WETLANDS AND URBANIZATION

Implications for the Future

Final Report of the Puget Sound Wetlands and Stormwater Management Research Program

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Edited by Amanda L. Azous and Richard R. Horner

Washington State Department of Ecology, Olympia, WA.
King County Water and Land Resources Division
and the
University of Washington, Seattle, WA.

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by Richard R. Horner

INTRODUCTION

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

This overview paper 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. The paper concludes by outlining the general experimental design of the study. Subsequent papers present the specific methods used in the various monitoring activities.

THE ISSUES

The PSWSMRP 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 (see Athanas 1988 and McArthur 1989 for discussion of the use of wetlands for runoff quantity control). 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 Athanas 1988, Chan et al. 1981, Hickok 1980, Lakatos and McNemar 1988, Livingston 1988, and McArthur 1989 for discussion of the use of wetlands for runoff quality control).

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 (Office of Technology Assessment 1984, Zedler and Kentula 1986). Resource managers further contended that using wetlands for stormwater management could damage their other functions (Livingston 1988; Newton 1989; Brown 1985; Canning 1988; ABAG 1986). They noted the general lack of information on the types and extent of impacts to wetlands used for stormwater treatment (Chan et al. 1981; Brown 1985; ABAG 1986; Canning 1988; Woodward-Clyde Consultants 1991).

Several researchers have suggested that findings about the impacts of municipal wastewater treatment in wetlands are relevant to stormwater treatment in wetlands (Chan et al. 1981; Silverman 1983). In some cases, wastewater treatment in wetlands has caused severe ecological disruptions (US EPA 1985), particularly when wastewater delivery is uncontrolled (Wentz 1987). 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 (Benforado 1981; Guntspergen and Stearns 1981; Sloey, Spangler, and Fetter 1978; Dawson 1989).

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 (Heliotis 1982; Brennan 1985). Wastewater treatment in natural northern wetlands tended to promote the dominance of cattails (Typha sp.) (R. H. Kadlec 1987). 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 (Stark and Brown 1988). Thirty years of effluent discharge to a peat bog caused parts of the bog to become monoculture cattail marsh (Bevis and Kadlec 1978). Application of chlorinated wastewater to a freshwater tidal marsh reduced the diversity of annual plant species (Whigham, Simpson, and Lee 1980). 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 (US EPA) handbook on use of freshwater wetlands for stormwater management (US EPA 1985) 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. 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 (McArthur 1989) and threatening their continued existence as wetlands. In addition, where a wetland’s soil substrate is subsiding, continuous sediment inputs are necessary to preserve the wetland in its current condition (Boto and Patrick 1978). Directing runoff to wetlands can help to furnish nutrients that support wetland productivity (McArthur 1989).

In its early years, the PSWSMRP 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 than a natural science perspective. 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 (Darnell 1976). Indirect impacts, including changes in hydrology, eutrophication, and sedimentation, can alter wetlands more than direct impacts, such as drainage and filling (Keddy 1983). 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 (Weller 1988). Over the past several decades, it has become increasingly apparent that untreated runoff is the primary threat to the country's water quality. There has, consequently, been substantial research about the relationship between urbanization and runoff quality and quantity. However, the PSWSMRP focused primarily on the impacts of runoff on 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 (US EPA 1993; Johnson and Dean 1987). Because impacts to wetland components are not distinct from one another but interact (US EPA 1993), 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 (Hemond and Benoit 1988). 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 (Gosselink and Turner 1978) because of its central role in maintaining specific wetland types and processes (Mitsch and Gosselink 1993). Moreover, impacts on water quality and other wetland components are, to a considerable degree, a function of hydrologic changes (Leopold 1968). 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 (Pedersen 1981).

Pollutants reach wetlands mainly through runoff (PSWQA 1986; Stockdale 1991). 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 (Stockdale 1991). 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 are, therefore, 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 (Loucks 1989; Canning 1988). 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 (Adamus and Stockwell 1983). Regional storm patterns also have a significant influence on impacts to wetlands (US EPA 1993). Hydrologic impacts are affected by such factors as watershed land uses; wetland to watershed areal ratios; and wetland soils, bathymetry, vegetation, and inlet and outlet conditions (Reinelt and Horner 1990; US EPA 1993). It is apparent that any assessment of the impacts of urbanization on a wetland should take into account the landscape in which the wetland is located. Whigham, Chitterling, and Palmer (1988), for example, suggested that a landscape approach might be useful for evaluating the effect of cumulative impacts on a wetland's water quality function. 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.

IMPACTS OF URBANIZATION ON WETLANDS

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. A SWMM model run reported by Hopkinson and Day (1980) predicted that urbanization bordering a swamp forest would increase runoff volumes by 4.2 times. Greater surface runoff is also likely to increase velocities of inflow to wetlands, which can disturb wetland biota and scour wetland substrates (Stockdale 1991). Increased amounts of stormwater runoff in wetlands can alter water level response times, depths, and duration of water detention (US EPA 1993). 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 ground water supplies to wetlands, lengthening dry periods and impacting species dependent on the water column (Azous 1991).

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 (Stockdale 1991). On the other hand, there have been extensive inquiries into the effects of urbanization on runoff and receiving water quality generally. See, e.g., US EPA 1983, summarizing the results of the Nationwide Urban Runoff Program. 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. See, e.g., ABAG 1986; Brown 1985; Chan et al. 1981; Dawson 1989;

Franklin and Frenkel 1987; Hickok et al. 1977; Hickok 1980; Lynard et al. 1980; Martin 1988; Morris et al. 1981; and Oberts and Osgood 1988. 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. See, e.g., Bevis and Kadlec 1978; Brennan 1985; Chan 1979; Ehrenfeld and Schneider 1983; Isabelle et al. 1987; Morgan and Philipp 1986; Mudrock and Capobianco 1979; Stark and Brown 1988; Tilton and Kadlec 1979; and Whigham, Simpson, and Lee 1980. 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 (see ABAG 1986; Brown 1985; Canning 1988; Chan et al. 1981; Galvin and Moore 1982; and Silverman 1983). Subsequent papers in this monograph describe the results of water quality impact studies performed by the program.

Hydrological Impacts on Water Quality -- Hydrology influences how water quality changes will impact wetlands. Hydrologic changes can make a wetland more vulnerable to pollution (Harrill 1985). Increased water depths or frequencies of flooding can distribute pollutants more widely through a wetland (Stockdale 1991). How wetlands retain sediment is directly related to flow characteristics, including degree and pattern of channelization, flow velocities, and storm surges (Brown 1985). Toxic materials can accumulate more readily in quiescent wetlands (Oberts 1977). In a study on use of wetlands for stormwater treatment, Morris et al. (1981) found that wetlands with a sheet flow pattern retained more phosphorus, nitrogen, suspended solids, and organic carbon than channelized systems, which were ineffective.

Changes in hydroperiod can also affect nutrient transformations and availability (Hammer 1992) and the deposition and flux of organic materials (Livingston 1989). Fries (1986) observed higher phosphorus concentrations in stagnant than in flowing water. In wetland soils, the advent of anaerobic conditions can transform phosphorus to dissolved forms (US EPA 1993). Lyon et al. (1987) reported that anaerobic conditions in flooded emergent wetlands increased nutrient availability to wetland plants, compared to infrequently flooded sites.

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 (Brown 1985). 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 (Loucks 1989), changing soil composition, and leading to more channelized flow. Materials accumulated over several hundred years could, therefore, be lost in a matter of decades (Brinson 1988).

Water Quality Impacts to Wetland Soils -- The physical, chemical, and biological characteristics of wetland soils change as they are subjected to urban runoff (US EPA 1993). The physical effects of runoff on wetland soils, including changes in texture, particle sizes distributions, and degree of saturation are not well documented (US EPA

1993). 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 (Stockdale 1991). Sedimentation, therefore, is a major mechanism of pollutant removal in wetlands (Chan et al. 1981; Silverman 1983). Chemical property changes in wetland soils typically reflect sedimentation patterns (ABAG 1979; Schiffer 1989). Materials are often absorbed by wetland soils after entering a wetland, as well (Richardson 1989).

When nutrient inputs to wetlands rise, temporary or long-term storage of nutrients in ecosystem components, including soils, can increase (J.A. Kadlec 1987). 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 (Whigham, Simpson, and Lee 1980). 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. (US EPA 1993). The capacity of wetland soils to retain phosphorus becomes saturated over time (Richardson 1985; Nichols 1983; R.W. Beck and Associates 1985). If the soil becomes saturated with phosphorus, release is likely.

Wetland soils can also trap toxic materials, such as metals (US EPA 1993). Horner (1988) found that there were high toxic metals accumulations in inlet zones of wetlands affected by urban runoff. Mudrock and Copobianco (1979) observed increased sediment metals concentrations in several locations in a wetland receiving wastewater. The quantity of metals that a wetland can absorb without damage depends on the rate of metals accretion and degree of burial (US EPA 1985). If stormwater runoff alters soil pH and redox potential, many stored toxic materials can become immediately available to biota (Cooke 1991).

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 (Stockdale 1991). Many wetlands have an ability to retain large amounts of sediment. For example, Hickok (1980) reported that a wetland captured 94% of suspended solids from stormwater. Oberts and Osgood (1988) 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.

Impacts to Vegetation

Impacts on wetland hydrology and water quality can, in turn, affect wetland vegetation. Horner (1988) stated that emergent zones in Pacific Northwest wetlands receiving urban runoff are dominated by an opportunistic grass species, Phalaris arundinaceae, while non-impacted wetlands contain more diverse groupings of species. Ehrenfeld and Schneider (1983) observed marked changes in community structure, vegetation dynamics, and plant tissue element concentrations in New Jersey Pine Barrens swamps receiving direct storm sewer inputs, compared to swamps receiving less direct runoff. However, human impacts on wetland ecosystems can be quite subtle. For example, Keddy (1983), upon reconsidering data from two prior studies of ecological changes in wetlands, 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.

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. Hickok et al. (1977) observed that microbial activity in wetland soils correlated directly to soil moisture. However, surface microbial activity decreased when soils were submerged and became anaerobic (Hickok 1980). To a greater or lesser degree, wetland plants are adapted to specific hydrologic regimes. For example, Bedinger (1978) observed that frequency and duration of flooding determined the distribution of bottomland tree species. 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 (Stockdale 1991). 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 (Azous 1991; US EPA 1985). Changes in average depths, duration, and frequency of inundation ultimately can alter the species composition of plant and animal communities (Stockdale 1991).

There have been numerous reports on the tolerance to flooding of wetland and non-wetland trees and plants. See, e.g., Green (1947); Brink (1954); Ahlgren and Hansen (1957); Rumberg and Sawyer (1965); Minore (1968); Gill (1970); Cochran (1972); Teskey and Hinckley (1977a, b, c, d); Bedinger (1978); Whitlow and Harris (1979); Davis and Brinson (1980); Walters et al. (1980); McKnight et al. (1981); Chapman et al. (1982); Jackson and Drew (1984); Kozlowski (1984); Thibodeau and Nickerson (1985); and Gunderson, Stenberg, and Herndon (1988). While flooding can harm some wetland plant species, it promotes others (US EPA 1993). There is little information available on the impacts of hydrologic changes on emergent wetland plants, although Kadlec (1962) identified several species that can tolerate extended dry periods. Rumberg and Sawyer (1965) reported that hay yields in native wet meadows 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.

Plant species often have specific germination requirements, and many are sensitive to flooding once established (Niering 1989). 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 (Stockdale 1991). 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 (van der Valk 1991). The result may be reduced plant diversity in a wetland. However, anaerobic conditions can increase the availability of nutrients to wetland plants (Lyon, Drobney, and Olsen 1986).

Hydrologic impacts on individual plant species eventually translate into long-term alterations of plant communities (US EPA 1985). Changes in hydroperiod can cause shifts in species composition, primary productivity (US EPA 1985), and richness (Cooke 1991). Ehrenfeld and Schneider (1983) theorized that changes in hydrology were among the causes of a decline of indigenous plant species and an increase in exotic species in New Jersey Pine Barrens cedar swamps. In general, periodic inundation yields more plant diversity than either constantly wet or dry conditions (Conner et al. 1981; Gomez and Day 1982). However, early results of the PSWSMRP indicated that wetlands with wider water level fluctuations have lower species richness than systems with lower water level fluctuations (Azous 1991, Cooke and Azous 1992). 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 (Franklin and Frenkel 1987). 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. Thibodeau and Nickerson (1985) examined a 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.

Please see Hydrologic Effects on Vegetation Communities, later in this volume, for the results of the PSWSMRP study on the effects of water level changes on wetland vegetation.

Water Quality Impacts on Vegetation -- High suspended solids inputs can reduce light penetration, dissolved oxygen, and overall wetland productivity (Stockdale 1991). However, inflow containing high concentrations of nutrients can promote plant growth. Tilton and Kadlec (1979) 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. When nutrient inputs to wetlands increase, they may be stored either temporarily or over the long-term in ecosystem components, including vegetation (J.A. Kadlec 1987). Rates of nutrient movement, by transfer among ecosystems components and through the system, may accelerate.

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 is, for some species, a function of supply. Ehrenfeld and Schneider (1983) reported that, 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. The degree to which plants bioaccumulate metals is highly variable. Chan (1979) stated that pickleweed (Salicornia sp.) concentrated metals, especially zinc and cadmium, more than mixed marsh and upland grass vegetation. 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 (Chan et al. 1981).

While toxic metals accumulate in certain species, such as cattails, without causing harm, they interfere with the metabolism of other species (Stockdale 1991). Toxic metals can harm certain species by interfering with nitrogen fixation (Wickcliff et al. 1980). Metals can also impinge on photosynthesis in aquatic plants, such as water weed (Elide sp.) (Brown and Rattigan 1979). Portele (1981) reported that roadway runoff containing toxic metals had an inhibitory effect on algae. Marshall (1980) found in a bioassay study of the effects of stormwater on algae, that nutrients did not stimulate growth as much as predicted because of the presence of metals in the stormwater. Isabelle et al. (1987) found that the germination rates of wetland plants exposed to roadside snow melt in several concentrations varied inversely with snow melt concentration.

Changes in plant community composition may be the major impact of pollution in wetlands. Morgan and Phillip (1986) stated that the major effect 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. Ehrenfeld and Schneider (1983) also reported marked changes in plant community structure and vegetation dynamics in Pine Barrens cedar swamps where direct storm sewer inputs were present. Isabelle et al. (1987) found that, where wetland plants had been exposed to roadside snow melt in several concentrations, community biomass, species diversity, evenness, and richness after one month of growth varied inversely with snow melt concentration. Impacts were not as severe where runoff was less direct.

Impacts to Wetland Fauna

Hydrologic Impacts on Wetland Fauna -- Hydrologic changes can have as great an effect on wetland animal as on plant communities. Nordby and Zedler (1991) reported that, in two coastal marshes, animal species richness and abundance declined as hydrologic disturbance increased. 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 (Azous 1991). 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 (Minton 1968 in Azous 1991). Because amphibians place their eggs in the water column, the eggs may be directly damaged by changes in water depth. Alterations in hydroperiods can be especially harmful to amphibian egg and larval development if water levels decline and eggs attached to emergent vegetation are exposed and desiccated (Lloyd-Evans 1989 in Azous 1991). Water temperature changes that accompany shifting hydrology may also impact egg development (Richter et al. 1991).

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 (Canning 1988). Mortality of the eggs and young of waterfowl during nesting periods may rise if water depths become excessive. (US EPA 1993). Johnsgrad (1956) reported that water level fluctuations resulting from an artificial impoundment in eastern Washington State caused a redistribution of bird populations. Flooding of potholes by the impoundment reduced waterfowl production and forced breeding waterfowl into the remaining smaller potholes. 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 (Lloyd-Evans 1989). There is concern about maintaining habitat around wetlands that are receiving stormwater in order to permit free movement of animals during storm events (US EPA 1993).

Water Quality Impacts to Wetland Fauna -- Pollutants can have both direct and indirect effects on wetland fauna. Portele (1981) reported that road runoff containing toxic metals had an inhibitory effect on zooplankton, in addition to algae. Azous (1991) reported a significant negative correlation between water conductivity, a general indicator of dissolved substance concentrations, and amphibian species richness. Aquatic organisms, particularly amphibians, readily absorb chemical contaminants (Richter and Wisseman 1990). Thus, the status of such organisms is 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 (Burstynsky 1986). 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 (Mitsch and Gosselink 1993; Weller 1987 and Lloyd-Evans 1989 in Azous 1991).

Please see the discussions of amphibian, emergent aquatic insect, bird, and small mammal communities in relation to watershed development and habitat conditions, later in this volume, for the results of the PSWSMRP 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 management needs survey.

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 (Stockdale 1986a) and an annotated bibliography (Stockdale 1986b) covering the reported research and observations relevant to the issue of stormwater and wetlands. The review was updated in 1991 (Stockdale 1991). 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 reported by Horner et al. (1988) and Horner (1989). 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. Reinelt and Horner (1995) discuss its methods and findings.

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 have been continuously updated and refined throughout the program, 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 (Cowardin et al. 1979). 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/or a forested community.

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/after, control/treatment" experimental design approach, the impact study included “control” and “treatment” wetlands. The stormwater impact study was conducted in 19 wetlands in King County, approximately half treatment and the remainder control sites. Figure 1 displays these 19 sites and four others, including three in Snohomish County to the north, where special studies were conducted.

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. Not all of the treatment watersheds developed as much as anticipated at the outset of the study. The watersheds of the control wetlands ranged from no urbanization to relatively high levels. However, the watersheds of all of these wetlands were characterized by relative stability in land use during the study. The use of control sites made 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 community types. In recognition of the imperfect matches that occur in pairing natural systems, data analyses were performed for various groupings of sites and not just with respect to paired wetlands.

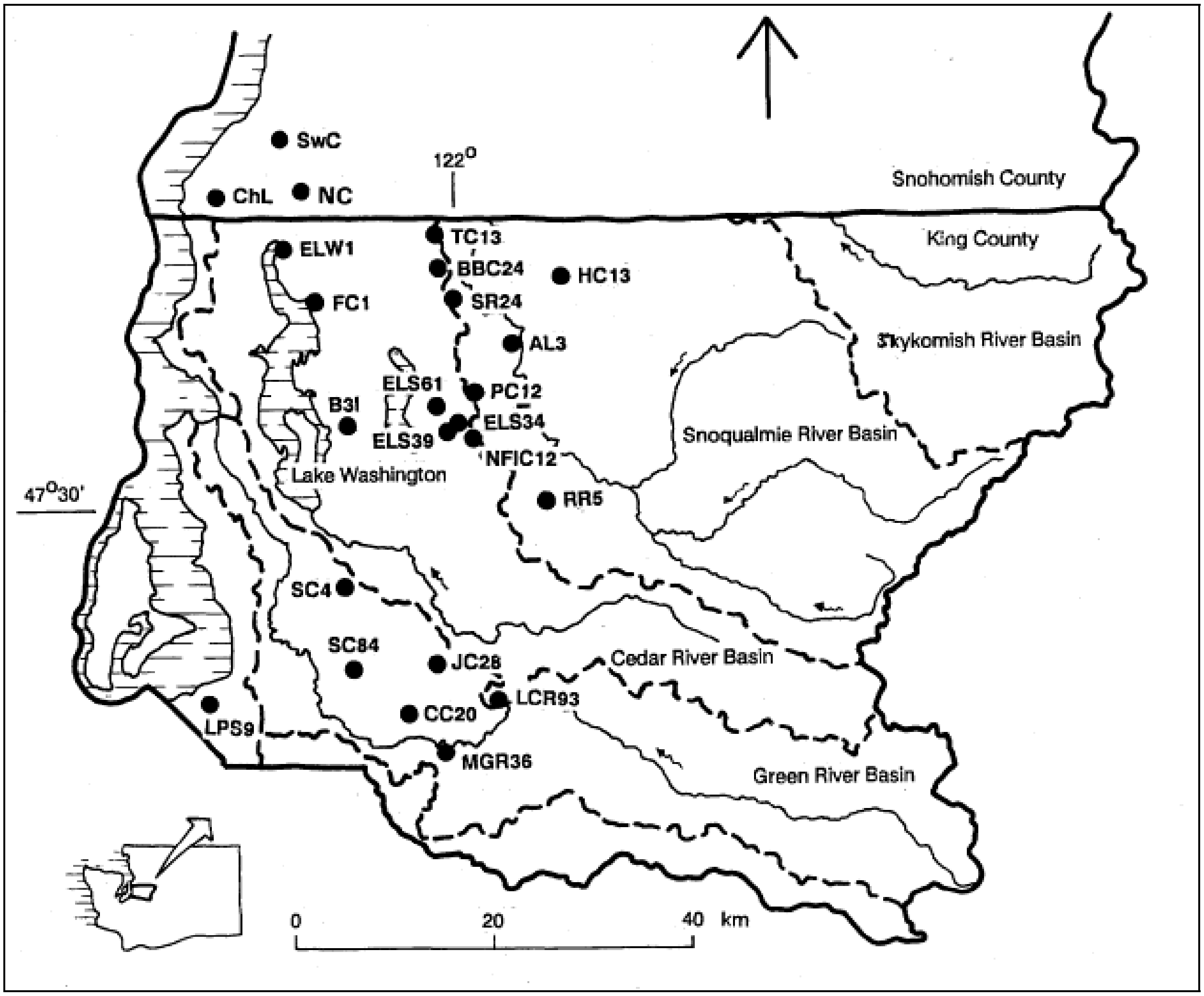

Figure 1. Puget Sound Wetlands and Stormwater Management Research Program study locations.

Because the program was interested in long-term as well as short-term effects, the impact monitoring 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, generally shortly after a phase of building in the watersheds ended. Monitoring in 1995 was intended to document effects that took longer to appear.

Figure 2 illustrates the conceptual framework of the designs of the specific sampling programs pursued in the stormwater impact study and analyzing and interpreting the resulting data. The two blocks on the left of the diagram represent the driving forces determining a wetland's character (Watershed and Surrounding Landscape 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.

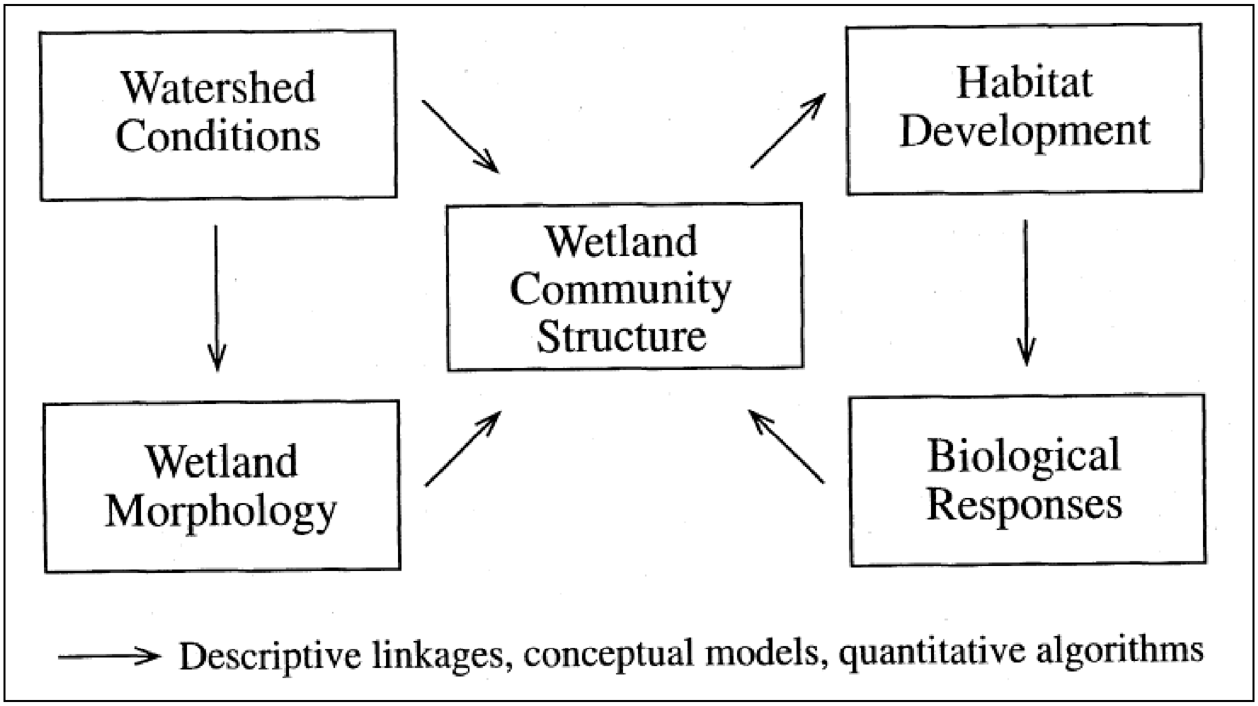

Figure 2. Puget Sound Wetlands and Stormwater Management Research Program experimental strategy.

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 left. 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, toward the ends of advancing 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.

The stormwater impact study examined the five major structural components of wetlands: (1) hydrology, (2) water quality, (3) soils, (4) plants, and (5) animals. Figure 3 presents a typical plan for monitoring of these components. A crest stage gage was used to register maximum water level since the preceding monitoring occasion, and a staff gage gave the instantaneous water level. These readings provided the basis for hydrologic analysis, as detailed in the paper on Morphology and Hydrology in Section 2.

Samples for water quality analysis were taken from the water column in an open water pool, and soil samples were collected at either three or four locations (see Water Quality and Soils in Section 2). Plant cover by species was determined along one or more transect lines, depending on wetland size and complexity of water and vegetation zones. Foliar tissue was sampled for analysis of metals content, and plant standing crop was cut for measurement of biomass gravimetrically. For more on the methods used in these monitoring activities refer to the Vegetation Community paper. Adult insect emergence was continuously monitored using triplicate emergence traps (see Emergent Aquatic Insect Community in Section 2). Amphibian breeding success was monitored along transects (labeled Herp. A, B in Figure 3). Adult amphibians as well as small mammals were live-trapped along other transects (labeled Mammal line A, B). The Section 2 papers titled Amphibian Community and Small Mammal Community elaborate on the methods. Birds were censused at one station as described by the Bird Community paper.

Definition of Watershed and Surrounding Landscape Characteristics

Essential to understanding the relationships between urban stormwater discharge and wetlands ecology was definition of the characteristics of wetland watersheds and surrounding landscapes. Each land use includes distinctive features, such as imperviousness and vegetative cover, that directly affect wetland conditions (Taylor 1993). Use of geographical information in the analysis of the effects of urbanization on wetlands allows the linking of effects with specific land use changes associated with urban development.

To this end, the program used a geographical information system (GIS) to inventory land uses in the watersheds of the study wetlands (Taylor 1993) (see Table 1). The GIS furnished quantitative and graphical representations of land use patterns. Study sites were located on U.S. Geographical Survey 7.5 minute series topographic maps

and the maps were used to locate wetland and watershed boundaries. Aerial photographs from 1989 were digitized into a computer data base and used to delineate wetland boundaries on the basis of wetland vegetation and open water. Land uses were classified according to a standard land use classification scheme. The GIS provided the areas of watersheds, wetlands, and land uses. These data were expressed in three ways: (1) wetland and watershed areas in hectares; (2) watershed land uses and vegetative cover as percentages of watershed areas; and (3) ratios of the areas of watersheds, land uses, and vegetative cover to wetland areas. The most important quantities yielded by the third method were the ratios of watershed and wetland areas (wetland areas were subtracted from their watershed areas in calculating these ratios). The method also was used to determine the ratios of impervious and forested areas to wetland areas. The 1989 GIS data were updated through manual examination of 1995 aerial photographs. In addition, in 1996, the same information was developed for 1000-meter wide bands of the surrounding landscapes using 1995 satellite images.

With regard to calculating watershed imperviousness, the program found that the relevant literature generally did not provide the level of detail necessary to establish the relationships between imperviousness and the land use definitions used in the GIS inventory. The program, therefore, relied on a variety of sources linking specific land uses to imperviousness levels. Estimates of imperviousness were made by using values from the literature for similar land uses (Alley and Veenhuis 1983; Prych and Ebbert 1986; Taylor 1993) and adjusting them according to best professional judgment.

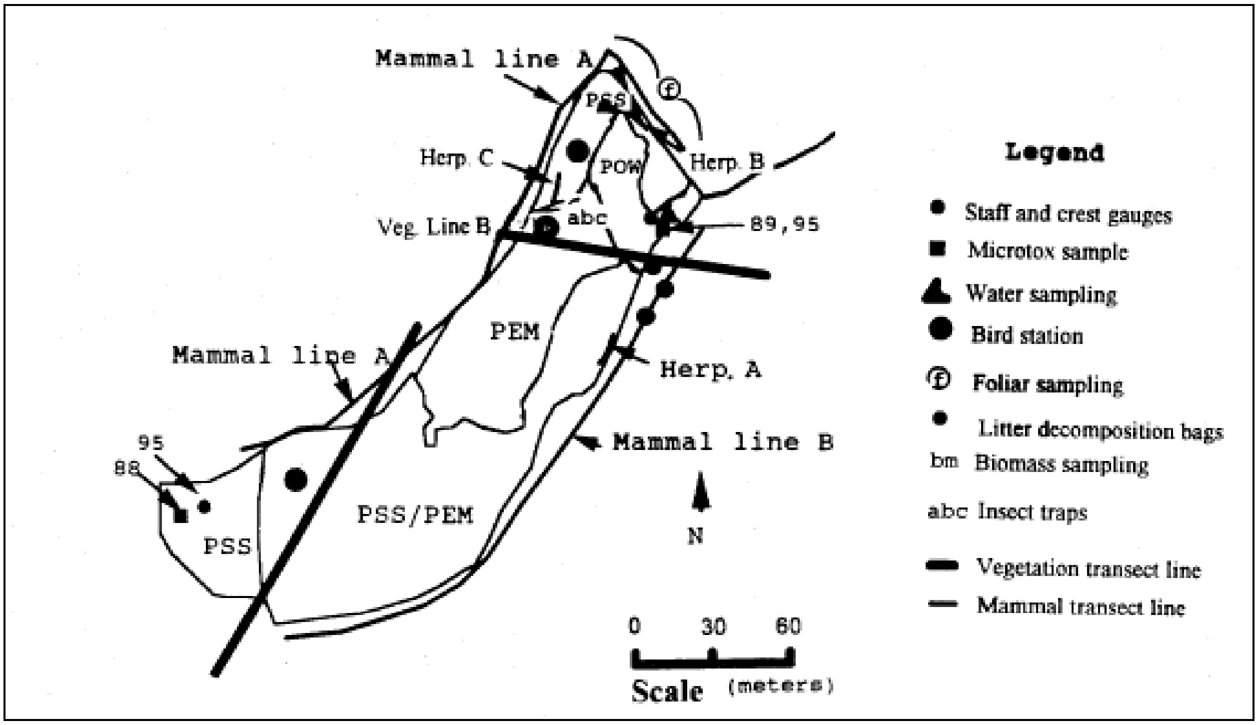

Figure 3. Typical monitoring plan (Patterson Creek 12 wetland).

Table 1. Landscape data for program wetlands.

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

a T=treatment wetlands; C=control wetlands.

b ELS39 developed was approximately 15% urban in 1988, before GIS analysis.

Effective Impervious Area (EIA) represents the impervious area that is actually connected to constructed drainage systems. This value was estimated as a proportion of Total Impervious Area (TIA) according to the formula EIA = 0.15 * TIA1.41 (Alley and Veenhuis 1983). This equation was developed in Denver and its accuracy (correlation coefficient = 0.98 and standard error = 0.075) probably varies in other areas. However, Alley and Veenhuis's estimates were compatible with those in Puget Sound lowland hydrologic models (PEI 1990; SCS 1982). After determining EIA and TIA values for each land use. EIAs for entire watersheds were determined using the formula $\mathrm{EIADB} = \Sigma 1 \rightarrow k\ (\mathrm{EIAk} * \mathrm{LUk})$, where EIADB is the percentage of watershed area that is effectively imperviousness, k corresponds to the land uses inventoried in the basin, EIAk is the percentage of watershed area associated with land use k, and LUk is the percentage of the watershed classified as land use k. TIAs were calculated using the same formula.

ORGANIZATION OF THE MONOGRAPH

The papers that follow trace the major areas of progress in filling in the conceptual framework presented in Figure 2. The first series of papers provides a descriptive ecology of the palustrine wetlands of the central Puget Sound lowlands, organized according to the major structural components monitored during the program. The next series of papers assesses the effects of urban stormwater and other influences of urbanization observed during the study. The final series makes recommendations for managing urban stormwater and the wetlands subject to it.

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