Wetlands and Urbanization

Implications for the Future

Edited by
Amanda L. Azous
Richard R. Horner

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Preface

In the early 1980s stormwater managers and developers were proposing to store urban runoff in wetlands to reduce flooding impacts and to protect stream channels from erosion. There was also interest in exploiting the known ability of wetlands to capture and retain pollutants in stormwater. In response to these proposals, natural resource managers argued that flood storage and pollutant trapping were only two of the numerous functions attributable to wetlands. Among other values were groundwater recharge and discharge, shoreline stabilization, food chain support, and habitat for wildlife. It was further claimed that using wetlands for stormwater management would likely damage these other vital functions.

Both stormwater and natural resources managers came together in early 1986 in the Puget Sound area of Washington State to consider how best to resolve these national issues concerning wetlands and stormwater management. Together, representatives from federal, state, and local agencies; academic institutions; and other local interests determined information and management needs required to guide policy and management of wetlands. Out of these requests was born the design of a research program that would produce such information to guide policy and management of wetlands. The research was to identify the short- and long-term impacts of urban stormwater on palustrine wetlands; develop management criteria by wetland type; recommend stormwater management strategies that avoided or minimized negative effects on wetlands; and to identify features critical to improving urban runoff water quality prior to entering wetlands.

Early in our studies, it became apparent that wetlands in urbanizing watersheds would inevitably be impacted by clearing, development, and other anthropogenic activities even if there was no intention to use them for stormwater management. We also learned it was essential to identify the characteristics of wetland watersheds and the surrounding landscapes in order to understand the relationships between urban stormwater discharge and wetland ecology. In this book you will learn what we found monitoring and analyzing the five major structural and ecological components of wetlands: hydrology, water quality, soils, plants, and animals in wetlands over an eight-year period. These pages provide a thorough descriptive ecology of studied wetlands, discussions of urbanization influences affecting these wetlands, and substantive recommendations for minimizing potential adverse stormwater impacts from urbanization. This information is developed from comparisons of wetlands located in watersheds undergoing urbanization to wetlands in watersheds remaining mostly undeveloped during our studies.

Continued urbanization of the natural landscape is an ongoing ever-increasing activity, driving efforts to protect remaining wetlands. The goal of this book is to support protection efforts by increasing professional and public knowledge of wetland functions in urbanizing environments and to improve the management of both wetland resources and urban stormwater management.

Puget Sound Wetlands and Stormwater Management Research Program

Richard R. Horner

Amanda L. Azous

Klaus O. Richter

Lorin E. Reinelt

Sarah S. Cooke

About the Puget Sound Wetlands and Stormwater Management Program Team

Amanda L. Azous is an environmental scientist, consultant, and sole proprietor of Azous Environmental Sciences, a private consulting firm established in Seattle, Washington in 1990 and located on Orcas Island, Washington since 1993. Ms. Azous received a Bachelor of landscape architecture and an M.S. in environmental engineering and science, from the University of Washington, Seattle and she is also a registered professional wetland scientist.

Amanda Azous has worked on a broad range of projects including development of environmental policy, writing environmental protection regulations, and developing performance standards for wetland restoration and mitigation projects. Her recent experience includes wetland design, enhancement and restoration, watershed analysis, environmental impact assessment, water quality studies, GIS analysis of landscapes, land use surveys, and environmental impact evaluations. Her firm specializes in land management plans for wetlands, forestry, conservation, and stewardship as well as evaluations of environmental factors as a basis for community planning. She has authored and co-authored several journal articles and numerous technical reports addressing community planning, urban stormwater impacts, and management of biological communities in urbanizing watersheds.

Richard R. Horner received his B.S. and M.S. degrees from the University of Pennsylvania and a Ph.D. in environmental engineering from the University of Washington in 1978. Following 13 years of college teaching and professional practice, he joined the University of Washington faculty in 1981. Since 1993 he has split his time between private consulting and teaching at the University of Washington, where he is a research associate professor with appointments in civil and environmental engineering, landscape architecture, and urban horticulture. Dr. Horner's principal interests involve analyzing the effects of human activities, especially diffuse landscape sources of water pollution, on natural freshwater resources, and solutions that protect those resources. He founded the Center for Urban Water Resources Management at the University of Washington in 1990 to advance applied research and education in these areas, directed the center for three years, and continues as an affiliated faculty member. Dr. Horner coordinated the Puget Sound Wetlands and Stormwater Management Research Program, the basis for this book, from its beginning in 1986 to its conclusion in 1997. He has also been a principal investigator on more than 30 other research projects in his area of interest, funded by agencies such as National Science Foundation, National Research Council, U.S. Environmental Protection Agency, the Washington State Departments of Ecology and Transportation, and a number of Puget Sound regional and local governments. His consulting clients have included many of these same agencies, the Natural Resources Defense Council, the Santa Monica and San Diego Baykeeper organizations, the Greater Vancouver (Canada) Regional District, and many of the national environmental consulting firms.

Dr. Horner is the author or co-author of one previously published book and more than 50 refereed journal publications, book chapters, and papers in conference proceedings. His current University of Washington teaching includes a graduate watershed analysis and design studio in landscape architecture and a number of continuing education courses through engineering professional programs.

Klaus O. Richter is the senior wetland ecologist in King County's Department of Natural Resources. He received his B.S. in forestry/wildlife biology at the State University of New York (SUNY) College of Environmental Sciences and Forestry in Syracuse, an M.S. in science education at SUNY in Oswego, and a Ph.D. in forest zoology at the University of Washington, Seattle. For the past 15 years Dr. Richter has specialized in freshwater wetland science, management, protection, and regulation. As co-recipient of the 1996 National Wetlands Award in Science Research sponsored by the Environmental Law Institute and the EPA, he was honored for his research of amphibian ecology and reproduction in urban areas. His models to account for amphibian declines in urbanizing landscapes are being applied to reduce amphibian losses through improved stormwater management and in implementing site-specific wetland enhancement, restoration and creation practices throughout the Puget Sound and the U.S.

Dr. Richter has authored numerous papers on the monitoring, distribution, and decline of amphibians as well as habitat mitigation criteria. Additionally, he helped develop Washington State's Hydrogeomorphic Wetlands Functional Assessment and is currently developing methods and metrics (i.e., biocriteria) applicable to employing amphibians as bioindicators of wetland/watershed condition for EPA's Wetland Division in Washington, D.C. Dr. Richter is also a popular instructor at local universities and colleges and leads numerous training courses on wetland monitoring, management, and restoration.

Lorin E. Reinelt is a Senior Water Resources Engineer for the Public Works Engineering Department at the City of Issaquah. He is responsible for stormwater capital projects, including stream rehabilitation projects for flood mitigation and habitat enhancement, water quality treatment, and local drainage control. He also works in a regional role as the Sammamish watershed coordinator, supporting the Sammamish Watershed Forum, and implementing fish habitat, water quality, and flood protection projects.

Dr. Reinelt has been involved in public service, research, education, and consulting on water resource issues for the past 15 years. This includes nonpoint source pollution management, wetlands and stormwater management, basin planning, aquatic resource monitoring, flood hazard mitigation, water quality assessment, and groundwater management. Previously, he was employed by the King County Surface Water Management Division, the Center for Urban Water Resources Management at the University of Washington, and in private consulting.

Dr. Reinelt has a B.S. in civil engineering from the University of the Pacific, a M.S. in environmental engineering and science from the University of Washington, and a Ph.D. in water and environmental studies from Linköping University in Sweden. He is a registered professional wetland scientist and engineer-in-training.

Sarah S. Cooke, Ph.D. (edaphic ecology), M.S. (plant taxonomy), M.S. (geology, biology), is a registered professional wetland scientist, soils scientist (SS), and has a national reputation in wetlands and plant-soil interactions (geobotany) research. Dr. Cooke has 20 years experience in ecological and geological research, with 14 years in wetlands ecological research and environmental consulting in the Pacific Northwest.

She specializes in wetland restoration design and implementation and has conducted wetland inventories, delineations, baseline studies, monitoring programs, rare plant surveys, soil assessments, vegetation mapping, and watershed analysis in the Pacific Northwest. Dr. Cooke developed the Semi-Quantitative Assessment Methodology (SAM) functional assessment used by many wetlands professionals; she was on the development team for the Washington State Wetlands Functional Assessment Methodology. Her most recent publication was *A Field Guide to the Common Wetland Plants of Western Washington and Northwestern Oregon* (Seattle Audubon Society, 1997), the definitive guide to the region's wetland plants.

Dr. Cooke has taught assessment methodologies, wetlands science and ecology, delineation protocols, hydric soil science, and wetland plant identification at the University of Washington and Portland State University. She has provided expert training for agency personnel and private consultants in soils and botany throughout the Pacific Northwest.

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Section I

Overview of the Puget Sound Wetlands and Stormwater Management Research Program

Introduction

Richard R. Horner

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The Puget Sound Wetlands and Stormwater Management Research Program (PSWSMRP) was a regional research effort intended to define the impacts of urbanization on wetlands. The wetlands chosen for the study were representative of those found in the Puget Sound lowlands and most likely to be impacted by urban devel-

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opment. The program's goal was to employ the research results to improve the management of both urban wetland resources and stormwater.

This overview section begins by defining the issues facing the program at its inception. It then summarizes the state of knowledge on these issues existing at the beginning and in the early stages of the program. It concludes by outlining the general experimental design of the study. Subsequent sections present the specific methods used in the various monitoring activities.

THE ISSUES

The program was inspired by proposals of stormwater managers and developers in the 1980s to store urban runoff in wetlands to prevent flooding and to protect stream channels from the erosive effects of high peak flow rates.[1,2] Stormwater managers were also interested in exploiting the known ability of wetlands to capture and to retain pollutants in stormwater, interrupting their transport to downstream water bodies (see listed citations for discussion of the use of wetlands for runoff quality control).[1-6]

In response to proposals to use wetlands for urban runoff storage, natural resources managers argued that flood storage and pollutant trapping are only two of the numerous ecological and social functions filled by wetlands. Among the other values of wetlands are groundwater recharge and discharge; shoreline stabilization; and food chain, habitat, and other ecological support for fish, waterfowl, and other species.[7,8] Resource managers further contended that using wetlands for stormwater management could damage other important wetland functions.[6,9-12] They noted the general lack of information on the types and extent of impacts to wetlands used for stormwater treatment.[3,10-13]

Several researchers have suggested that findings about the impacts of municipal wastewater treatment in wetlands are relevant to stormwater treatment in wetlands.[3,14] In some cases, wastewater treatment in wetlands has caused severe ecological disruptions, particularly when wastewater delivery is uncontrolled.[15,16] A number of studies have raised concerns about possible long-term toxic metal accumulations, biomagnification of toxics in food chains, nutrient toxicity, adverse ecological changes, public health problems, and other impacts resulting from wastewater treatment in wetlands.[17-20]

Other researchers have reported negative impacts on wetland ecosystems from wastewater treatment. Wastewater additions can lead to reduced species diversity and stability, and a shift to simpler food chains.[21,22] Wastewater treatment in natural northern wetlands tended to promote the dominance of cattails (*Typha* spp.).[23] In addition, animal species diversity usually declined. Discharge of wastewater to a bog and marsh wetland eliminated spruce and promoted cattails in both the bog and marsh portions.[24] Thirty years of effluent discharge to a peat bog caused parts of the bog to become a monoculture cattail marsh.[25] Application of chlorinated wastewater to a freshwater tidal marsh reduced the diversity of annual plant species.[26] These findings on the effects of wastewater applications to wetlands have probable implications for the use of wetlands for stormwater treatment.

Despite the controversy over use of natural wetlands for stormwater treatment, it became apparent in early discussions on the subject that wetlands in urbanizing watersheds will inevitably be impacted by urbanization, even if there is no intention to use them for stormwater management. For example, the authors of a U.S. Environmental Protection Agency (USEPA) handbook on use of freshwater wetlands for stormwater management stated that the handbook was not intended to be a statement of general policy favoring the use of wetlands for runoff management, but acknowledged that some 400 communities in the Southeast were already using wetlands for this purpose.[15] Moreover, directing urban runoff away from wetlands in an effort to protect them can actually harm them. Such efforts could deprive wetlands of necessary water supplies, changing their hydrology and threatening their continued existence as wetlands.[2] In addition, where a wetland's soil substrate is subsiding, continuous sediment inputs are necessary to preserve the wetland in its current condition.[27] Directing runoff to wetlands can help to furnish nutrients that support wetland productivity.[2]

In its early years, the program focused on evaluating the feasibility of incorporating wetlands into urban runoff management schemes. Given this objective, the researchers initially viewed the issues more from an engineering perspective rather than natural science. However, in later years, an appreciation of the fact that urban runoff reaches wetlands, whether intended or not, led the researchers to shift their inquiry to more fundamental questions about the impact of urbanization on wetlands. Thereafter, the program's point of view ultimately merged natural science and engineering considerations. The information yielded by the program will, therefore, be useful to wetland and other scientists, as well as to stormwater managers.

IMPACTS OF URBANIZATION ON WETLANDS

Urbanization impacts wetlands in numerous direct and indirect ways. For example, construction reportedly impacts wetlands by causing direct habitat loss, suspended solids additions, hydrologic changes, and altered water quality.[28] Indirect impacts, including changes in hydrology, eutrophication, and sedimentation, can substantially alter wetlands in addition to direct impacts, such as drainage and filling.[29] Urbanization may affect wetlands on the landscape level, through loss of extensive areas, at the wetland complex level, through drainage or modification of some of the units in a group of closely spaced wetlands, and at the level of the individual wetland, through modification or fragmentation.[30]

Over the past several decades, it has become increasingly apparent that untreated runoff is a significant threat to the country's water quality. There has, consequently, been substantial research about the relationship between urbanization and runoff quality and quantity. However, this program focused on the impacts of runoff to wetlands themselves, and not on the effects of urbanization on runoff flowing to wetlands.

Runoff can alter four major wetland components: hydrology, water quality, soils, and biological resources.[31,32] Because impacts to individual wetland components affect the condition of others, it is difficult to distinguish between the effects of each impact or to predict the ultimate condition of a wetland component by simply aggregating the effects of individual impacts.[31,33] Moreover, processes within wetlands interact in complex ways. For example, wetland chemical, physical, and biological processes interact to influence the retention, transformation, and release of a large variety of substances in wetlands. Increased peak flows transport more sediment to wetlands that, in turn, may alter the wetlands' vegetation communities and impact animal species dependent on the vegetation.

SOURCES OF IMPACTS TO WETLANDS

Brief consideration of how urbanization affects runoff illustrates the potential for dramatic alteration of wetlands. Hydrologic change is the most visible impact of urbanization. Hydrology concerns the quantity, duration, rates, frequency, and other properties of water flow. It has been called the linchpin of wetland conditions because of its central role in maintaining specific wetland types and processes.[34,35] Moreover, impacts on water quality and other wetland components, to a considerable degree, are a function of hydrologic changes.[36]

Of all land uses, urbanization has the greatest ability to alter hydrology. Urbanization typically increases runoff peak flows and total flow volumes and damages water quality and aesthetic values. For example, one study comparing a rural and an urban stream found that the urban stream had a more rapidly rising and falling hydrograph, and exhibited greater bed scouring and suspended solids concentrations.[37]

Pollutants reach wetlands mainly through runoff.[38,39] Urbanized watersheds generate large amounts of pollutants, including eroded soil from construction sites, toxic metals and petroleum wastes from roadways and industrial and commercial areas, and nutrients and bacteria from residential areas. By volume, sediment is the most important nonpoint pollutant.[39] At the same time that urbanization produces larger quantities of pollutants, it reduces water infiltration capacity, yielding more surface runoff. Pollutants from urban land uses, therefore, are more vulnerable to transport by surface runoff than pollutants from other land uses. Increased surface runoff combined with disturbed soils can accelerate the scouring of sediments and the transport and deposition of sediments in wetlands.[11,40] Thus, there is an intimate connection between runoff pollution and hydrology.

INFLUENCE OF WETLAND AND WATERSHED CHARACTERISTICS ON IMPACTS TO WETLANDS

Watershed and wetland characteristics both influence how urbanization affects wetlands. For example, impacts of highways on wetlands are affected by such factors as highway location and design, watershed vulnerability to erosion, wetland flushing capacity, basin morphology, sensitivity of wetland biota, and wetland recovery capacity.[41] Regional storm patterns also have a significant influence on impacts to wetlands.[31] Hydrologic impacts are affected by such factors as watershed land uses; wetland to watershed area ratios; and wetland soils, bathymetry, vegetation, and inlet and outlet conditions.[31,42]

Clearly, an assessment of the impacts of urbanization on a wetland should take into account the landscape in which the wetland is located. Some have suggested that a landscape approach might be useful for evaluating the effect of cumulative impacts on a wetland's water quality function.[43] The rationale for such an approach is that most watersheds contain more than one wetland, and the influence of a particular wetland on water quality depends both on the types of the other wetlands present and their positions in the landscape.

HYDROLOGIC IMPACTS

The direct impacts of hydrologic changes on wetlands are likely to be far more dramatic, especially over the short term, than other impacts. Hydrologic changes can have large and immediate effects on a wetland's physical condition, including the depth, duration, and frequency of inundation of the wetland. It is fair to say that changes in hydrology caused by urbanization can exert complete control over a wetland's existence and characteristics. One study, using the Surface Water Management Model (SWMM), predicted that urbanization bordering a swamp forest would increase runoff volumes by 4.2 times.[44] Greater surface runoff is also likely to increase velocities of inflow to wetlands, which can disturb wetland biota and scour wetland substrates.[39] Increased amounts of stormwater runoff in wetlands can alter water level response times, depths, and duration of water detention.[31] Reduction of watershed infiltration capacity is likely to cause wetland water depths to rise more rapidly following storm events. Diminished infiltration in wetland watersheds can also reduce stream baseflows and groundwater supplies to wetlands, lengthening dry periods and impacting species dependent on the water column.[15,45]

WATER QUALITY IMPACTS

Direct Water Quality Impacts

Prior to the PSWSMRP study, there was very little information specifically covering the impacts of urban runoff on water quality within wetlands.[39] On the other hand, there have been extensive inquiries into the effects of urbanization on runoff and receiving water quality generally.[122] Much of this information undoubtedly is suggestive of the probable effects of urban runoff on wetland water quality. There have also been numerous "before and after" studies evaluating the effectiveness of wetlands for treatment of municipal wastewater and urban runoff.[3,4,10,12,20,46-51] Many of these studies have focused on the effectiveness of wetlands for water treatment rather than on the potential for such schemes to harm wetland water quality.

Nevertheless, data on the quality of inflow to and pollutant retention by wetlands are likely to give some indication of the effects of urban runoff on wetland water quality. Studies on the effects of wastewater and runoff on other wetland components, such as vegetation, also may provide indirect evidence of impacts on wetland water quality.[22,24-26,52-57] A number of researchers have warned of the risks of degradation of wetland water quality and other values from intentional routing of runoff through wetlands.[3,10-12,14,58] Subsequent sections in this monograph describe the results of water quality impact studies performed by the program.

Hydrologic Impacts on Water Quality

Hydrology influences how water quality changes will impact wetlands. Hydrologic changes can make a wetland more vulnerable to pollution.[59] Increased water depths or frequencies of flooding can distribute pollutants more widely through a wetland.[39] How wetlands retain sediment is directly related to flow characteristics, including degree and pattern of channelization, flow velocities, and storm surges.[10] Toxic materials can accumulate more readily in quiescent wetlands.[60] A study on use of wetlands for stormwater treatment found that wetlands with a sheet flow pattern retained more phosphorus, nitrogen, suspended solids, and organic carbon than channelized systems, which were found to be ineffective.[50]

Changes in hydroperiod can also affect nutrient transformations and availability and the deposition and flux of organic materials.[36,61] One study observed higher phosphorus concentrations in stagnant than in flowing water.[62] In wetland soils, the advent of anaerobic conditions can transform phosphorus to dissolved forms.[31] Another study reported that anaerobic conditions in flooded emergent wetlands increased nutrient availability to wetland plants, compared to infrequently flooded sites.[63]

IMPACTS TO WETLAND SOILS

Hydrologic Impacts to Wetland Soils

Flow characteristics within wetlands directly influence the rate and degree of sedimentation of solids imported by runoff.[22] If unchecked, excessive sedimentation can alter wetland topography and soils, and, ultimately result in the filling of wetlands. Alternatively, elevated flows can scour a wetland's substrate, changing soil composition, and leading to a more channelized flow.[40] Materials accumulated over several hundred years could, therefore, be lost in a matter of decades.[64]

Water Quality Impacts to Wetland Soils

The physical, chemical, and biological characteristics of wetland soils change as they are subjected to urban runoff.[31] The physical effects of runoff on wetland soils, including changes in texture, particle size distributions, and degree of saturation are not well documented.[31] However, a wetland's soil can be expected to acquire the physical characteristics of the sediments retained by the wetland.

Suspended matter has a strong tendency to absorb and adsorb other pollutants.[39] Sedimentation, therefore, is a major mechanism of pollutant removal in wetlands.[3,14] Chemical property changes in wetland soils typically reflect sedimentation patterns.[65,66] Materials are often absorbed by wetland soils after entering a wetland, as well.[67]

When nutrient inputs to wetlands rise, temporary or long-term storage of nutrients in ecosystem components, including soils, can increase.[23] Rates of nutrient transfer among ecosystem components and flow through the system may also accelerate. When chlorinated wastewater was sprayed onto a freshwater tidal marsh, surface litter accumulated nitrogen and phosphorus.[26] However, although wetland soils can retain nutrients, a change of conditions, such as the advent of anaerobiosis and changed redox potential, can transform stored pollutants from solid to dissolved forms, facilitating export from the soil.[31] The capacity of wetland soils to retain phosphorus becomes saturated over time.[68-70] If the soil becomes saturated with phosphorus, release is likely.

Wetland soils can also trap toxic materials, such as metals.[31] High toxic metals accumulations have been found in inlet zones of wetlands affected by urban runoff.[71] One study observed increased sediment metals concentrations in several locations in a wetland receiving wastewater.[56] The quantity of metals that a wetland can absorb without damage depends on the rate of metals accretion and degree of burial.[15] If stormwater runoff alters soil pH and redox potential, many stored toxic materials can become immediately available to biota.[72]

Water quality impacts on wetland soils can eventually threaten a wetland's existence. Where sediment inputs exceed rates of sediment export and soil consolidation, a wetland will gradually become filled. Filling by sediment is a particular concern for wetlands in urbanizing areas.[39] Many wetlands have an ability to retain large amounts of sediment. For example, it was reported that a wetland captured 94% of suspended solids from stormwater.[4] Other scientists observed that a stormwater treatment wetland lost 18% of permanent storage volume and 5% of total storage volume because of high rates of solids retention.[51]

IMPACTS TO VEGETATION

Impacts on wetland hydrology and water quality can, in turn, affect wetland vegetation. Emergent zones in Pacific Northwest wetlands receiving urban runoff are dominated by an opportunistic grass species, *Phalaris arundinacea*, while nonimpacted wetlands contain more diverse groupings of species.[73] Marked changes in community structure, vegetation dynamics, and plant tissue element concentrations were observed in New Jersey Pine Barrens swamps receiving direct storm sewer inputs, compared to swamps receiving less direct runoff.[53] However, human impacts on wetland ecosystems can be quite subtle. For example, upon reconsidering data from two prior studies of ecological changes in wetlands, one inquiry concluded that human influences, and not natural succession, as originally believed, were the principal causes of change in the vegetation of two New England wetlands.[29]

HYDROLOGIC IMPACTS ON VEGETATION

Hydrologic changes can have significant impacts on the livelihood of the whole range of wetland flora, from bacteria to the higher plants. It was observed that microbial activity in wetland soils correlated directly to soil moisture.[47] However, surface microbial activity decreased when soils were submerged and became anaerobic.[4] To a greater or lesser degree, wetland plants are also adapted to specific hydrologic regimes. For example, the frequency and duration of flooding was documented to have determined the distribution of bottomland tree species.[74] Flood plain terraces with different flooding characteristics had distinct species compositions. Increased watershed imperviousness can cause faster runoff velocities during storms that can impact wetland biota.[39] However, as watersheds become more impervious, stream base flows and groundwater supplies can decline. As a result, dry periods in wetlands may become prolonged, impacting species dependent on the inundation.[15,45] Changes in average depths, duration, and frequency of inundation ultimately can alter the species composition of plant and animal communities.[39]

There have been numerous reports on the tolerance to flooding of wetland and non-wetland trees and plants.[75-94] While flooding can harm some wetland plant species, it promotes others.[31] There is little information available on the impacts of hydrologic changes on emergent wetland plants, although some species that can tolerate extended dry periods have been identified.[95] Hay yields in native wet meadows were reported to have increased with the length of flood irrigation if depths remained at 13 cm or less, and declined if depths stayed at 19 cm for 50 days or longer.[78]

Plant species often have specific germination requirements, and many are sensitive to flooding once established.[96] The life stage of plant species is an important determinant of their flood tolerances. While mature trees of certain species may survive flooding, the establishment of saplings could be retarded.[39] Where water levels are constantly high, wetland species may have a limited ability to migrate, and may be able to spread only through clonal processes because of seed bank dynamics.[97] The result may be reduced plant diversity in a wetland. However, anaerobic conditions can increase the availability of nutrients to wetland plants.[63]

Hydrologic impacts on individual plant species eventually translate into long-term alterations of plant communities.[15] Changes in hydroperiod can cause shifts in species composition, primary productivity, and richness.[15,72] It has been theorized that changes in hydroperiod were among the causes of a decline of indigenous plant species and an increase in exotic species in New Jersey Pine Barrens cedar swamps.[53] Early results of the PSWSMRP study indicated that wetlands with hydroperiods that fluctuated significantly between monthly high and low water levels have lower species richness than systems with lower monthly changes in water level.[45,100] (See Chapter 10, Wetland Plant Communities in Relation to Watershed Development, for the results of the PSWSMRP study on the effects of water level changes on wetland vegetation.)

In general, periodic inundation yields more plant diversity than either constantly wet or dry conditions.[98,99] Monitoring in a Cannon Beach, Oregon wastewater treatment wetland revealed little change in herbaceous and shrub plant cover after two years of operation, except in channelized and deeply flooded portions, where herbaceous cover decreased.[46] Slough sedge cover increased slightly in a shallowly flooded area. In 1986, flooding stress was observed in red alder trees in deeper parts of the wetland. In another wetland, part of which was drained and part of which was impounded to a greater depth, vegetation in the drained portion became more dense and diverse, but there was a marked decline in the number of species in the flooded portion after three years.[93]

Water Quality Impacts on Vegetation

High suspended solids inputs can reduce light penetration, dissolved oxygen, and overall wetland productivity.[39] Inflow containing high concentrations of nutrients can also promote plant growth. One study reported, for example, that in a wastewater treatment wetland, plants closer to the discharge point had greater biomass and higher concentrations of phosphorus in their tissues, and the cattails were taller.[57] When nutrient inputs to wetlands increase, they may be stored either temporarily or over the long-term in ecosystem components, including vegetation.[101] Rates of nutrient movement, by transfer among ecosystems components and through the system, may accelerate as a result.

Toxic materials in runoff can interfere with the biological processes of wetland plants, resulting in impaired growth, mortality, and changes in plant communities. The amount of metals absorbed by plants, for some species, is a function of supply. In cedar swamps in the New Jersey Pine Barrens, plants took up more lead when direct storm sewer inputs were present than when runoff was less direct.[53] The degree to which plants bioaccumulate metals is highly variable. Pickleweed (*Salicornia* sp.) was found to concentrate metals, especially zinc and cadmium, more than mixed marsh and upland grass vegetation.[52] However, plants in a brackish marsh that had received stormwater runoff for more than 20 years did not appear to concentrate copper, cadmium, lead, and zinc any more than plants in control wetlands not receiving storm water.[3]

While toxic metals accumulate in certain species, such as cattails, without causing harm, they interfere with the metabolism of other species.[39] Toxic metals can harm certain species by interfering with nitrogen fixation.[102] Metals can also impinge on photosynthesis in aquatic plants, such as waterweed (*Elodea* spp.).[103] Another study (1981) reported that roadway runoff containing toxic metals had an inhibitory effect on algae.[104] A bioassay study of the effects of stormwater on algae showed that nutrients did not stimulate growth as much as predicted because of the presence of metals in the stormwater.[105] The germination rates of wetland plants exposed to roadside snowmelt in several concentrations were found to vary inversely with the concentration of snowmelt.[54]

Pollution in wetlands may impact plant community composition the most. The major effect observed of residential and agricultural runoff with high pH and nitrate concentrations was to cause indigenous aquatic macrophytes of the New Jersey Pine Barrens to be replaced by non-native species.[55] Marked changes in plant community structure and vegetation dynamics in Pine Barrens cedar swamps were also reported where direct storm sewer inputs were present.[53] Wetland plants that were exposed to roadside snowmelt in several concentrations, showed differences in community biomass, species diversity, evenness, and richness after one month of growth that varied inversely with snowmelt concentration.[54] Impacts were not as severe where runoff was less direct.

IMPACTS TO WETLAND FAUNA

Hydrologic Impacts on Wetland Fauna

Hydrologic changes also greatly affect wetland animal communities. In two coastal marshes, animal species richness and abundance declined as hydrologic disturbance increased.[106] Shifts in plant communities as a result of hydrologic changes can have impacts on the preferred food supply and cover of such animals as waterfowl.

Increased imperviousness in wetland watersheds can reduce stream base flows and groundwater supplies, prolonging dry periods in wetlands and impacting species dependent on the water column. Many amphibians require standing water for breeding, development, and larval growth. Amphibians and reptile communities may experience changes in breeding patterns and species composition with changed water levels.[107] Because amphibians place their eggs in the water column, the eggs may be directly damaged by changes in water depth. Alterations in hydroperiod can be especially harmful to amphibian egg and larval development if water levels decline and eggs attached to emergent vegetation are exposed and desiccated.[108] Water temperature changes that accompany shifting hydrology may also impact egg development.[109]

Hydrologic changes have implications for other wetland animals, as well. Alterations to water quality and wetland soils caused by hydrologic changes may negatively affect animal species. For example, increased peak flows that accelerate sedimentation in wetlands or cause scouring can damage fish habitat.[11] Mortality of the eggs and young of waterfowl during nesting periods may rise if water depths become excessive.[31] Water level fluctuations resulting from an artificial impoundment in eastern Washington State caused a redistribution of bird populations. When potholes were flooded by the impoundment, waterfowl production was reduced, and breeding waterfowl were forced into the remaining smaller potholes.[110] Hydrologic changes may impact mammal populations in wetlands by diminishing vegetative habitat and by increasing the potential for proliferation of disease organisms and parasites as base flows become shallower and warmer.[108] Also, research has indicated a need to maintain habitat around wetlands that are receiving stormwater in order to permit free movement of animals during storm events.[31]

Water Quality Impacts to Wetland Fauna

Pollutants can have both direct and indirect effects on wetland fauna. Road runoff containing toxic metals had an inhibitory effect on zooplankton, in addition to algae.[104] A significant negative correlation between water conductivity (a general indicator of dissolved substance concentrations) and amphibian species richness was reported.[45] Aquatic organisms, particularly amphibians, readily absorb chemical contaminants.[111] Thus, the status of such organisms can be an effective indicator of a wetland's health. The degree of bioaccumulation of metals in wetland animals varies by species. In a brackish marsh that had received storm runoff for 20 years, there was no observed bioaccumulation of metals in benthic invertebrates.[112] However, a filter-feeding amphipod (*Corophium* sp.), known for its ability to store lead in an inert crystal form, accumulated significant amounts of lead. Water quality changes can indirectly harm fish and wildlife by reducing the coverage of plant species preferred for food and shelter.[35,108,113] (Please see Section III for discussions of amphibian, emergent aquatic insect, bird, and small mammal communities in relation to watershed development and habitat conditions, and for the results of the program's study on the effects of hydrologic and water quality changes on wetland animals.)

USE OF WETLANDS FOR STORMWATER TREATMENT

Impacts from intentional use of wetlands for stormwater management could be more harmful than those that would occur with incidental drainage from an urbanized watershed. For example, raising the outlet and controlling the outflow rate would, in general, change water depths and the pattern of rise and fall of water. Structural revisions to improve pollutant trapping ability would increase toxicant accumulations, in addition to the direct effects of construction. On the other hand, stormwater management actions could be linked with efforts to upgrade wetlands that are already highly damaged.

PUGET SOUND WETLANDS AND STORMWATER MANAGEMENT RESEARCH PROGRAM DESIGN

Representatives of the stormwater and resource management communities in the Puget Sound area of Washington State formed a committee in early 1986 to consider how to best resolve questions concerning wetlands and stormwater runoff. Committee members came from federal, state, and local agencies, academic institutions, and other local interests. The Resource Planning Section of the government of King County, Washington coordinated the committee's work. The committee's initial effort was to enumerate the wetland resources that are implicated in urban stormwater management decisions and to identify the general types of effects that runoff could have on these resources. The committee members also oversaw the preparation of a literature review, designed to determine the extent to which previous work could address the issues before them, and a survey of management needs.

LITERATURE REVIEW AND MANAGEMENT NEEDS SURVEY

The principal activity of the program's first year was a comprehensive literature review, which concluded with a report and an annotated bibliography covering the reported research and observations relevant to the issue of stormwater and wetlands.[114,115] The review was updated in 1991.[39] These reviews concentrated on what was known and what was not known about these issues at the time. Best known was the performance of wetlands in capturing pollutants, mostly derived from studies on their ability to provide advanced treatment to municipal wastewater effluents. Only a small body of information pertained to stormwater. The greatest shortcoming of the literature concerned the ecological impacts to wetlands created by any kind of waste stream. The literature reviews also made clear the dearth of research on any aspect of Pacific Northwest wetlands, in contrast to some other areas of the country. Many detailed aspects of the subject of stormwater and wetlands were very poorly covered, including the relative roles of hydrologic and water quality modifications in stressing wetlands and the transport and fate of numerous toxicants in wetlands.

On the basis of their discussions and the literature review, the committee members participated in a formal survey designed to identify the most important needs for reaching the goal of protecting wetlands in urban and urbanizing areas, while improving the management of urban stormwater. The survey involved rating a long list of candidate management needs with respect to certain criteria. Computer processing of the ratings led to the following list of consensus high-priority management needs:

- Definition of short- and long-term impacts of urban stormwater on palustrine wetlands;
- Management criteria by wetland type;
- Allowable runoff storage schedules that avoid or minimize negative effects on wetlands and their various functions; and
- Features critical to urban runoff water quality improvement in wetlands.

RESEARCH PROGRAM DESIGN

After completion of the literature review and management needs survey, the committee and staff assembled by King County turned to defining a research program to serve the identified needs. The program they developed included the following major components:

- Wetland survey;
- Water quality improvement study;
- Stormwater impact studies; and
- Laboratory and special field studies.

The purpose of the wetland survey was to provide a broad picture of freshwater wetlands representative of those in the Puget Sound lowlands. The survey covered 73 wetlands throughout lowland areas of King County. One important goal of the survey was to identify how urban wetlands differ from those that are lightly affected by human activity. The survey's design, results, and conclusions were published in previous reports.[73,74] The survey results assisted in designing the remainder of the research program.

The water quality improvement study was an intensive, two-year (1988–1990) effort to answer remaining questions about the water quality functioning of wetlands and is also discussed elsewhere.[116] The results from the various portions of the program were used to develop extensive guidelines for coordinated management of urban wetlands and stormwater. These guidelines were continuously updated and refined as more information became available.

WETLANDS IMPACTED BY URBANIZATION IN THE PUGET SOUND BASIN

The research program focused primarily on palustrine wetlands because urbanization in the Puget Sound region is impacting this wetland type more than other types. Palustrine wetlands are freshwater systems in headwater areas or isolated from other water bodies.[117] They typically contain a combination of water and vegetation zones. Some palustrine wetlands consist of open water with only submerged or floating plants, or with no vegetation. Others include shallow or deep marsh zones containing herbaceous emergent plants, shrub-scrub vegetation, and sometimes forested plant communities.

Two “poor fens” being impacted by urban development were also monitored during the study. Poor fens, commonly confused with true bogs, are a special wetland type that is of considerable interest in northern regions. Under natural conditions, water supply to poor fens consists only of precipitation and groundwater. The lack of surface water inflow restricts nutrient availability, resulting in a relatively unusual plant community adapted to low nutrition and the attendant acidic conditions. Such a community is vulnerable to increased nutrient supply and buffering by surface water additions.

STORMWATER IMPACT STUDIES

The stormwater impact studies formed the core of the program. This field research was supplemented by the laboratory and special field studies, which allowed investigation of certain specific questions under more control than offered by the broader field studies. A special effort was made to ensure that research was conducted according to sound scientific design, so that the results and their application in management would be defensible. In order to approximate the classic “before and after, control and treatment” experimental design approach, the impact study included “control” and “treatment” wetlands. Nineteen wetlands were included in the stormwater impact study, with approximately half the treatment sites and the remainder of the control sites (general locations are shown in Figure 1).

The treatment wetlands, located in areas undergoing urban development during the course of the study, were monitored before, during, and after urbanization. The goals of studying these wetlands were to characterize preexisting conditions and to assess the consequences of any changes accompanying urbanization and modification of stormwater inflow. The use of control sites was intended to make it possible to judge whether observed changes in treatment wetlands were the result of urbanization or of broader environmental conditions affecting all wetlands in the region. Control wetlands were paired with treatment sites on the basis of size, water and plant zone configuration, and vegetation habitat classifications.

Not all of the treatment watersheds developed as much as anticipated at the outset of the study. Only six watersheds developed 10% or more than the developed area at the start of the study. Of these six, only three wetlands had significant increases in watershed development of 100, 73, and 42% with the remaining three having increases of only 10.5, 10.3, and 10.2%. Fortunately, watersheds of most of the control wetlands were characterized by relative stability in land use during the study.

The unexpected slowness of development in the study watersheds affected our ability to identify differences between control and treatment pairs attributable to stormwater and urbanization. Also, the watersheds of control wetlands ranged from no urbanization to relatively high levels so no comparisons could be made unless the matched treatment wetland underwent significant urbanization in the watershed.

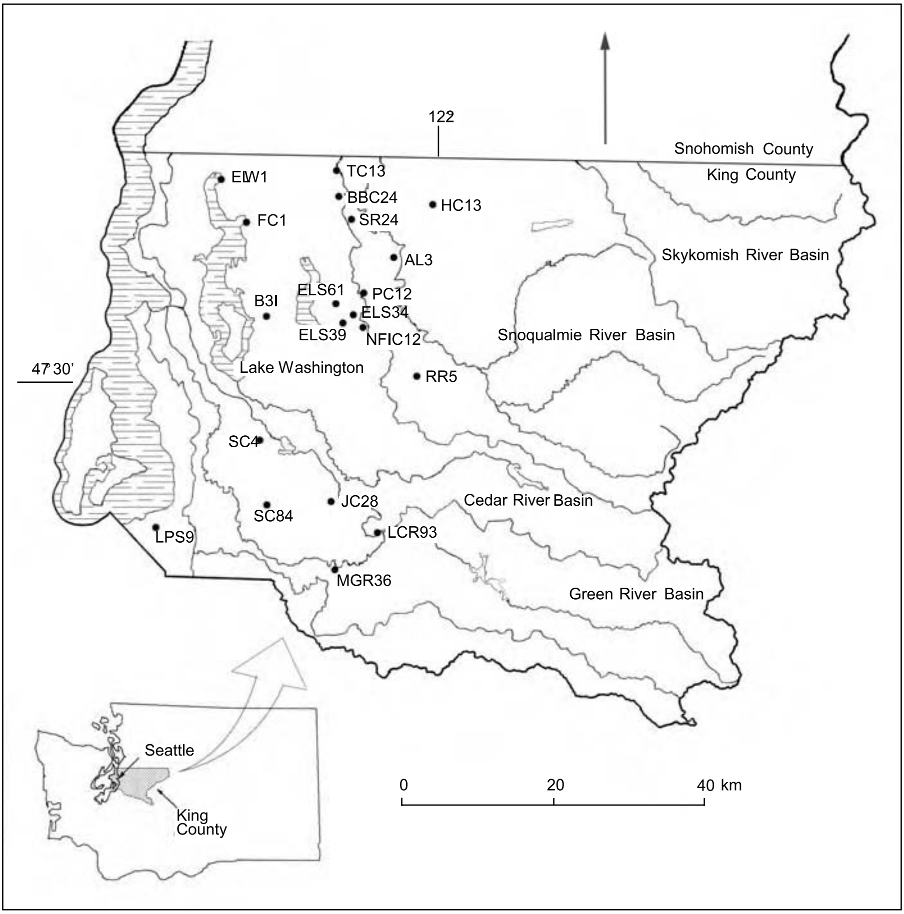


FIGURE 1 Puget Sound Wetlands and Stormwater Management Research Program study locations.

Under the circumstances, the plan to compare control and treatment pairs of wetlands was abandoned and revisions to the categories for data analyses were made.

Several categories of wetlands related to land use and watershed changes were used in the program's analyses and are shown in Table 1. Wetlands are identified as a control or a treatment wetland and land uses present in the watersheds of the wetlands at the start and completion of the study are listed. The table also lists watershed area, wetland area, and a categorization of wetland morphology.

Because the program was interested in long-term as well as short-term effects, the monitoring of impacts was continued for eight years. Research in 1988 and 1989 generally provided the baseline data for the treatment wetlands. Data from 1990 reflected the early phase of urbanization in these wetlands. Monitoring resumed in 1993, shortly after a phase of building in the watersheds ended. Monitoring in 1995 was intended to document effects that took longer to appear.

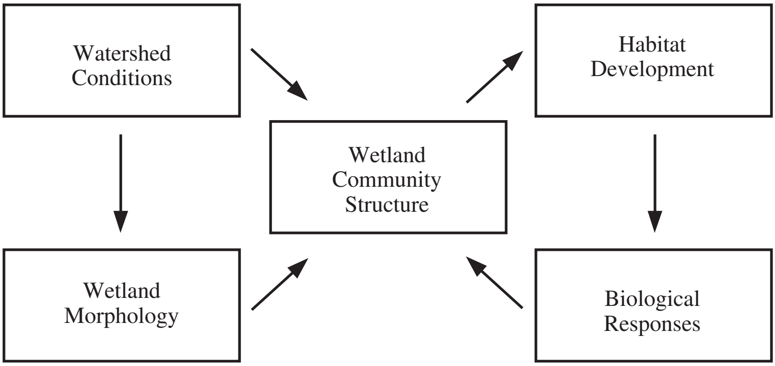
TABLE 1
Landscape Data for Study Wetlands

Site	Watershed Area (ha)	Wetland Area (ha)	Wetland Type OW = open water FT = flow through	Treatment (T) or Control (C)	Land Use Treatment and Controls[a]	Urbanization Category[b]	% Urban Cover			% Forest Cover			% Impervious Cover		
							1989	1995	Change	1989	1995	Change	1989	1995	Change
AL3	47.35	0.81	OW	C	RC	N	13.3	13.3	0.0	73.9	73.9	0.0	4.1	4.1	0.0
B3I	183.73	1.98	FT	C	UC	H	74.7	75.2	0.5	0.0	0.0	0.0	54.9	55.4	0.5
BBC24	38.45	2.10	OW	T	T	L	10.5	52.7	42.2	89.5	47.4	–42.1	3.4	10.6	7.2
ELS39	69.20	1.74	OW	T	T	M	88.8	87.9	–0.9[c]	18.5	10.8	–7.7	24.6	24.2	–0.4
ELS61	27.11	2.02	OW	T	T	M	23.9	34.4	10.5	2.5	3.7	1.2	5.1	10.6	5.5
ELW1	54.63	3.84	FT	C	UC	M	56.6	56.6	0.0	0.0	0.0	0.0	19.9	19.9	0.0
FC1	357.34	7.28	FT	C	UC	M	81.2	81.2	0.0	14.7	14.7	0.0	30.8	30.8	0.0
HC13	359.36	1.62	OW	C	RC	N	1.5	1.5	0.0	76.6	75.1	–1.5	3.6	3.6	0.0
JC28	296.64	12.55	FT	T	T	M	54.7	64.9	10.2	34.4	19.8	–14.6	20.0	20.6	0.6
LCR93	198.22	6.09	FT	C	RC	N	12.8	11.0	–1.8	44.1	13.0	–31.1	5.8	6.1	0.3
LPS9	183.32	7.69	FT	C	UC	H	69.8	73.8	4.0	0.0	0.0	0.0	21.8	21.6	–0.2
MGR36	45.73	2.23	FT	C	RC	N	4.1	4.1	0.0	88.8	88.8	0.0	2.9	2.9	0.0
NFIC12	3.24	0.61	OW	T	T	H	0.0	100.0	100.0	100.0	0.0	–100.0	2.0	40.0	38.0
PC12	84.58	1.50	OW	T	T	N	23.5	34.0	10.5	75.2	64.7	–10.5	5.1	6.8	1.7
RR5	64.35	10.52	OW	C	RC	N	2.4	2.4	0.0	62.4	62.4	0.0	3.4	3.4	0.0
SC4	3.64	1.62	FT	C	RC	M	12.5	12.5	0.0	46.1	46.1	0.0	11.8	11.8	0.0
SC84	193.04	2.83	OW	C	UC	M	77.8	78.2	0.4	20.1	19.7	–0.4	18.5	17.0	–1.5
SR24	88.22	10.12	OW	C	RC	N	0.0	0.0	0.0	100.0	100.0	0.0	2.0	2.0	0.0
TC13	11.74	2.06	OW	C	RC	N	0.0	0.0	0.0	100.0	89.7	–10.3	2.0	2.3	0.3

[a] RC = rural control (less than 12% impervious area and greater than 40% forest); UC = urban control (greater than 12% impervious area and less than 40% forest); T = treatment (wetlands that changed during the study period).

[b] Column represents watershed urbanization at start of study: N = less than 4% impervious area and greater than 40% forest; H = greater than 20% impervious area and less than 7% forest; M = watershed conditions intermediate between N and H.

[c] The watershed of ELS39 was estimated to be 15% developed in 1988 when the study began. The watershed was developed prior to the GIS analysis of 1989 and no accurate cover data is available until 1995.



Descriptives linkages, conceptual models, quantitative algorithms

FIGURE 2 Puget Sound Wetlands and Stormwater Management Research Program experimental strategy.

Figure 2 illustrates the conceptual framework of the designs of the specific sampling programs pursued in the stormwater impact study to analyze and interpret the resulting data. The two blocks on the left of the diagram represent the driving forces determining a wetland's character (Watershed Conditions and Wetland Morphology). The term "surrounding landscape" signifies that not only a wetland's watershed (the area that is hydrologically contributory to the wetland) but also adjacent land outside of its watershed can influence the wetland. The surroundings include the wetland buffer, corridors for wildlife passage, and upland areas that provide for the needs of some wetland animals. Wetland morphology refers to form and structure and embraces shape, dimensions, topography, inlet and outlet configurations, and water pooling and flow patterns.

The central block (Wetland Community Structure) represents the physical and chemical conditions that develop within a wetland and constitute a basis for its structure. Included are both quantity and quality aspects of its water supply and its soil system. Together, these structural elements develop various habitats that can provide for living organisms, represented by the block at the upper right of the diagram. Biota will respond depending on habitat attributes, as illustrated by the block at the lower right. It is a fundamental goal of the Puget Sound Wetlands and Stormwater Management Research Program to describe these system components for the representative wetlands individually and collectively.

Connecting lines and arrows on Figure 2 depict the interactions among the components. It is a second fundamental goal of the program to understand and be able to express these interactions, to advance wetlands science and the management of urban wetlands and stormwater. Expression could come in the form of qualitative descriptions, relatively simple conceptual models, or more comprehensive mathematical algorithms. The extent to which definition of these interactions can be developed will determine the thoroughness with which management guidelines and new scientific knowledge can be generated by this research program.