels for the relative and economic evaluation of freshwater wetlands. The submodels evaluate wildlife, visual-cultural, groundwater, and economic values. The wildlife and visual-cultural models are based on physical characteristics which, for the most part, can be measured from existing maps and aerial photographs. The groundwater model places wetlands into classes of probable groundwater yield based on surficial geological deposits under the wetland. The economic submodel assigns values for wildlife, visual-cultural aspects, groundwater and flood control. The authors believe that the strength of their assessment model is its basis on physical features that can be identified and measured by individuals who have an introductory knowledge of wetlands, maps, and aerial photographs. Personal judgments do not enter into its application in the field.

WATER QUALITY AND BIOLOGICAL ASSESSMENTS

Assessment of an aquatic system usually focuses on the water quality and biological aspects of the system. Horner and Mar (*61*) have prepared a manual that provides stepwise procedures for assessing stormwater runoff impacts on receiving waters resulting from highway operation and maintenance. The receiving water may be either a stream, lake, or wetland. Assessment organization includes three levels ranging from a rapid screening method (Level I) intended to identify those cases having a low probability of extensive impacts to a detailed evaluation focusing on impact mitigation (Level III). Each level of analysis uses runoff quantity and quality (both concentration and loadings). The procedure also includes methods for assessing water quality impacts of sanding, deicing, pesticide application, woodwaste fill leachate, and accidental spills. The three levels of assessment can be summarized as follows:

1. *Level I*—Screens highway area in terms of its proportion of the total watershed, type of runoff drainage system, and traffic volume. Highways with low traffic, occupying a small percentage of the watershed, and/or having drainage through a vegetated drainage course may be declared to have minimal impact.
2. *Level II*—Used if Level I analysis indicates the potential for a significant impact. Based on annual predictions.
3. *Level III*—Used to more thoroughly analyze the extent of aquatic impact. Based on monthly projections.

For a Level I assessment, if the ratio of impervious roadway surface/total watershed area is less than 0.01 and if either the traffic volume is less than 10,000 ADT or highway drainage is over a vegetated ditch, it can be stated with assurance that the input would be insignificant and a higher level analysis is not required. For Level II and Level III assessments, land uses in the watershed are defined and drainage patterns and pollution sources are established. In this way, the highway impact is assessed in context with the entire pollution burden created by all activities in the watershed.

The procedure developed by Horner and Mar (*61*) is representative of conditions prevalent in Washington State. However, the general premise of the procedure could be used with the appropriate data obtained for any particular locale.

As part of an ongoing project for the Federal Highway Administration entitled, "Effects of Highway Runoff on Receiving Waters" (Contract No. DTFH-6180-C00001), procedural guidelines for assessing impacts to receiving waters due to highway runoff are being prepared. This manual will provide those individuals and agencies responsible for preparing environmental assessments with adequate guidance to properly address the impacts of highway stormwater runoff on receiving waters. This procedural manual will be a user-oriented document containing the assessment methodologies and data gathered as a result of the literature review and field monitoring tasks of that study. Study completion date is April 1, 1984.

Adams and Stockwell (*322*) have produced a rapid assessment technique that evaluates the impact of highways on wetland functions using the Fish and Wildlife Service Wetland Classification Scheme (*14*). Their manual provides specific guidance for estimating the magnitude of the potential impact based on user-gathered field and office information. The reliability of their methodology to predict the value of any potential wetland function and possible impact thresholds for that function is ranked from high to low. The proposed methodology is explained in Volume II of the reference along with an example. Several states have field tested the methodology and one, Wisconsin, is adopting it as a general wetland evaluation methodology.

Models which can be used to generate the data required for water quality/biological assessments are described in the following.

Models to Estimate Highway Runoff

A predictive procedure for determining pollutant characteristics in highway runoff was developed as part of FHWA's program on the constituents of highway runoff (*323*). This model predicts runoff quantities and quality from highway systems based on data gathered from six sites in Milwaukee, Wisconsin; Harrisburg, Pennsylvania; Nashville, Tennessee; and Denver, Colorado. Equations for three highway site types are used to predict runoff volume and pollutant concentrations and loadings for 17 water quality parameters including total solids (TS), suspended solids (SS), volatile suspended solids (VSS), total volatile solids (TVS), total Kjeldahl nitrogen (TKN), biological oxygen demand (BOD), total organic carbon TOC), chemical oxygen demand (COD), NO_2+NO_3, total phosphorus (TPO_4), C1, Pb, Zn, Fe, Cu, Cr, and Cd. The three highway site types include:

1. *Type I sites*—urban, elevated bridgedeck, 100 percent paved with impact barriers containing each set of lanes.
2. *Type II sites*—mountable curbs and inlets on paved area with paved and nonpaved drainage area.
3. *Type III sites*—rural sites with flush shoulders, paved, and nonpaved runoff through ditches.

Model inputs include the rainfall record (total rain, rainfall duration, dry days) and site characteristics (size of total drainage area, average daily traffic, type of site, site length). Rainfall record may be a historical record (typical year, extreme year, etc.) or a design storm (10 yr, 15 yr, etc., recurrence interval storm). Both desktop and computerized versions of this model are available (*323*).

A highway runoff pollutant loading model has been developed for the State of Washington (*324, 325*). Rainfall of long duration and low intensity is characteristic of this State. This model should provide reasonable estimates of runoff quantity and quality for areas with long duration, low intensity rainfall patterns. Predicted water quality parameters include TSS, VSS, COD, TOC, Pb, Zn, Cu, TKN, NO_2+NO_3, and TP. Currently, research is being conducted to extend the model to more effectively reflect sanding operations.

The California Department of Transportation (Caltrans) is currently developing a predictive procedure for estimating potential pollutant loads from road surfaces. The model, California Pavement Runoff Model (CALPROM-1), is being developed from data collected at monitoring sites in Los Angeles, Walnut Creek, Sacramento, and Placerville, California (*326*). Water quality parameters include TS, SS, B, Pb, Fe, NH_4, TP, ortho-P, TKN, NO_3, oil and grease (O&G), Cu, Cr, Cd, Ni, Zn, COD, Cl, Hg, SO_4, and Mg.

Wanielista et al. (*327*) suggest that order of magnitude estimates of traffic-related pollutant loadings for a specific section of roadway can be obtained using deposition rates based on a study by Shaheen (*5*) (Table 23) and the following equations:

$$Y_i = y_i \, LH \sum j \; TD_j \, AX_j$$

where:

Y_i = loading of pollutant *i*, kg/day;
y_i = deposition rate of pollutant *i*, kg/axle-km;
LH = length of roadway section, km;
TD_j = traffic density of vehicle with *j* axles, vehicles/day; and
AX_j = number of axles per *j* vehicle.

The deposition rates given in Table 22 represent dry weather accumulation of pollutants on the roadway surface and do not include pollution from other nontraffic-related sources, such as atmospheric fallout, litter, and runoff from adjacent areas.

Field data that characterize highway runoff have been collected for the States of California (*328, 329*), Colorado (*11*), Florida (*331, 332*), Minnesota (*330*), North Carolina (*328*), Ohio (*333*), Pennsylvania (*328, 11*), Tennessee (*11*), Washington (*334* through *340*), Washington, DC (*5*), and Wisconsin (*328, 11*).

Models to Estimate Runoff from Other Land Uses

If the surrounding land use is urban, an appropriate model to estimate quantity and quality may be the U.S. Army Corps of Engineers Storage, Treatment, Overflow, Runoff Model (STORM). This model (*341*) computes runoff quantity and quality, contributions from land surface erosion and treatment, storage, and overflow. The treatment, storage, and overflow computation block will be useful if treatment plant effluents are being discharged to the wetland. Twenty land uses including agricultural can be specified using STORM. STORM is designed for a period of record analysis using continuous hourly precipitation data. In this respect, STORM is a continuous simulation model, although it can be used for single events or design storm analysis. Loads and concentrations of six basic water quality parameters are computed; suspended and settleable solids, bio-

Table 23. Composite concentration and loading ranges for constituents in highway runoff (*11, 328*).

Parameter	Pollutant Concentration (mg/l / event)		Pollutant Loading (lb/hwy mi[a]/event)	
	Minimum	Maximum	Minimum	Maximum
pH	4.90	8.1		
TS	68	57,400	0.85	17,400
TVS	10	1520	0.25	1,200
SS	6	2,160	0.22	6,080
VSS	1	837	0.04	1,460
Pb	<0.1	13.1	ND	20.3
Zn	0.01	3.4	0.00003	7.52
Fe	0.10	115	0.00001	207
Cr	<0.02	0.19	ND	4.06
Cu	<0.02	0.88	ND	4.06
Cd	<0.02	0.40	ND	0.196
Ni	<0.05	0.49	ND	0.66
Hg	<0.0002	0.067	ND	0.001
As	<0.01	0.03	ND	0.13
Na	2.1	22,500	0.02	12,600
Ca	4.0	450	0.92	202
Cl	2.0	35,000	0.07	13,500
O&G	1	55	0.002	81
PO_4-P	0.03	4.45	0.002	11.5
TKN	<1	14.0	ND	44.8
NO_2+NO_3	<0.01	9.00	ND	18.3
BOD_5	2	133	0.011	197
TOC	4	290	0.056	679
COD	5	1058	0.112	1,930
SO_4	<1	180	ND	51
PCBx10^{-3}	<0.00005	4.33	ND	8.93

[a] Both directions irrespective of number of lanes.

ND = Not detectable

chemical oxygen demand, total nitrogen, orthophosphate, and total coliform.

Another model that may be appropriate for estimating the quantity and quality of runoff from other land uses is the Air Force Runoff Model (AFRUM). AFRUM (*342*) is a stormwater runoff simulation model designed to predict stormwater flow and quality resulting from real or design storms for small watersheds of 2,000 acres or less. The principal model inputs are watershed area, land-use characteristics, percent forested, percent impervious, and percent denuded.

Data that may be useful in assessing the quantity and quality of runoff from an urban area can be found in a U.S. EPA Report entitled, "Water Quality Management Planning for Urban Runoff" (*343*). This manual also provides technical assistance enabling an individual to quantify within reasonable limits the urban nonpoint water pollution problem in a specified area without extensive data generation.

If the land use surrounding the wetland is predominantly agricultural, an appropriate model may be the Agricultural Runoff Management (ARM) Model. The ARM Model (*344*) simulates runoff quantity, sediment, pesticides, and nutrient contributions to receiving waters from both surface and subsurface sources on small agricultural watersheds.

A series of planning models for nonpoint runoff assessment are available from EPA (*345*). These planning models are tools designed for initial gross assessments with refinement capabilities to provide general estimates for decision-making. The individual planning models include:

1. Urban, commercial, and industrial runoff.
2. Erosion, sedimentation, and rural runoff.
3. Total loadings from point and nonpoint sources to waterbodies.

Models one and two produce independent data that can be used as loading factors for model three. Source programs and test case run decks for all three planning models are in library files on an EPA-OSI computer system and may be reproduced on 80-column cards if a request is made through normal EPA channels.

EPA has also prepared a handbook on loading functions (a loading function is a mathematical expression used to calculate the emission of a pollutant from a nonpoint source and discharge of the pollutant into surface waterways) for assessment of water pollution from nonpoint sources (*346*). The objectives of the handbook include:

1. To present loading functions together with the methodologies for their use.
2. To present some of the needed data, to provide references to other sources of data, and to suggest approaches for generation of data when available data are inadequate.

If modeling is not feasible, Horner and Mar (*61*) have compiled literature data that will provide order of magnitude values for pollutant loadings from both general land-use categories (Table 24) and specific land-use categories (Table 25).

Wetland Modeling

Models can be used to simulate biological and water quality interactions in surface waters. Zison et al. (*355*) have prepared a state-of-the-art report on formulations used in surface water quality modeling along with accepted values for rate constants and coefficients. Areas discussed include geometric system representation (spatial and temporal), physical processes (mass transport, heat budgets, ice formation, light extinction), biological systems (fish, benthic organisms), and chemical processes (nutrient cycles, carbonate system). Other processes and biological activities are also discussed including reareation, dissolved oxygen saturation, photosynthesis, deoxygenation, benthic oxygen demand, coliform bacteria, algal growth, and zooplankton growth. The discussion also includes factors affecting the specific phenomena and methods of measurement in addition to data on rate constants.

Mitsch et al. (*356*) review models that simulate processes associated with freshwater palustrine wetlands. The models discussed can be used to assess environmental impact due to management of wetlands, to describe the patterns of energy and nutrient dynamics, to estimate hydrological conditions and storage capacity, and to organize concepts, theories, and data collection in wetlands.

A state-of-the-art review of marine wetland and estuarine water quality and ecosystems models has been prepared by Hamilton and Fucik (*357*). This literature review surveyed published models of hydrodynamics, sediment transport, and water quality in estuarine and intertidal wetlands. In other publications, Olufeagba (*358*), Hamilton (*359*), Ross (*360*), and Wiegert (*361*) further discuss modeling as an approach to solving ecological problems in marine wetlands and estuaries.

A model has been prepared by Dixon and Kadlec (*362*) that predicts the effect of sewage effluent on wetland ecosystems. This mathematical model focuses on the organic matter com-

Table 24. Storm runoff pollutant loadings for general land-use categories (*61*).

Land Use	Loading (lb/acre/yr)							
	TSS	COD	Pb	Zn	Cu	NO_3+NO_2-N	TKN	TP
General Urban	400	18-240	0.13-0.45	0.3- 0.5	0.04-0.12	0.3- 4.0	7.1	1.8
General Residential	375	27-270	0.05	0.02	0.03	0.3- 3.4	5.4	1.6
General Agricultural	17,900- 44,000	NA	0.002- 0.07	0.004- 0.3	0.002- 0.08	0.3- 7.1	0.3- 30	0.1- 8.0
Forested or Open	6-76	1.8	0.01- 0.03	0.01- 0.03	0.02- 0.03	0.3- 0.5	1.5-2.7	0.06- 0.08

Notes: 1. Means given where available; otherwise ranged are reported. References (347 through 354).

2. NA = Not available.

Table 25. Storm runoff pollutant loadings for specific land-use categories (*61*).

Land Use	Loading (lb/acre/yr)							
	TSS	COD	Pb	Zn	Cu	NO_3+NO_2-N	TKN	TP
Central Business District	964	955	6.3	2.7	1.9	4.0	13	2.5
Other Commercial	750	906	2.7	2.9	NA	0.6	13	2.4
Industrial	50	56	1.8-6.3	3.1-11	0.3-1.0	0.4	2-13	0.8-3.6
Single-Family Residental	15	25	0.1	0.2	0.03	0.3	1-5	0.2-1.3
Multiple-Family Residential	390	297	0.6	0.3	0.3	3.4	3-4	1.2-1.4
Cropland	402	NA	0.004- 0.005	0.03- 0.07	0.01- 0.05	7.0	1.5	0.3
Pasture	306	NA	0.003- 0.013	0.02- 0.15	0.02- 0.04	0.3	0.6	0.06
Forested	76	NA	0.01- 0.03	0.01- 0.03	0.02- 0.03	0.5	2.6	0.08
Open	6	1.8	NA	NA	NA	0.3	1.5	0.06

Notes: 1. Means given where available; otherwise ranges are reported. References (347 through 354).

2. NA = Not available.

ponents of a wetland ecosystem. The major variables of the model are water and nutrients, and the data used to develop the model are primarily from data in the published literature. Major ecosystem components include vascular plants, standing dead biomass, stem and leaf litter, and soil. Other models and impact analysis procedures dealing with nutrients are also available (*363* through *368*).

Highway runoff characteristically has elevated levels of heavy metals that are potentially toxic to biota. Several models are available dealing with the distribution and effects of heavy metals in aquatic ecosystems (*369*, through *372*). Jorgensen (*369*) has reviewed the literature on modeling the distribution and effects of heavy metals in aquatic ecosystems in an attempt to set up a general modeling approach. Because of the interacting processes in a complex system, such as an aquatic ecosystem, Jorgensen felt that modeling was a proper way to investigate the processes involving heavy metals. The basic differential equations described in the article include the variation in concentration of the toxicant per biomass dry matter in a given trophic level and the exchange of toxicant between sediment and water. The author stresses that a model used for an impact statement should use the maximum concentration level rather than the seasonal variation.

The fate of toxic organic substances in the aquatic environment can also be modeled (*373, 374, 375*). One model, entitled PEST (*374*), is a dynamic simulation model for evaluating the fate of toxic organic materials in freshwater environments. Toxic organic matter carriers utilized in the model include phytoplankton, macrophytes, zooplankton, waterbugs, zoobenthos, fish, particulate organic matter, floating organic matter, clay, and water. The model simulates toxic organic matter degradation by hydrolysis, oxidation, photolysis, microbial metabolism and biotransformation by higher organisms. Transformations include solution, volatilization, sorption, adsorption onto gills, consumption, excretion, defecation, biodeposition, mortality, and throughflow. Time-varying environmental factors considered by the model include pH, temperature, dissolved oxygen, wind, solar radiation, and biomass and condition of organisms.

It should be pointed out, however, that although certain hydrologic, sediment transport, and water quality models have been refined to the point at which they can be used to predict the quantity and quality of runoff and its constituents or predict the loading to a body of water, biological models have not advanced as far. Most relationships have been described for aquatic (deep-water, streams and lakes) systems, making their use in shallow wetlands tenuous. Equations have been generated for specific wetland situations, but these are not generally applicable and seldom involve hydrocarbon pollutants or toxic substances. Because each wetland has a unique combination of plants, animals, and substrate, one can only predict the components of the food web. Rates of pollutant uptake, exchange, degradation, and loss cannot be predicted with useful accuracy yet.

HYDROLOGICAL ASSESSMENTS

Hydrological considerations are important in assessing a wetland because hydrology directly affects water quality (concentration of parameters, parameter retention time, etc.) and the biota of wetlands. Hydrodynamic modeling as it applies to this study is discussed in the following. Mitsch et al. (*356*) list three types of models that describe water flow through wetlands:

1. *Ecosystems*—These models describe a water budget for a homogeneous individual wetland and do not consider uplands or other bodies of water as part of the model (*376*).
2. *Regional*—These models present overall gains and losses for a large-scale region or watershed that includes wetland areas (*377, 378, 381*).
3. *Hydrodynamic transport*—These models, popular with engineers for streamflow and runoff calculations, can be applied to describe wetland hydrology and pollutant transport over short periods and large areas (*379*).

The majority of wetland modeling effort has been devoted to shallow coastal bays and estuaries (*380, 382, 383, 384*) with one specific application of a numerical two-dimensional model to a brackish marsh in Louisiana (*385*). This is significant because wetlands in estuarine areas can be more hydrodynamically complex than freshwater systems due to both tidal influences and salinity gradients (i.e., density layering). For example, storm water runoff into the Parramatta River estuary in Australia tends to form a temporary but relatively stable buoyant surface water plume over brackish estuarine water (*386*). Tidal effects on circulation and salinity patterns have been studied by Moreau (*386*), Murray (*381*), and Paulson (*387*) for coastal marshes in Florida, Louisiana, and Mississippi, respectively. A comprehensive literature review of marine wetland and estuarine ecosystem models (including hydrodynamics) was conducted by Hamilton and Fucik (*357*). Water circulation is driven primarily by tides, river inflows, salinity gradients, and wind forces. The complexity of modeling estuarine hydrodynamics is exemplified not only by the interactions of these four driving forces but also by the phenomenon of turbulence in a stratified system. The authors review one-dimensional (longitudinal dispersion only), two-dimensional (inclusion of depth in the analysis), three-dimensional (inclusion of longitudinal, lateral, and depth dimensions), and box models. Because one-dimensional models tend to oversimplify certain systems and three-dimensional models are so complex to have precluded extensive development and application, two-dimensional models are often most appropriate. According to the authors, "inclusion of the depth dimension makes possible the inclusion of the majority of the fundamental physical processes that contribute to advection and diffusion of salt and pollutants."

An interesting example of an application of a two-dimensional hydrodynamic numerical model to a tidal brackish marsh in Louisiana was carried out by McHugh (*384*). Included in this model were Coriolis forces (deflecting force of the earth's rotation), wind stresses and bottom stress due to frictional drag (determined by the Chezy-Manning formula). Although only minimal quantitative verification of the model was attempted, the authors contend that qualitative validation (including manipulation of the bottom roughness factor) indicates that it can serve as a useful tool for the study of estuarine marsh circulation patterns, water exchange rates, wind effects, and even water composition if a dispersion-diffusion function is included.

Reports on hydrodynamic modeling of freshwater wetlands are not frequently encountered in the technical literature. More typically, specific water budget calculations have been made for a local study area. Elements in a typical wetland water budget have been described. Hydrologic modeling of riverine and lacustrine systems has been extensive. A comprehensive review of such models and recommendations for their application has been provided by Zison et al. (*388*).

CHAPTER EIGHT

HIGHWAY CONSTRUCTION, DESIGN, AND MAINTENANCE CONSIDERATIONS IN WETLAND MANAGEMENT

INTRODUCTION

This chapter discusses highway construction, design features, and maintenance practices that should be considered in evaluating highway-wetland interactions and in managing a wetland for the purpose of treating highway runoff.

HIGHWAY CONSTRUCTION

The construction of highways through wetlands can alter the normal physical, chemical, and biological processes of this ecosystem type. The scope of this research did not include an evaluation of the effects of highway construction on wetlands.

However, planners and agencies performing an overall evaluation of the interaction between highways and wetlands may be required to assess the effect of highway construction or modification on an existing wetland. The purpose of this section is to familiarize those individuals with this information and to direct them to the sources of detailed information.

A literature review was performed by Shuldiner et al. (*389, 390*) for the National Cooperative Highway Research Program on the ecological effects of highway fills on wetlands. Research results appear in a two-volume report: *NCHRP Report 218A,* the research report, and *NCHRP Report 218B,* the user's manual. Case studies presented in the research report indicate that highway fills can affect adjacent wetlands and related areas removed from the immediate site of construction by altering hydrologic regimes or by impairing water quality. The literature also indicated the potential for ecological damage from erosion of construction fill materials, salinity regime changes, disturbance of tidal exchanges, and water quality degradation from the inadvertent introduction of heavy metals, nutrients, and road salts to surface and ground water. The user's manual (*390*) provides a framework for performing two of the basic procedures in environmental impact analysis: (1) describing the environmental setting of a project, and (2) assessing the potential ecological effects of project construction. The user's manual also describes the most common physical, chemical, and ecological effects likely to be encountered when placing fills in wetlands, and graphically displays the effects and their interactions.

The Federal Highway Administration has published a two-volume report (*391, 392*) on highway and wildlife relationships. Volume One (*391*) is a state-of-the-art review and Volume Two (*392*) is an annotated bibliography. The purpose of that literature review was to assess highway and wildlife relationships and to suggest research and management approaches to protect and enhance fish, wildlife, and environmental quality. The report discusses the effects of highways and highway construction on fish and wildlife.

DESIGN FEATURES

Highway design features can greatly affect the type and quantity of pollutants reaching a wetland. For example, highway runoff that is discharged to a wetland through scupper drains from a bridge deck, sewer systems, paved ditches, or unvegetated ditches will discharge essentially all of the available highway pollutants to a wetland. In contrast, vegetated ditches, shallow water ditches, and detention basins will retain large quantities of highway generated pollutants. Data in the literature indicate that these design features may be a cost-effective means of removing solids and associated pollutants from highway runoff, prior to discharge into a wetland.

Drainage Considerations

Vegetated channels appear to reduce contamination by promoting sedimentation and possibly by creating other conditions conducive to dissolved constituent removal. In the State of Washington, grassy drainage channels (200 ft long) were shown to effectively capture and retain more than 80 percent of the original lead concentration (*61*). The more soluble metals, such as zinc and copper, were reduced by approximately 60 percent. Approximately 80 percent of the total suspended solids and chemical oxygen demand were also removed. Table 26 presents data for the metal removal efficiency with distance in a grass channel. Average daily traffic was approximately 100,000 vehicles per day at the I-5 site and 90,000 vehicles per day at the I-405 site. The data collected also showed that unvegetated drainage ditches provided no filtering action, and residues deposited in them were easily entrained by subsequent runoff. These data indicate the importance of nurturing vegetation in drainage channels rather than removing it in order to increase velocities (*62*). Larger drainage channels may be required to prevent back-up and flooding on the highway due to slower movement of runoff. Succession from grasses to larger growth should be prevented. Soils at channel end should be tested periodically to indicate pollutant break-through. Highway-contaminated channels may require "cleaning" through sediment removal and revegetation. Zimdahl (*393*) and Hassett (*394*) have shown that lead immobilization in the soil is directly correlated to soil CEC and inversely related to pH. An estimate of the maximum lead holding capacity in a soil can be obtained by measuring soil pH and CEC and applying these data to an equation developed by Zimdahl and Skogerboe (*395*).

Amussen et al. (*396*) studied the efficiency of a vegetated ditch in removing the herbicide 2,4-D from cropland runoff. The ditch was grassed and 24.4 m long with a slope of 2 percent. Simulated rainfall was used to produce runoff to examine the effects of wet weather and dry weather conditions on removal efficiencies. The data in Table 27 indicate that the combination of vegetation and organic debris in the ditch effectively removed most of the herbicide.

Wanielista et al. (*327*) studied the ability of shallow water ditches to reduce metal and hydrocarbon concentrations in highway stormwater runoff. Shallow water ditches are defined as those aerobic waters holding natural vegetation and receiving highway runoff. The principal sources of hydrocarbons in highway runoff include grease, oils, and unburned exhaust hydrocarbons. Data collected in that study indicate that shoulder areas without surface waters in the ditches are capable of degrading at most 48 percent of hydrocarbon substrates in 60 days. However, 99 percent of the hydrocarbon substrates are degraded within 60 days by bacteria present in shallow water ditches. The authors found that metals and other potential pollutants can be retained in shallow water ditches by deposition into the sediments. The authors recommend the following:

In the design of highways:

- Rainfall excess (runoff) should be directed as overland flow as much as possible to promote water percolation and metal removal.
- Shallow-water ponding of runoff in aerobic-maintained ditches should be encouraged to increase petroleum (hydrocarbon) degradation.
- A "muck" blanket should be spread on the soil before vegetation is planted to promote metal removals.
- Subsurface soil should be alkaline to promote metal removals. Also, organic matter and clay minerals aid in removal of metals.

In the maintenance of highways:

- Soils adjacent to pavements need to be replaced on a periodic basis because of metal saturation. Care should be exercised in disposal of these soils.

Table 26. Grass channel metal removal efficiencies (*62*).

Site	Distance[a] m	No. Samples	Removal Efficiency (%)[b]					
			Cd	Cu	Fe	Mn	Pb	Zn
I-5 @ N.E. 158th	15-21	6	51.4 (46.0)	24.6(24.3)	53.8(31.2)	40.5(25.2)	59.3(18.8)	35.5(16.1)
	31	1	60.0	53.5	53.1	50.6	70.4	31.4
	40-50	6	80.0(44.7)	39.2(22.6)	73.4(12.6)	61.2(32.3)	72.0(15.0)	69.7(10.4)
	67	6	100(0)	63.1(24.0)	76.7(9.2)	54.3(43.2)	83.8(11.7)	69.7(10.4)
I-5 @ N.E. 159th	15-20	2	100[c]	40.1(37.8)	39.7(11.4)	59.4(1.4)	37.5(0.1)	23.6(14.6)
	30-40	2	100[c]	51.1(19.2)	35.1(17.6)	62.0(0.6)	54.1(5.0)	50.8(9.8)
	50-60	2	34.8[c]	20.3(19.7)	54.0(2.1)	75.0(7.8)	66.9(20)	64.2(1.3)
	67	1	c	43.4	62.0	93.3	90.2	65.4
	77	2	c	57.5(7.4)	70.5(33.9)	91.8(6.5)	80.6(15.3)	72.1(14.6)
I-405 @ Kirkland	2.5	1	c	0	3.6	1.2	2.9	2.1
	10.0	1	c	29.3	39.8	49.2	58.6	16.6
	15.0	1	c	51.9	54.9	83.6	68.1	19.4
	20.0	1	c	63.7	49.9	81.9	77.3	45.9
	25.0	1	c	70.7	63.3	83.4	86.7	57.1
I-5*	2.5	1	0	0	8.1	19.3	2.1	12.9
	5.0	1	45.8	34.4	68.0	72.9	72.4	60.2
	15.0	1	100	68.1	80.4	84.7	78.5	93.2
	25.0	1	100	53.3	76.0	78.1	82.4	94.0

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[a] Distance runoff flowed in channel from beginning of vegetated area.

[b] Mean (standard deviation) given for multiple samples.

[c] One or more values were below detectable limit.

Table 27. **Reduction in water, sediment, and 2, 4-D in a grassy ditch (*327*).**

	% Reduction	
	Antecedent Dry Weather	Antecedent Wet Weather
Runoff (water)	50	2
Sediment	98	94
2,4-D in water phase	71	69
2,4-D in sediment phase	99	99
Total 2,4-D	72	69

- Roadside vegetation should remain on the ground after cutting to allow nutrients to recycle.
- Planting of leguminous plants, such as clover, will provide nitrogen that is a limiting factor in petroleum degradation and therefore necessary.

Other nonstructural treatment facilities can be incorporated in a highway design to treat runoff prior to discharge into a wetland. Chan et al. (*15*) summarized various nonstructural facilities that were used in Orange County, Florida (*397, 398*), to control and treat stormwater runoff near its source including:

1. Percolation facilities providing for infiltration, detention, and overland treatment of runoff.
2. Underdrains providing for collection and drainage of stormwater after passage through permeable surface soils.
3. Residential swales providing for an on-site percolation of ponded stormwater in grassed depressions.
4. Detention/sedimentation basins equipped with debris traps and baffle arrangements.

Table 28 gives performance data for each of these control measures. The basis for the high removal rates is the combined processes of detention, percolation, and soil adsorption. Wanielista et al. (*327*) also discuss the value of retention ponds with underdrains or natural percolation for treating the first flush of highway stormwater. Sylvester and DeWalle (*399*) state that the most effective sedimentation basin for the removal of floating and settling material in highway runoff is one that has a large surface area, is well baffled, and has a large detention period. A properly designed sedimentation basin should remove essentially all of the litter that might otherwise be discharged to a wetland, a significant portion of the particulate fractions with their adsorbed metals and oil, and most of the oily substances. Oils and other hydrocarbons retained on the basin surface should largely disappear within a few days or weeks.

If highway stormwater runoff is discharged directly into a receiving water body (i.e., if dilution alone is used to reduce the impact of highway runoff on the receiving waters), a solution of 80 percent (four parts dilution/one part runoff) is needed to avoid an oxygen debt (*59*). At sites where the average daily traffic (ADT) exceeds 10,000 vehicles per day, a dilution of 100/1 is required to protect biota from heavy metals, a level recommended by the U.S. Environmental Protection Agency (*60*). This means that inputs of highway runoff to a receiving water body should not exceed 1 percent of the system's total volume.

Distance is an important consideration if atmospheric deposition of highway-generated pollutants and the overland migration of metals to the wetland are to be avoided. Getz et al. (*400*) observed that lead concentrations were highest in topsoil layers (10 cm) and decreased sharply with distance from edge-of-pavement, with lead concentrations approaching background levels at 20 to 50 m for high ADT sites and 5 to 10 m for low ADT sites (less than 2,000 vehicles per day) along Illinois highways. Motto et al. (*401*) also observed that the accumulation of lead in topsoil layers (15 cm) was approximately twice that in substrate layers (15 to 30 cm) and that concentrations of lead in the topsoil layer decreased with distance from edge-of-pavement for several New Jersey highways. Scanlon (*402*) observed that Pb, Zn, Cd, and Ni approached background levels at a distance of 48 m for most highway sites that were sampled in Virginia. Kobriger et al. (*11*) demonstrated that the area impacted by atmospheric deposition of metals was approximately 35 m from edge-of-pavement at Milwaukee and Sacramento (116,000 and 85,900 vehicles per day, respectively), 15 m at Harrisburg (27,800 vehicles per day), and 12 m at Efland (25,300 vehicles per day). Laxen and Harrison (*403*) observed that lead deposition from highway sources is confined to a strip of land roughly 30 m wide to either side of the highway. They also observed that lead is effectively immobilized within the top few centimeters of soil and that this lead causes an insignificant contribution to water pollution. Zimdahl (*393*) also found that lead in the top centimeter of soil along I-25 in Colorado approached background at 30 m. Wang et al. (*62*) performed surface soil (upper 1 cm) studies of metal concentrations at three highway sites in Washington State. Their data suggest that there is little movement of metals once they are deposited on the ground and that background levels are approached at 15 m from edge-of-pavement at all three sites.

Traffic Characteristics

The quantity and quality of highway runoff constituents can also be affected by traffic characteristics, such as speed, volume (average daily traffic), vehicular mix (cars/trucks), congestion factors, and state regulations controlling exhaust emissions. Average daily traffic (vehicles per day) has been shown to be highly correlated to total solids accumulation (pounds per mile per day) (*404*). This relationship for 25,000 to 90,000 vehicles per day is graphically displayed in Figure 4. Data collected as part of that study also show that a relationship exists between the total solids accumulated and other common highway constituents including heavy metals, oxygen demand parameters, nutrients, and chlorides. Therefore traffic volume and anticipated changes in traffic volume are important considerations in assessing highway runoff and wetlands, and in formulating wetland management plans. Data collected in Washington State (*61*) indicate that if the ratio of impervious roadway surface/total watershed area is less than 0.01, and if either the traffic volume is less than 10,000 ADT or highway drainage is over a vegetated ditch, the input to a receiving water can be considered insignificant.

Another traffic consideration is vehicular mix. Higher truck traffic increases pollution potential because of increased pavement wear, accidental spills, and increased particulate emissions from the combustion of diesel fuel. Accidental spills can cause slug loads of a wide range of toxic constituents to be deposited

Table 28. Performance of retention/detention controls, Orange County, Florida (*15*).

Stormwater Control Measure	Storms Sampled	Influent Load, lb/yr				Effluent Load, lb/yr				Average Removal, %			
		BOD_5	N	P	SS	BOD_5	N	P	SS	BOD_5	N	P	SS
Swale/ Percolation	4	221.95	72.42	21.36	6,092.98	16.36	9.44	1.72	237.91	93	90	92	96
Underdrain	4	260.10	53.10	14.40	11,477.00	11.70	24.30	1.08	138.6	96	54	93	99
Residential Swale	2	74.14	15.34	4.16	3,315.00	46.67	12.85	4.40	362.47	38	16	0	89
Detention/ Sedimentation	6	424.94	130.31	47.98	17,884.39	171.21	31.38	11.55	2,936.54	60	76	76	84

Source: Refs. (258, 259).

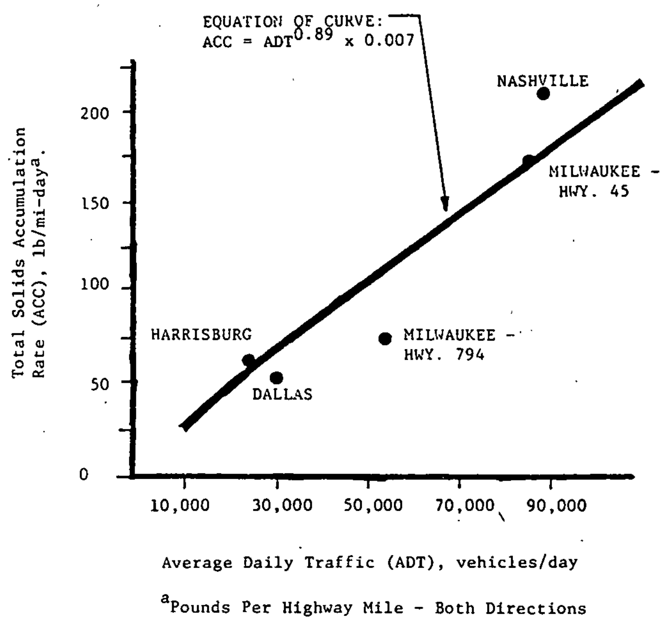

Figure 4. Selected total solids accumulation rates versus average daily traffic (11).

on highway surfaces that can migrate to surrounding areas. For example, Scheidt (*405*) has pointed out that because of the large number of highways crossing receiving waters, and because commodities are carried on highways in a large number of separately controlled units, the potential is high for accidental spills on highways that can cause water pollution. A single truck can carry up to 20,000 gallons. This quantity of oil or toxic chemicals spilled into a receiving water would probably cause considerable damage to the aquatic ecosystem receiving this slug load. Such impacts, i.e., fish kills and coating of stream beds, have been documented. (*405*). Another type of spill is the gradual release or periodic "seeding" of a constituent to the highway surface. For example, trucks hauling livestock or stockyard waste are believed to periodically "seed" the highway surface with enteric bacteria (*11*). Highway runoff may exhibit increased sodium and chloride levels during summer months because of spillage from trucks hauling deicing agents to storage yards (*11*).

Surrounding Land-Use

The surrounding land-use associated with the highway and wetland can greatly influence the type and quantity of pollutants eventually reaching a wetland. All sources of pollutants entering the system must be assessed in evaluating the interaction of highway runoff and wetlands. Effects of surrounding land-use are discussed in more detail in Chapter Seven.

MAINTENANCE

Deicing Chemicals

Sodium chloride, has been applied to street and highway pavements for snow and ice control since early in this century.

Salt and other deicing agents are applied to highways to meet the public demand to maintain open travel routes for fast speeds and safety. To meet this demand, highway authorities maintain a policy that ice and snow should be removed as quickly as possible from highways, and that "bare pavement" conditions are essential to maintain safety and protect lives. However, maintaining bare pavement conditions does require frequent and liberal applications of road deicers. Deicers are commonly applied during the beginning of snowstorms to prevent the bonding of snow to pavement. Procedures vary, but a common sequence includes salting, snowplowing, and resalting. Sodium chloride and calcium chloride and sand combinations are used in varying degrees, frequencies and quantities depending on temperature, storm condition, volume of traffic, time allowed for reactions, distribution of salt over the road surface, and amount of ice on the road.

Highway salts can cause injury and damage across a wide environmental spectrum, and these effects, although not yet evident in certain areas of the country, may appear in the future (*406*). All living organisms must survive in a precarious balance between too little, tolerable, and too much salt, each in accordance with its genetic limitations and special adaptions (*407*). Salt concentrations greater than 1 percent (1g/100 g of water) endanger health, reproduction, and longevity in all species adapted to freshwater environments including humans (*407*). High salt concentrations in drinking water pose a possible threat to persons with heart disease (*406, 408*). A new development in salt pollution concerns the potential role of sodium serving as a trace element toward stimulating excessive growth of blue-green algae (*408, 409*). Salt added to ponds or small lakes can affect their physical characteristics (*407*). The failure of seasonal mixing due to salinity-induced stratification has been observed in Irondequoit Bay, New York (*410*) and in First-Sister Lake, Michigan (*411*). The lower depths in lakes depend on this seasonal mixing for oxygen. Therefore, failure of seasonal mixing by significant additions of salt could contribute to the biological process of aging in lakes called eutrophication (*407*).

Increased salt levels can cause deterioration in habitat for both plants and animals in freshwater wetlands (*218*). Plant communities shift species or die, and animal diversity is diminished. Deicing chemicals can also produce some indirect effects. For example, salt accumulation on wetland plants and highway surfaces has been known to attract deer, increasing a potential roadway hazard. Inevitably, some animals will be hit and killed by vehicles. Deer pose the greatest hazard because they can cause major automobile accidents. In some areas, fencing, traffic warning signs, or improved lighting will be necessary for the protection of both wetland animals and humans (*218*).

The impact to freshwater wetlands from deicing chemicals is potentially a problem for northern states that use these agents during winter periods. The general conclusion is that, if possible, the use of deicing salts should be minimized (*218, 406, 407, 409*) or that optimal mixtures of salt and abrasives for particular geographic areas should be used (*412*).

Sand

Although biologically and chemically stable, sand applied to highways as deicing abrasives can contribute to the solids loadings of a receiving water. Factors that can reduce the quantity of applied sand entering the drainage system are as follows (*61*):

1. Larger particle sizes and/or denser particles are preferred because smaller particles are easily transported by stormwater runoff. Larger particles require removal as soon as possible before they can be pulverized by traffic.
2. A period between application and the first extensive runoff is desirable during which traffic-generated winds can remove particles from the highway.
3. Plowing throws sand particles to the side before melting and runoff occur.
4. Sweeping cleans the shoulder and avoids any chance of accumulated material in the larger size fractions being carried along with runoff from a heavy storm.

Studies by Kobriger et al. (*11*) indicate that commercially sweeping the highway surface immediately after the winter period removes large quantities of total solids (particles less than 3.35 mm in size) and associated pollutants. Efficiency of pickup by commercial sweepers is generally highest for solids and those constituents associated with solids including metals, sodium, oil and grease, TKN, PO_4-P, and rubber. Efficiency is lowest for the more soluble constituents including NO_2+NO_3, chlorides, and sulfates.

Herbicide Use

Herbicides are used to maintain roadsides by preventing the growth of undesirable vegetation. One problem encountered in herbicide application is drift, which carries the chemical to contact with nontarget plants (*218*). Herbicides as a group are not as toxic to fish and wildlife as are many of the insecticides (*218*). However, combinations of herbicides may increase their toxicity. Pesticides in general can impact aquatic life through acute toxicity and chronic effects resulting from bioaccumulation (*61*). Herbicide application to highway rights-of-way near wetlands should be minimized and selective spraying should be used instead of blanket applications. Mowing or cultivation of plants of low stature may be acceptable alternatives.

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APPENDIX A

SUMMARY OF STATE REGULATIONS

This appendix summarizes in Table A-1 information obtained from the literature about state wetland and floodplain regulatory programs *(11)*. The contents of this table are not intented to represent a legal guide to state wetland legislation. Its function, rather, is to serve illustrative purposes.

Table A-1. Select state wetland and floodplain regulatory programs (*284*).

ALABAMA

State Coastal Area Board currently developing a coastal management plan. When the plan is put into effect, the Board will issue permits regulating dredge and fill in tidally influenced areas [ALA. CODE TIT. 8 Sec. 312-320.]

ARKANSAS

Local units not adopting adequate ordinances regulating activities in floodways and floodplains may be required to adopt and enforce state developed regulations [ARK. STAT. ANN. Sec. 21-1901 to 21-1904.]

ALASKA

State Department of Natural Resources issues permits regulating activities on state-owned land and intertidal zones. [ALASKA STAT. Sec. 38.05330, 38.05070, 38.05107.]

State Department of Natural Resources issues permits to appropriate water, which may become right to appropriation of that water. Wetlands are defined to be waters of the state. [ALASKA STAT. Sec. 46.15030 - 46.15185.]

State Department of Environmental Conservation regulates wetlands through water quality standards and Clean Water Act Sec. 401 certification. [ALASKA STAT. Sec. 46.03100, 46.03110.]

ARIZONA

Local units delineate and then regulate floodplains pursuant to Department of Water Resource's guidelines [ARIZ. REV. STAT. Sec. 45-2341 to 45-2346.]

CALIFORNIA

State Lands Commission issues permits and leases regulating dredging, sand and gravel excavation and other activities in any tidal or submerged lands under state ownership. CAL. GOVT. CODE Sec. 13109, CAL. RES. CODE Sec. 6301-6312, 6321-6327.]

State and Regional Coastal Commissions issue permits regulating dredge and fill to 1000 yards above mean high tide. [CAL. PUB. RES. CODE. Sec. 3000-3900.]

State Reclamation Board issues permits regulating dredge and fill activities in the Sacramento-San Joaquin River System and its tributaries. [CAL. WATER CODE pt. 4, Sec. 8520-9377.]

San Francisco Bay Conservation and Development Commission issues permits regulating dredge and fill activities in and near San Francisco Bay. [CAL. GOVT. CODE Sec. 65600-66661.]

Local units regulate activities in state designated floodways pursuant to state minimum standards. Failure to meet state standards results in loss of state funds for flood control projects. [CAL. WATER CODE Sec. 8400-8415.]

COLORADO

Counties regulate land use, including floodplain and, to a minor extent, wetland use. State Water Conservation Board designates floodplains and may request county to stop dangerous land uses. State Department of Game and Fish can designate significant wildlife habitat, pursuant to a county request. [COL. REV. STAT. Sec. 24-65.1-101 et seq.]

State Department of Game and Fish has authority to acquire water rights to protect wildlife by maintaining minimum stream flows, affecting wetlands adjacent to streams [COL. REV. STAT. Sec. 37.92.102(3).]

CONNECTICUT

State Department of Environmental Protection issues permits regulating dredge and fill, construction, and other activities in tidally influenced areas. [CONN. GEN. STAT. ANN. Sec. 22a-28 to 22a-35.]

Municipalities issue permits regulating most dredge, fill, and construction activities in inland wetlands and water courses. Where local units fail to adopt regulations which conform to state standards, the State Department of Environmental Protection issues the permits. [CONN. GEN. STAT. ANN. Sec. 22a-36 to 22a-45.]

State Department of Environmental Protection establishes stream channel encroachment lines based on previously recorded floods. Construction activities within these lines require state permits. [CONN. GEN. STAT. Sec. 25-4a to 25-4g.]

DELAWARE

State Planning Office issues permits regulating activities in coastal zone. Specified heavy industrial development prohibited. Appeal to Coastal Zone Industrial Control Board. [DEL. CODE tit. 7 Sec. 7001-7013.]

FLORIDA

State Department of Environmental Regulation issues permits regulating dredge and fill activities adjacent to or in navigable waters and state-owned tidally influenced areas. Locals issue permits regulating certain fill activities adjacent to or in navigable waters, subject to approval by Department of Environmental Regulations. State Department of Environmental Regulation district centers are authorized to issue permits for certain minor projects. [FLA. STAT. ch. 253, ch. 403 pt. 5.]

State Department of Environmental Regulation issues permits regulating the construction, modification and expansion of stationary installations which may adversely affect the quality of any waters or bodies of water in the state. [FLA. STAT. ch. 403 pt. 1.]

State Department of Natural Resources manages specified Aquatic Preserves and may establish additional areas. Department of Environmental Regulations may issue permits allowing only certain limited activities in preserve areas. [FLA. STAT. ch. 258.]

State Department of Environmental Regulation issues permits and establishes rules regulating construction activities in a specified area of the coastline [FLA. STAT. ch. 161.]

State may designate Areas of Critical State Concern. Local regulation of such areas must comply with state development principles. State will regulate areas where local units fail to adopt adequate controls. [FLA. STAT. ch. 380.]

GEORGIA

State Coastal Marshlands Protection Committee issues permits regulating dredge and fill in tidally influenced areas. [GA. CODE ANN. Sec. 45-136 to 45-148.]

HAWAII

State Land Use Commission issues permits regulating activities in conservation districts, which include some wetlands and floodplains. [HAW. REV. STAT. Sec. 179.1-179.4, 205.2.]

IDAHO

State Department of Water Resources issues permits regulating dredge and fill in stream channels. [IDAHO CODE tit. 42, ch. 38.]

State Conservation Commission conducted a Protected Water Area Study to develop a plan for the preservation of natural and cultural resources along certain rivers, lakes, wetlands, and adjacent land areas. [S.F. 2267 Sec. 2C and H.F. 734 Sec. 4-1(7)]

KANSAS

State Division of Water Resources must approve plans for channel changes, dam construction, and levees and similar structure. [KAN. STATE. ANN. Sec. 82a-301 to 82a-305a (as amended, 1978 supp.), 24-126.]

Local units regulate activities in floodplains pursuant to state standards. Local ordinances must be approved by State Division of Water Resources. [KAN. STAT. ANN. Sec. 12-734, 12-735.]

KENTUCKY

State Department of Natural Resources and Environmental Protection, Division of Water Resources, issues permits regulating construction and other activities which will obstruct the flow of waters in streams and floodways. [KY. REV. STAT. Sec. 151.250, 151.260, 151.310.]

LOUISIANA

State Wildlife and Fisheries Commission issues permits regulating the discharge of dredge and fill material in and on banks of streams designated as Natural and Scenic Rivers. Channelization, channel realignment, clearing and snagging, and reservoir construction and prohibited in such streams. [LA. REV. STAT. ANN. Sec. 56.1841-56:1849.]

State Department of Natural Resources issues permits and grants leases for construction of wharfs, piers, bulkheads, fills, and other encroachments on or reclamation of water bottoms. [LA. REV STAT. ANN. Sec. 41:1131, 41:1701-41:1714.]

MAINE

State Board of Environmental Protection issues permits regulating dredge and fill and other activities in all tidally influenced areas. Local units may be authorized to issue permits, subject to overrride of local decision by the Board. [Alteration of Coastal Wetlands, ME. REV. STAT. tit. 38 Sec. 471 et seq.]

State Board of Environmental Protection (B.E.P.) issues permits regulating alterations of great ponds and lakes. [Great Ponds Act, ME. REV. STAT. tit. 38 Sec. 386-396].

State Department of Inland Fish and Wildlife issues permits regulating dredge, fill and the erection of permanent structures in, on, over or adjacent to, and affecting, rivers and streams, including contiguous wetlands. Certain dams and crossings are exempt from this regulation. [Alteration of Rivers and Streams, [ME. REV. STAT. tit. 12 Sec. 2206-2212 (as amended).]

State B.E.P., Land Use Regulatory Commission, in cooperation with the Planning Office, sets standards for mandatory zoning of shoreland areas along the coast, rivers which drain 25 square miles or more, and great ponds. One of the districts, the Resource Protection District, includes shoreland wetlands and floodplains and slopes greater than 25 percent. If local units do not adopt adequate regulations, the B.E.P. or the State Lane Use Regulation Commission will. [Mandatory Shoreland Zoning Act. ME. REV. STAT. tit. 12 Sec. 4811-4814.]

The B.E.P. and the municipalities issue permits regulating the construction of wharves and weirs in navigable waters. [Wharves and Weirs ACT, ME. REV. STAT. Tit. 38 Sec. 1021.]

MARYLAND

State Department of Natural Resources issues permits regulating dredge and fill in tidally influenced private areas. State Board of Public Works similarly regulated state tidal areas. [MD. ANN. CODE Sec. 9-101 et seq.]

Department of Natural Resources issues permits for construction of dams and any other obstruction in water courses. [MD. ANN. CODE Sec. 8-901.]

MASSACHUSETTS

Local conservation commission issue permits either regulating or prohibiting work that could remove, dredge, fill or alter coastal and inland wetlands, land subject to flooding and other areas in the state. Notice and appeal to Department of Environmental Quality Engineering. [MASS. GEN. LAWS ANN. ch. 131 Sec. 40.]

State Department of Environmental Management may issue orders designating specific coastal wetlands and areas subject to flooding in which dredge and fill activities are to be restricted. [MASS GEN. ANN. ch. 130 Sec. 105.]

State Department of Environmental Management may designate specific inland waters or wetland areas, including flood-prone areas, and issue orders restricting activities in such areas. [MASS. GEN LAWS ANN. ch. 131 Sec. 40A.] The state regulates the use of specific floodplains. [MASS. GEN LAWS ANN. ch. 5-18, 554; Mass. Acts 459, 463.]

MICHIGAN

State Department of Natural Resources issues permits regulating dredge, fill, construction, and other alterations below ordinary high water on inland lakes and streams. [Inland Lakes and Streams Act, MICH. COMP. LAWS ANN. Sec. 281-951 - 281-965.]

State Department of Natural Resources issues deeds, leases, agreements, permits and certificates regulating work on public trust lands below ordinary high water in the Great Lakes. [Great Lakes Submerged Lands Act, MICH. COMP. LAWS ANN. Sec. 322.709, 16.352, 24.102, 24.104.]

State Department of Natural Resources and Water Resources Commission establish comprehensive plan for the use and management of shorelands. Local units adopt ordinances, which must be approved by the state with respect to the regulation of "high risk" (erosion-prone) and "environmental" (important to fish and wildlife) areas. [Shorelands Protection and Management Act, MICH. COMP. LAWS ANN. Sec. 281.631 - 281.645.]

State permits are required for activities in floodway and floodplain areas identified by the state [MICH. COMP. LAWS ANN. Sec. 323.5b, 560.117.]

The Department of Natural Resources, in cooperation with local units of government, issues permits regulating all alteration activities in all inland wetlands. [GEOMAERE - ANDERSON WETLAND PROTECTION ACT. No. 203, MICH. PUBL. ACTS OF 1979.]

MINNESOTA

State Department of Natural Resources issues permits regulating the use of all "public waters" serving a public purpose. Counties may administer the permit program for certain public waters, pursuant to state standards. [MINN. STAT. ch. 105.]

Local units must regulate critical areas designated by State Department of Natural Resources by issuing development permits pursuant to a comprehensive plan. Where local units fail to adopt controls, state regulates areas. [STAT. Sec. 116G.01 - 116G.14.]

Counties must adopt shoreland zoning consistent with state standards. Where local units fail to adopt adequate regulations, State Department of Natural Resources regulates shorelands. [STAT. Sec. 105.485.]

Local units issue permits regulating activities in floodplains in conformance to state standards. Where local units fail to adopt adequate regulations, the State Department of Natural Resources regulates floodplains. [MINN. STAT. Sec. 104.01 - 104.07.]

MISSISSIPPI

State Marine Resources Council issues permits regulating most dredge and fill activities in tidally influenced areas. [MISS. CODE ANN. Sec. 49-27-1 et seq.]

MISSOURI

Landowners may petition county circuit court for authority to erect a private dam for mills, electric power, or light works across a non-navigable stream. (MO. REV. STAT. Sec. 236.010, 236.020, 236.030.]

Owners of any swamp, wet, or overflowed land have the right to drain or protect the land for sanitary reasons or agricultural purposes with an open ditch, tiles or a levee. [MO. REV. STAT. Sec. 244.010.]

MONTANA

State Department of Fish and Game must give approval of dredge and fill activities by public agencies in stream beds and their immediate banks. [MONT. REV. CODES ANN. tit. 87, ch. 5.]

Local Conservation Districts must give approval of dredge and fill activities in stream beds and their immediate banks for private projects in accordance with state approved rules. [MONT. REV. CODES ANN. tit. 75, ch. 7.]

NEBRASKA

Local units regulate activities in floodways pursuant to state standards. Where local units fail to adopt adequate regulations, state enforces the state standards. [NEB. REV. STAT. Sec. 2-1506.01 to 2-1506.17.]

NEVADA

State Division of Lands issues letters of authorization regulating dredge and fill activities in navigable waters. Permits issued for activities in Lake Tahoe must receive Department of Environmental Protection concurrence. [NEV. REV. STAT. Sec. 321.595.]

State Department of Fish and Game issues permits regulating dredge and fill activities in all streams and their watersheds. [NEB. REV. STAT. SEC. 501.105.]

NEW HAMPSHIRE

State Wetlands Board issues permits regulating all dredge and fill activities in tidally influenced areas, and all surface waters flowing and standing (except small ponds). [N.H. REV. STAT. ANN. ch. 483-A, 482 Sec. 41-e to 41-i, 488-A, 149 sec. 1.]

NEW JERSEY

State Department of Environmental Protection issues permits regulating all dredge and fill activities in tidally influenced areas along specified rivers and bays. [N.J. STAT. ANN. Sec. 13:9A-1 to 13:9A-10.]

Department of Environmental Protection issues permits regulating construction of new facilities in coastal areas. Areas regulated under the wetlands act above are excluded. [N.J. STAT. ANN. Sec. 13:9A-1 to 13:9A-21.]

State regulates floodways. Local units regulate floodplains pursuant to state standards. State regulates floodplains where local units fail to adopt adequate regulations. [N.J. STAT. ANN. Sec. 58:16A-50 to 58:16A-66.]

NEW YORK

State Department of Environmental Conservation issues permits regulating activities in tidal wetlands. [N.Y. ENVIR. CONSERV. LAW art. 25.]

Local units issue permits regulating activities in freshwater wetlands in accordance with state standards. Department of Environmental Conservation regulates wetlands where local units fail to adopt regulations and in wetland areas of statewide significance. The Adirondack Park Agency regulates activities in wetlands within its jurisdiction. Appeals from local and state issued permits to Freshwater Wetlands Appeals Board. [N.Y. ENVIR. CONSERV. LAW art. 24.]

State Department of Environmental conservation issues permits regulating dredge and fill in wetlands that are adjacent to or contiguous to navigable waters. [N.Y. ENVIR. CONSERV. LAW ART. 15-0505.]

NORTH CAROLINA

State Department of Natural and Economic Resources issue permits regulating dredge and fill in tidally influenced areas and state owned lakes. [N.C. GEN. STAT. Sec. 113- 229.]

State Department of Natural and Economic Resources may issue orders restricting or prohibiting dredge and fill activities in coastal wetlands. [N.C. GEN. STATE. Sec. 113 - 230.]
Cities and counties issue permits regulating certain activities in coastal areas of environmental concern (including wetlands) pursuant to state guidelines. State Coastal Resources Commission may develop land use plan and issue permits for such areas if local units fail to adopt adequate plans. [N.C. GEN. STAT. Sec. 113A - 100 to 113A - 128.]

Local units issue permits regulating obstructions in state-identified floodways. [N.C. GEN. STAT. Sec. 143 - 215.51 to 143 - 215.61.]

NORTH DAKOTA

State Water Resources Commission issues permits regulating dikes, dams and other channel modifications in waters of the state, and drainage of certain ponds, sloughs, and lakes. [N.D. CENT. CODE Sec. 61-01-22, 61-02-14, 61-02-20.]

State Health Department regulates discharges into state waters. [N.D. CENT. CODE Ch. 23-26.]

OKLAHOMA

State Water Resources Board issues permits regulating all discharges of dredge and fill materials in all waters. [OKLA. STAT. tit. 82 Sec. 926.1 et seq.]

OREGON

State Division of State Lands issues permits regulating the removal of material from and the filling in of all natural waterways and their beds and banks. [OR. REV. STAT. Sec. 541.605 - 541.665.]

State Land Conservation and Development Commission may recommend designation of, and regulate, areas of critical state concern. [OR. REV. STAT. Sec. 197.005 - 197.430.]

State Highway Engineer, Division of State Lands, and State Land Board regulate specific scenic rivers, and issue permits regulating certain activities in the scenic river and along its banks. [OR. REV. STAT. Sec. 390.805-390.925]

State Forester regulates all forest practices, and must give written approval of stream channel changes resulting from forest practices. [OR. REV. STAT. Sec. 527.610 - 527.730.]

PENNSYLVANIA

State Department of Environmental Resources issues permits regulating construction of dams and encroachments in all state waterways. [PA. STAT. ANN. tit. 32 Sec. 681-691.]

PUERTO RICO

Puerto Rico Department of Natural Resources and Puerto Rico Planning Board, through Regulations and Permits Administration, issue permits regulating activities in the coastal zone, which includes coastal waters, submerged lands, offshore islands, and a shoreland area including wetlands. [LAW No. 75 (June 24, 1975), Law No. 76 (June 24, 1975), Law No. 23 (June 20, 1972), Puerto Rico Coastal Management Program.]

Puerto Rico Planning Board, with Regulations and Permits Administration, issues permits regulating development in zoned areas and restricts construction in floodable areas. [Law No. 75 (June 24, 1975), Law No. 76 (June 24, 1975), Act No. 3 (September 27, 1961.]

RHODE ISLAND

Coastal Resources Management Council issues permits regulating dredge and fill below mean high water mark in tidally influenced areas. [R.I. GEN. LAWS Sec. 46-23-1 to 46-23-16.]

State Department of Natural Resource issues permits regulating dredge and fill in intertidal salt marshes. [R.I. CEN. LAWS Sec. 2-1-18 et. seq.]

State Department of Natural Resources issues permits regulating dredge and fill in all inland waters. Local concurrence required. (R.I. GEN. LAWS Sec. 2-1-18 to 2-1-24.]

Table A-1 (continued)

SOUTH CAROLINA

South Carolina Coastal Council issues permits regulating activities in coastal critical areas (primary dunes, coastal waters to high tide, periodically inundated wetlands and marshlands subject to saline influence, and beaches). Coastal management plan sets performance standards as criteria. [S.C. Code Sec. 48-39-10 to 48-39-240.]

State Water Resources Commission issues permits regulating construction activities in navigable waters (below mean high water in tidally influenced areas and below normal high water elsewhere) outside the jurisdiction of the South Carolina Coastal Council. [Budget Control Board, art. 6,R19-100.]

SOUTH DAKOTA

State Division of Game Fish and Parks issues permits regulating special uses of lake bottoms held in public trust. [S.D. COMPILED LAWS ANN. Sec. 41-2-32., 41-2-18.]

TEXAS

General Land Office, State School Land Board regulate dredge and fill activities in coastal public lands by granting easements. [NAT. RES. CODE ch. 32, Sec. 32.001-33.176.]

Department of Parks and Wildlife issues permits regulating the extraction of sand, marl, gravel, mudshell in coastal bays, rivers, streams and lakes except within the limits of certain incorporated cities. Dredging activities in connection with mineral leases granted by the General land Office, State School Land Board. [PARKS AND WILDLIFE CODE ch. 86.]

County Commissioners Court issues permits regulating certain extractions of sand, marl, gravel, etc., in certain shoreline and island areas. (NAT. RES. CODE Sec. 61.211 - 61.227.]

VERMONT

Vermont Water Resources Board issues permits regulating dredge and fill in certain lakes, ponds, and streams. (VT. STAT. ANN. tit 29, ch. 11]

Local ordinance regulating activities in floodplains developed in accordance with state standards. Permits issued locally with state oversight. [VT. STAT. - ANN. tit. 10, Sec. 751-3.]

VIRGIN ISLANDS

Territorial Department of Conservation and Cultural Affairs regulated activities in shoreline areas. [V.I. CODE ANN. tit. 12 Sec. 401-407.]

Cutting and/or injuring vegetation in and along streams requires written permission from Department of Conservation and Cultural Affairs. (V.I. CODE. ANN. tit. 12 Sec. 121-125.]

VIRGINIA

Local Wetland Boards issue permits regulating activities in tidally influenced areas pursuant to state guidelines. Where local units fail to establish a Wetland Board, the Virginia Marine Resources Council issues permits. Local decisions are subject to review by, and appeal to, the V.M.R.C. [VA. CODE ch. 2.1 Sec. 62.1-13.1 to 62.1-13.20]

WASHINGTON

State issues permits regulating activities in floodways and floodplains. Permitting authority may be delegated to local units. (WASH. REV. CODE Sec. 86.16.-0100-86.16.900.]

State sets standards for local shoreline zoning and permitting programs for shorelines and associated wetlands of navigable rivers and lakes. State may adopt regulations of statewide significance. State issues permits regulating certain uses of statewide significance. (WASH. REV. CODE Sec. 90.58.010-90.58.-930.]

WEST VIRGINIA

State Department of Natural Resources responsible for the management of the state's water resources. The Public Lands Corporation within the D.N.R. issues permits and may otherwise regulate certain activities in navigable streams of the state. [W.VA. CODE ch. 20 Sec. 1-15.]

WISCONSIN

State Department of Natural Resources establishes a comprehensive plan for navigable waters and their shorelands. Counties adopt zoning ordinances in compliance with state standards. Where local units fail to adopt adequate controls, the state adopts an acceptable ordinance. [Shoreland Zoning Act, WIS. STAT. ANN. Sec. 144.26,59.971.]

State Department of Natural Resource sets standards for the regulation of floodplains by cities, villages, and counties. Where local units fail to adopt adequate regulations, the state adopts an acceptable ordinance. [Flood Plain Zoning Act. WIS. STAT. ANN. Sec. 87.30.]

WYOMING

State identified areas of critical or more than local concern are to be regulated by local units according to state development guidelines. State may adopt land use plan for areas if local units fail to. [WYO. STAT. Sec. 89-849 to 89-862.]

APPENDIX B

BIBLIOGRAPHY BY SUBJECT AREA

A. PROCESSES AND PATHWAYS

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B. RUNOFF CONSTITUENTS AND AQUATIC ECOSYSTEMS

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