EFFECTS OF WETLANDS ON QUALITY OF RUNOFF ENTERING LAKES IN THE TWIN CITIES METROPOLITAN AREA, MINNESOTA

By R. G. Brown

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CONVERSION FACTORS

For the convenience of readers who may prefer to use inch-pound units rather than the metric (International System) units used in this report, the following conversion factors are provided.

Multiply Metric Unit	By	To obtain Inch-Pound Unit
millimeter	0.03937	inch
meter	3.281	foot
cubic meter	35.31	cubic foot
hectare	2.471	acre
milligram	0.0000352	ounce

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ABSTRACT

Four wetlands were compared with respect to their effectiveness in decreasing suspended solids and nutrient concentrations in runoff to lakes immediately downstream from the wetlands. An artificial impoundment in one of the wetlands increased settling of suspended solids. A decrease of nutrients in this wetland was probably the result of high assimilation rates associated with a dense stand of cattails.

Two of the other three wetlands consist of open water and land areas, both of which contain abundant vegetation. Drainage from land areas within the wetlands may have lowered the overall effectiveness of the wetlands in decreasing sediment and nutrient concentrations.

The third wetland was a constructed wetland that was ineffective in decreasing sediment or nutrient concentrations, because its storage capacity was too small to prevent frequent flushing of accumulated sediment. Sediment concentrations in discharge from this wetland were as much as 22 times greater than the already high sediment concentrations in the inflow.

INTRODUCTION

Background

Studies throughout the United States indicate that materials carried in runoff contribute to degradation of the quality of streams, rivers, and lakes (Federal Water Pollution Control Administration, 1969; Lager and Smith, 1974; Sliter, 1976; Bradford, 1977; Sonzogni and others, 1980). Runoff from rural and urban watersheds commonly contains high concentrations of suspended solids and nutrients that promote algal blooms and the growth of nuisance aquatic plants. These high concentrations may result in degradation of fish and other aquatic habitats. Control of pollution by runoff from nonpoint sources is expensive and various alternatives are being considered by local and State agencies.

One alternative being considered in the Twin Cities Metropolitan Area is the use of natural and constructed wetlands as treatment areas for improving quality of runoff entering lakes. Wetlands are an interface between terrestrial and aquatic systems and commonly intercept runoff before it reaches receiving waters. Constructed wetlands can function in a manner similar to natural wetlands with respect to interception of runoff, but these wetlands usually are structured like reservoirs and lack the aquatic vegetation found in natural wetlands.

A study of runoff in the Twin Cities Metropolitan Area was begun by the U.S. Geological Survey in 1979. That study focused on runoff quality and quantity problems, including the influence of wetlands. The present study is an extension of the first, and focuses on the effects of wetlands on quality of runoff entering lakes.

The efficiency of a wetland in removing suspended solids, nitrogen, and phosphorus from runoff passing through the area is unique to the individual wetland and its associated hydrologic characteristics (Spangler and others, 1977; Boto and Patrick, 1978; Van der Valk and others, 1978). The results are not readily applied to other areas such as the Twin Cities Metropolitan Area. Wetlands in the metropolitan area are most commonly classified as persistent wetlands with emergent vegetation dominated by common cattail (Typha latifolia) and are either intermittently or permanently flooded (Werth and others, 1977; Owens and Meyers, 1978). The major differences between metropolitan-area wetlands are (1) the types and extent of associated wetland vegetation (for example, bull rush, reed-canary grass, willow-alder shrub) and (2) variations in hydrologic characteristics of the wetland. Physical characteristics of constructed wetlands differ to a larger degree than those of natural wetlands, but the differences also are strongly based on vegetational composition and hydrologic characteristics. The hydrologic characteristics of constructed wetlands usually have been an engineered feature, at least in theory. Wetlands can be grouped, based on hydrologic characteristics, into two general types--permanently flooded (water table at or above land surface) and intermittently flooded (surface water trapped above the water table subsequently either enters the ground-water system or evaporates). Generally, constructed wetlands are engineered to detain runoff for short periods and to remove suspended solids by sedimentation during retention.

Purpose and Scope

The specific objective of this report is to describe the effects of wetlands on quality of runoff entering lakes in the Twin Cities Metropolitan Area. Studies were made of four wetlands (Fish Lake, Lake Elmo, Lake Riley, and Spring Lake wetlands). Samples of runoff entering and leaving the wetlands were collected in 1982 and analyzed for concentrations of suspended solids, phosphorus, and nitrogen.

Previous Investigations

Although this section provides a review of the literature on natural wetlands, it also is applicable to constructed wetlands where conditions in the constructed wetlands imitate natural wetlands. The literature on constructed wetlands is limited because the impact of these types of wetlands on nutrient inputs to lakes is specific to the design and purpose of the wetland. The differences between natural wetlands and constructed wetlands must be taken into consideration when applying results from natural wetlands to constructed wetlands.

As runoff flows through wetlands, suspended and dissolved nutrients can be retained on site by sorption and assimilation by wetland vegetation. In recent years, many authors have suggested that wetlands are indeed traps for various nutrients and suspended solids and are, as a result, important in terms of removing these constituents from runoff flowing through the wetland (Bender and Correll, 1974; Lee and others, 1975; Tourbier and Pierson, 1976; Boyt and others, 1977; Gaudet, 1977; Kadlec and Kadlec, 1978; Sloey and others, 1978; Van der Valk and others, 1978; Boto and Patrick, 1979).

Wetlands throughout the United States have been noted to decrease concentrations of suspended solids, nitrogen, and phosphorus in runoff with the rate of decrease, or efficiency, dependent on season and geographical location (Kitchens and others, 1975; Klopatek, 1975; Fetter and others, 1978; Prentki and others, 1978; Simpson and others, 1978). These studies reported that the efficiency of a wetland as a trap for suspended solids and nutrients varies considerably between sites because of the differences between the hydrologic regime, water chemistry, vegetational composition, basin morphology, and substrate of the wetlands studied (Lee and others, 1976; Sloey and others, 1978; Van der Valk and others, 1978; Boto and Patrick, 1979).

Suspended-Solids Removal

Retention of suspended solids in wetlands is directly related to flow characteristics in the particular wetland. As flow velocity decreases in a wetland, sedimentation increases (Boto and Patrick, 1978). The velocity decrease, along with the presence of vegetation, promotes fallout of suspended solids. However, discussion of the relative efficiency of fresh-water wetlands in promoting deposition of sediment by the "filtering" action of plants would be speculative (Boto and Patrick, 1979). Studies have indicated that soil properties of the contributing basin also are important. As the percentage of clay in the soil decreases, the sedimentation rate in wetlands increases (Paulet and others, 1972). The rates of sedimentation in wetlands differ widely according to hydrologic regimes, such as elevation of input versus output, size of the wetland, number of inputs and outputs, channel configurations, flow velocities, and storm surges. The average decrease in annual sediment load in runoff after passing through a wetland is 30 percent (Lee and others, 1976; Fetter and others, 1978; Boto and Patrick, 1979).

Nutrients Removal

The removal of nutrients in wetlands depends on both ecological and hydrological conditions found in the individual wetland (Kadlec and Kadlec, 1978; Van der Valk and others, 1978). The ecological factors affecting removal of nutrients differ with the nutrient, whereas the hydrologic characteristics generally are similar (Kadlec and Kadlec, 1978).

Nitrogen

Denitrification has been noted in wetlands (Patrick and others, 1976) and generally is cited as the major reason for removal of nitrogen from runoff in wetlands (Klopatek, 1975; Lee and others, 1975). Wetlands are ideal habitats for denitrification because (1) there are large amounts of organic carbon in the substrate, (2) the lower part of the water column is commonly anaerobic, (3) ammonia and organic forms of nitrogen entering or originating in a wetland can be converted to nitrate nitrogen, and (4) bacteria are present (Van der Valk and others, 1978). Nitrate nitrogen then either can be assimilated by plants or converted by bacteria to gaseous nitrogen. Denitrification in constructed wetlands is not well documented but may occur with the conditions enumerated above.

Dissolved nitrogen in runoff is in a highly mobile state and can be quickly removed by either denitrifcation or assimilation by emergent and submergent plants and their associated epiphytes (Klopatek, 1975; 1978; Nichols and Keeney, 1976). Epiphytes are plants that grow on and need the support of the emergent and submergent plants. Wetland vegetation is capable of using nitrogen from either the soil or water. Emergent plants obtain the bulk of their nitrogen from the soil. In contrast, epiphytes remove nitrogen directly from the water as it flows through the wetland (Allen, 1971).

Although leaching of fresh litter releases large quantities of nitrogen, possibly reducing effluent quality, older litter often acts as a nitrogen sink, improving effluent quality (Brinson, 1977). As a result of microbial activity after the initial leaching of nitrogen, the litter begins to accumulate nitrogen, commonly to higher levels than those found in fresh litter (Mason and Bryant, 1975; Davis and Van der Valk, 1978a; 1978b).

The balance between release and accumulation of nitrogen depends primarily on the hydrologic regime of the wetland. A low velocity through the wetland is essential for net accumulations of nitrogen in the litter because nitrogen is in a highly mobile state (Van der Valk and others, 1978). If the velocity is high, the wetland can be a source rather than a sink for nutrients.

Phosphorus

Removal of dissolved phosphorus by wetlands generally parallels removal of nitrogen. Dissolved phosphorus in runoff enters the wetland as either inorganic or organic phosphorus. Inorganic phosphorus (phosphate) forms insoluble complexes with several ions in the presence of oxygen, most importantly iron (Stumm and Morgan, 1970), and precipitates from the water column. Phosphate under anaerobic conditions diffuses from the substrate into the water column (Stumm and Morgan, 1970; Wetzel, 1975). This process in littoral wetlands can cause phosphate to move from the shoreline into deeper areas of the lake; therefore, littoral wetlands can become a phosphorus source instead of a trap.

Two major mechanisms for removing phosphorus from runoff in wetlands have been postulated in previous studies: (1) Precipitation or sorption of phosphorus on organic matter (Spangler and others, 1976), and (2) assimilation of phosphorus by flora and fauna (Kitchens and others, 1975). The inorganic form of phosphorus is highly mobile and quickly moves from the water into the soil and from the soil into the plants, similar to dissolved-nitrogen cycling (Correll and others, 1975; Steward and Ornes, 1975).

Dissolved phosphorus generally is removed from runoff in wetlands during the growing season and released, to some extent, in autumn and spring, depending on hydrologic and environmental conditions. Dissolved phosphorus can be released from wetlands in large quantities through leaching of litter during autumn and spring. Leaching during adverse hydrologic conditions, such as high flows, can yield such large quantities of phosphorus that the net effect of the wetland in removing phosphorus is significantly reduced. The impact of hydrologic conditions in the wetland on removal of phosphorus from runoff is similar to the impact on removal of nitrogen; both are largely dependent on water velocity and detention time (Davis and Harris, 1978).

Description of the Study Area

The Twin Cities Metropolitan Area includes Anoka, Carver, Dakota, Hennepin, Ramsey, Scott, and Washington Counties in Minnesota (fig. 1). Land use in the metropolitan area is 43 percent agricultural, 27 percent urban, 8 percent wetland, and 22 percent open space (Oberts and Jouseau, 1979). Urban growth is concentrated around the Minneapolis and St. Paul metropolitan centers, with most urbanization to the north, south, and west. Major agricultural areas are to the south and west in Dakota, Scott, and Carver Counties.

The topography is characterized by gently undulating, glaciated uplands dissected by the Mississippi, Minnesota, and St. Croix River valleys. Total relief is about 600 feet; altitudes range from less than 700 feet along the lower river reaches to more than 1,200 feet in northwestern Washington County.

The climate is one of generally mild, humid summers and relatively long, severe winters. Mean annual precipitation is 27 inches, with 44 inches of snow in winter. May and June generally are the wettest months and February the driest. Most rain comes as frontal storms and some as warm-weather convective storms.

Four lake watersheds were selected to analyze the effects of wetlands on sediment and nutrient input to lakes based on (1) a 1980 trophic-level survey by the Metropolitan Council of 60 metropolitan-area lakes, (2) the size of wetlands in the contributing drainage basin of the lake watershed, (3) the size of the watershed, and (4) watershed land use. The four lakes chosen, Fish Lake, Lake Elmo, Lake Riley, and Spring Lake, represent the range of lake-watershed types in the metropolitan area based on statistics compiled by the Metropolitan Council. Land use in the lake watersheds was determined by the Metropolitan Council through the use of field surveys and aerial photos (table 1). Watershed characteristics also were collected by the Metropolitan Council (table 2). Watershed characteristics are used in the discussion section to describe how differences in watershed characteristics can cause variations in the effects of nutrient loading to lakes between sites. Maps of the wetland watersheds are shown in figures 2, 3, 4, and 5.

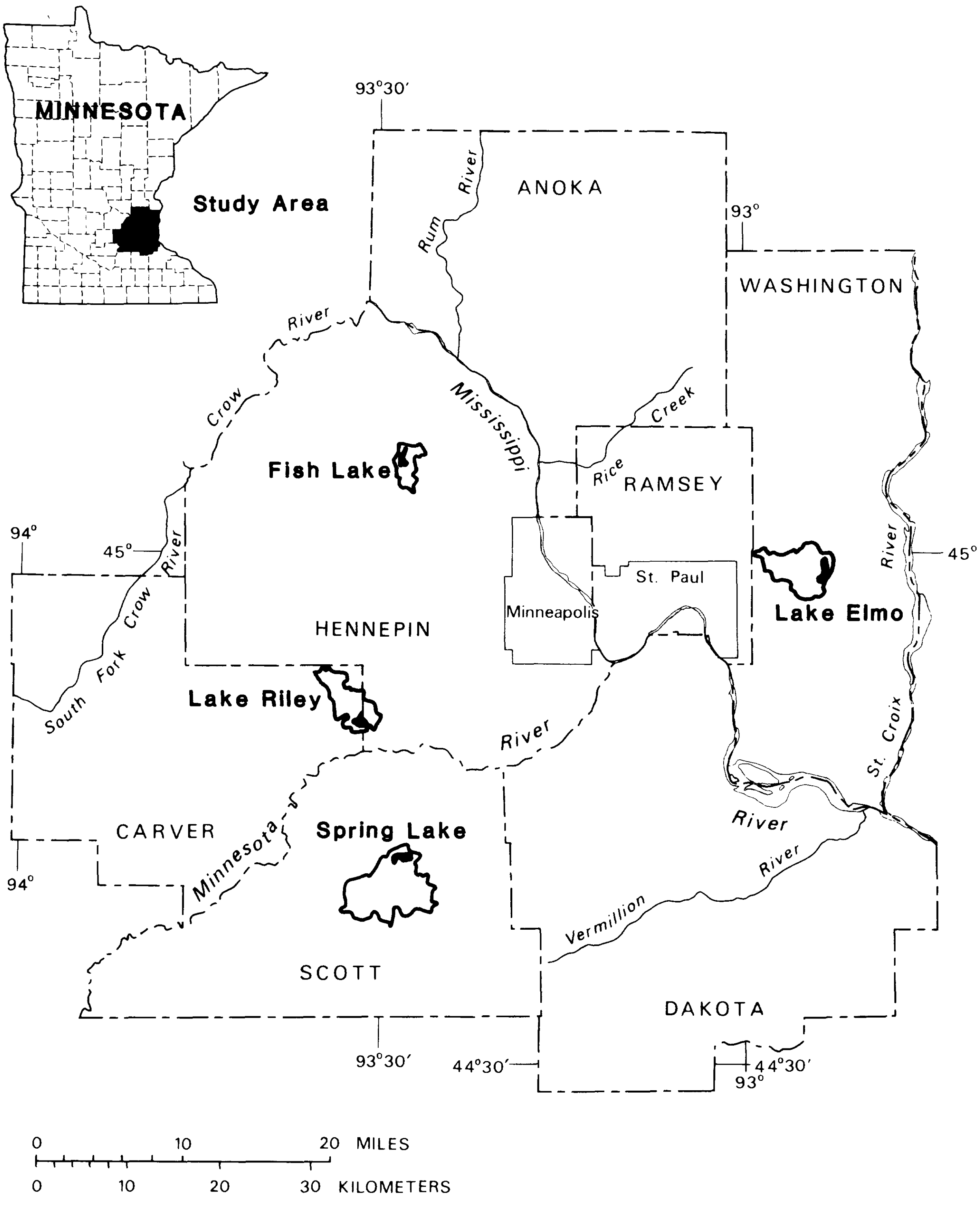


Figure 1.--Location of study wetlands and watersheds in the Twin Cities Metropolitan Area

Table 1.--Land use in lake watersheds

Lake watershed and area	County	General land-use characteristics
Fish Lake (838 hectares)	Hennepin	Watershed is 30 percent residential (mostly single family), 29 percent grassland or woodland, 24 percent wetlands and lakes, 12 percent agricultural, and 5 percent commercial.
Lake Elmo (1,954 hectares)	Washington	Watershed is 37 percent grassland or woodland, 34 percent agricultural, 16 percent wetlands and lakes, 12 percent residential, and 1 percent commercial.
Lake Riley (2,061 hectares)	Carver	Watershed is 30 percent agricultural, 29 percent grassland or woodland, 26 percent wetlands and lakes, 13 percent residential, and 2 percent commercial.
Spring Lake (5,084 hectares)	Scott	Watershed is 57 percent agricultural, 21 percent wetlands and lakes, 16 percent grassland or woodland, 5 percent residential, and 1 percent commercial.

Table 2.--General characteristics of wetlands

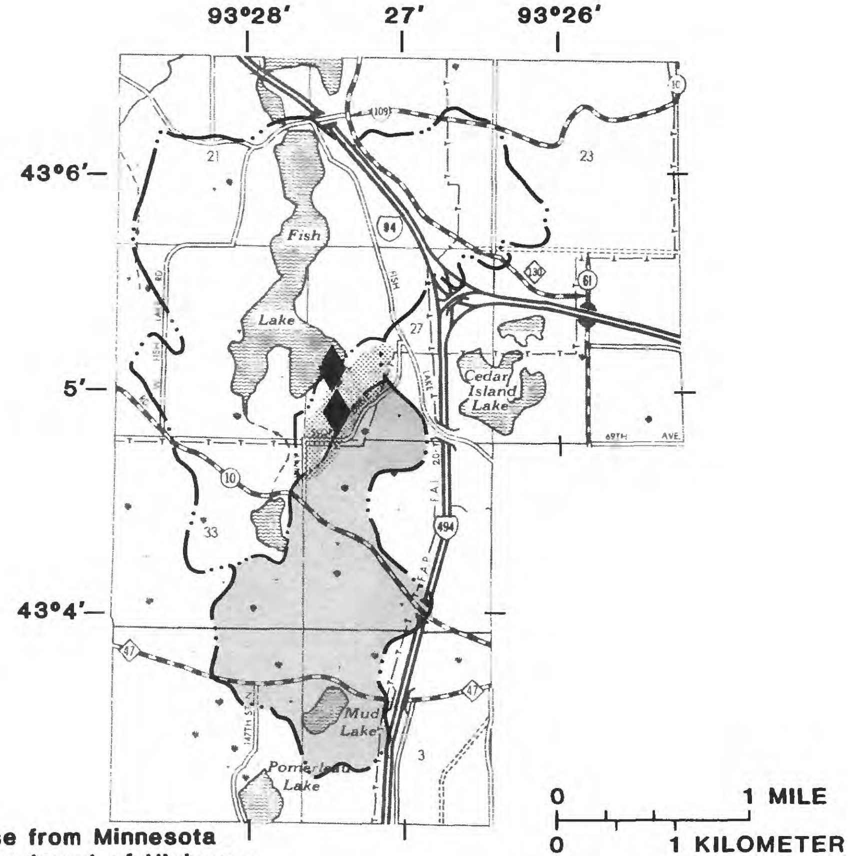
Watershed and area	General characteristics
Fish Lake wetland (6.4 hectares)	The wetland has approximately 5 percent open water, no defined channel, and a mean water depth of 1.2 meters. The vegetation is dominated by reed-canary grass (Phalaris arundinacea) on the edges and cattails (Typha spp.) in the center. The cattails cover 80 percent of the wetland. The natural outlet was changed prior to the study from unchannelized flow to the lake to a culvert that acts as a spillway for an impoundment. The impoundment causes the water depth in the wetland to increase approximately 0.3 meter before the wetland begins to drain through the culvert.
Fish Lake wetland inlet watershed (284 hectares)	The wetland has one inlet that is a storm sewer draining 284 hectares, of which 26 percent is grassland or woodland, 25 percent residential, 21 percent in crops, 19 percent wetlands or lakes, and 9 percent impervious area. The population density of the inlet watershed is 4.2 persons per hectare. The density of conveyance channel in the inlet watershed is 11 meters of conveyance channel per hectare.
Lake Elmo wetland (752 hectares)	Of the 752 hectares in the wetland, 91 hectares are flooded or lacustrine. These 91 hectares generally are dominated by reed-canary grass and cattail. The area of Lake Elmo wetland not flooded or palustrine (601 hectares) is primarily woods and meadows with saturated soils. The 60-hectare marsh within the lacustrine area (Eagle Point Lake) has a mean water depth of 1.2 meters and is important with respect to fish-spawning and waterfowl habitats. Several fish species travel from Lake Elmo to Eagle Point Lake during spring snowmelt to spawn in the shallow sand and gravel areas of the marsh. Egrets, geese, and ducks use the marsh for nesting and feeding. The marsh is mostly open water with the littoral areas vegetated with cattail and willow (salix spp.). The wetland drains into Lake Elmo through a natural channel.

Table 2.--General characteristics of wetlands--Continued

Watershed and area	General characteristics
Lake Elmo wetland inlet watersheds (835 hectares)	Drainage to the wetland is from the southwest (170 hectares) and from the northwest (665 hectares). The southwestern inlet watershed is comprised of agricultural land (50 percent), forest (30 percent), and grassland (20 percent). The northwestern inlet watershed is comprised of agricultural land (30 percent), grassland (35 percent), residential area (25 percent), and wetland (10 percent).
Lake Riley wetland (475 hectares)	Of the 475 hectares of wetland, 97 hectares are lacustrine. The other 376 hectares are palustrine, consisting of meadows and woods with saturated soils. The 97 hectares of lacustrine area are covered by reed-canary grass, cattail, and mixed willow. The 31-hectare marsh that is located within the lacustrine area (Rice Marsh Lake) has a mean depth of less than 1 meter. The marsh has about 60-percent open water and is surrounded by flooded woods. The outlet of Lake Riley wetland drains into Lake Riley. The wetland outlet is the continuation of Riley Creek.
Lake Riley wetland inlet watershed (1,002 hectares)	The inlet is the upper drainage of Riley Creek and has a drainage basin of 1,002 hectares. The inlet watershed is comprised of agricultural land (30 percent), lakes and wetlands (30 percent), woodland (20 percent), and grassland (20 percent).
SpringLake wetland (26 hectares)	The 26-hectare constructed wetland in the Spring Lake watershed has 1.5 hectares of open water with a mean water depth of 1.3 meters. The wetland was designed as a detention area for runoff for the purpose of removing sediment from the incoming water. The wetland is primarily open water with reed-canary grass in the littoral zone. Some bulrush (*Scirpus* spp.) and ditch grasses (*Ruppia* spp.) grow along the inlet and outlet channels. The wetland also has floating mats of duckweed (*Lemna* spp.) and water lilies (*Nymphaea* spp.). Retention

Table 2.--General characteristics of wetlands--Continued

Watershed and area	General characteristics
Spring Lake wetland (Cont.)	of sediment in the wetland was achieved originally by a spillway and drop culvert designed so that only the uppermost layer of water in the wetland would drain out. The design was changed to a ditch outlet because the drop culvert became plugged. Water in the ditched outlet flows through a natural wetland before reaching Spring Lake.
Spring Lake wetland inlet watershed (2,256 hectares)	The constructed wetland inlet is a ditch that is part of a ditch system in the watershed. The inlet watershed area is 2,256 hectares. Land use in the inlet watershed is 61 percent agricultural, 20 percent wetlands and lakes, 15 percent grassland and forest, and 4 percent residential.



Base from Minnesota
Department of Highways
General Highway Map of
Hennepin County, 1977

EXPLANATION

Inlet watershed

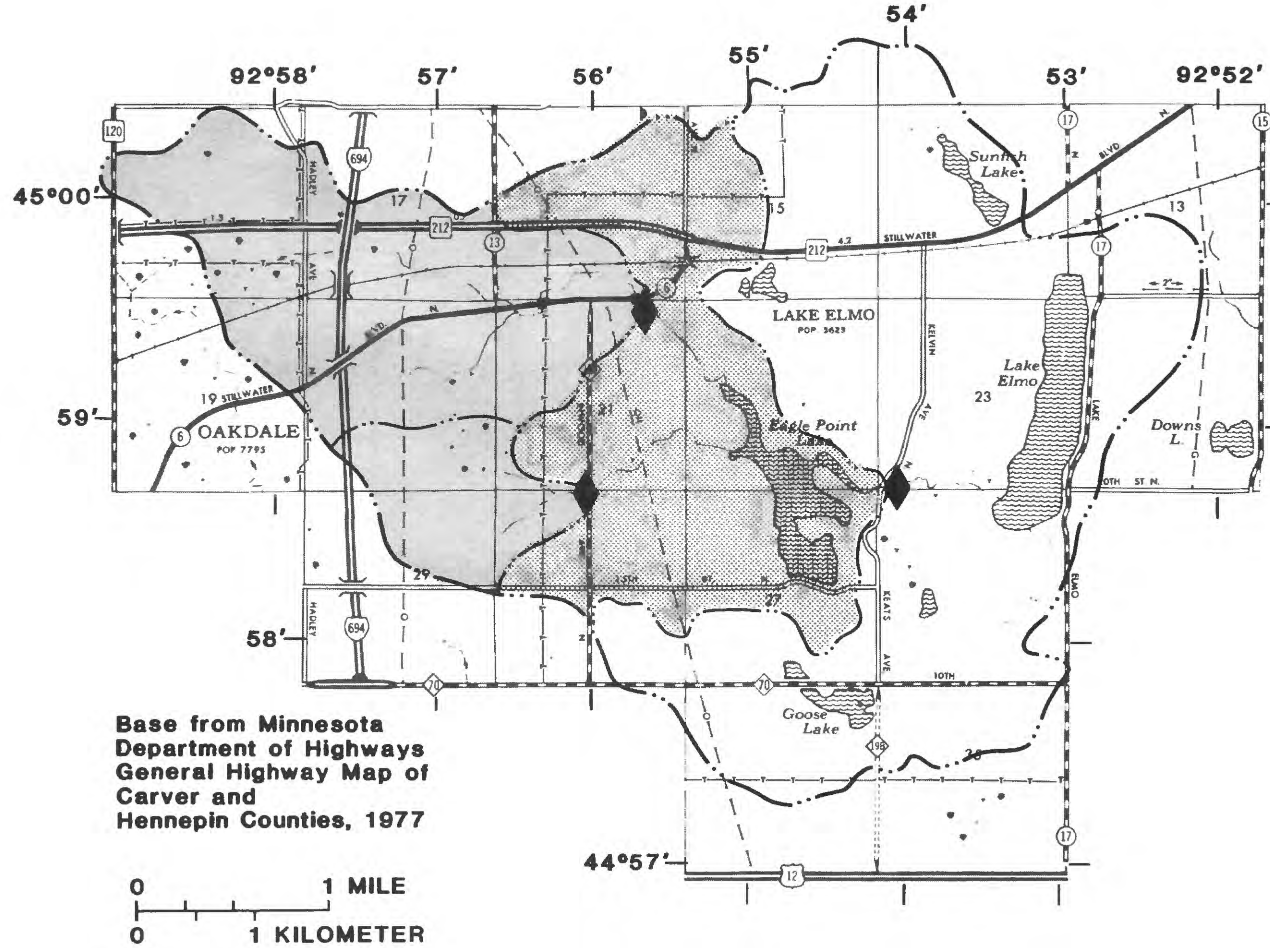
Wetland

Gaging station and monitoring site

Watershed boundary

Subwatershed boundary

Figure 2.--Location of Fish Lake wetland, watershed and data-collection sites



EXPLANATION

- Inlet watershed
- Wetland
- Gaging station and monitoring site
- Watershed boundary
- Subwatershed boundary

Figure 3.--Location of Lake Elmo wetland, watersheds, and data-collection sites

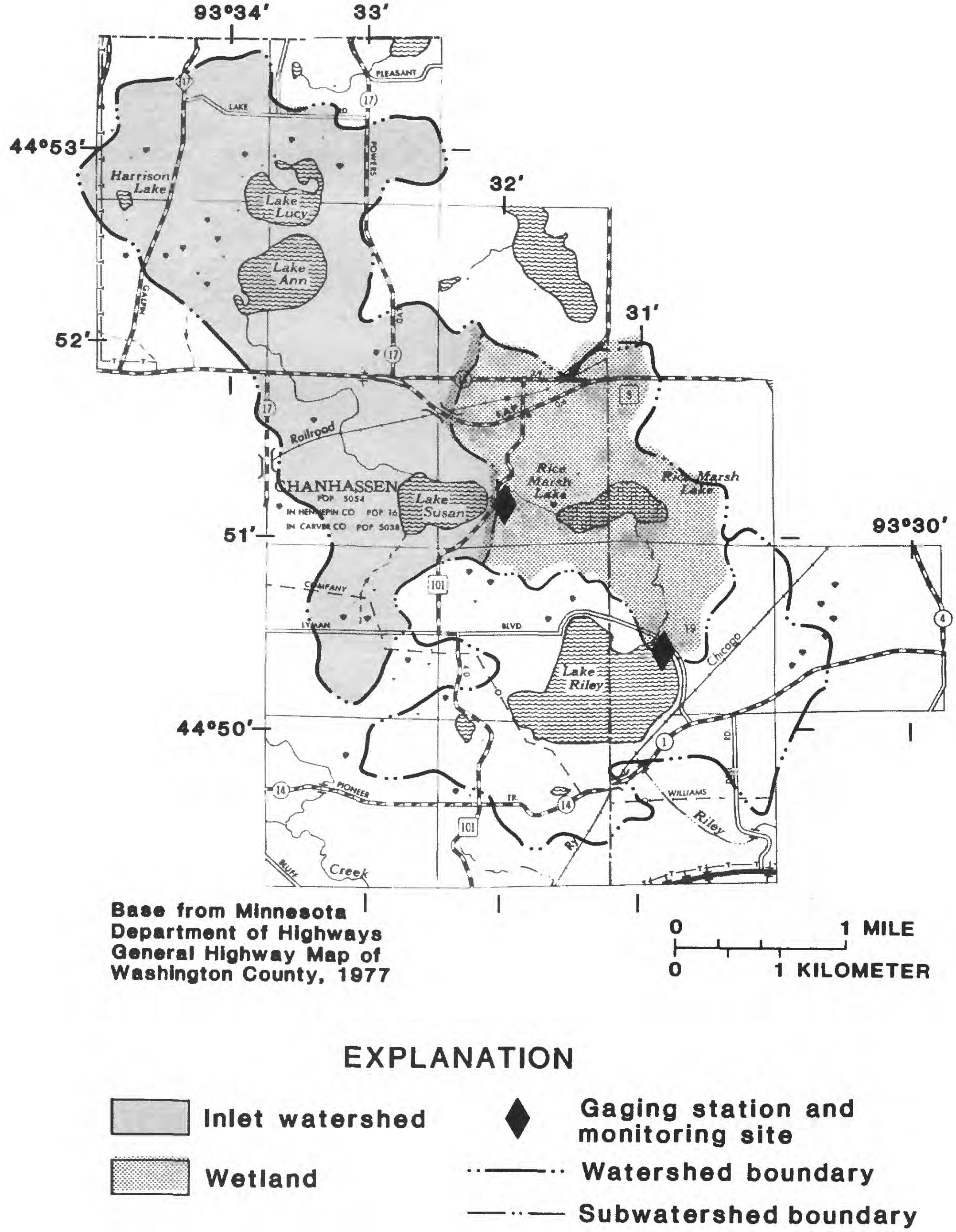
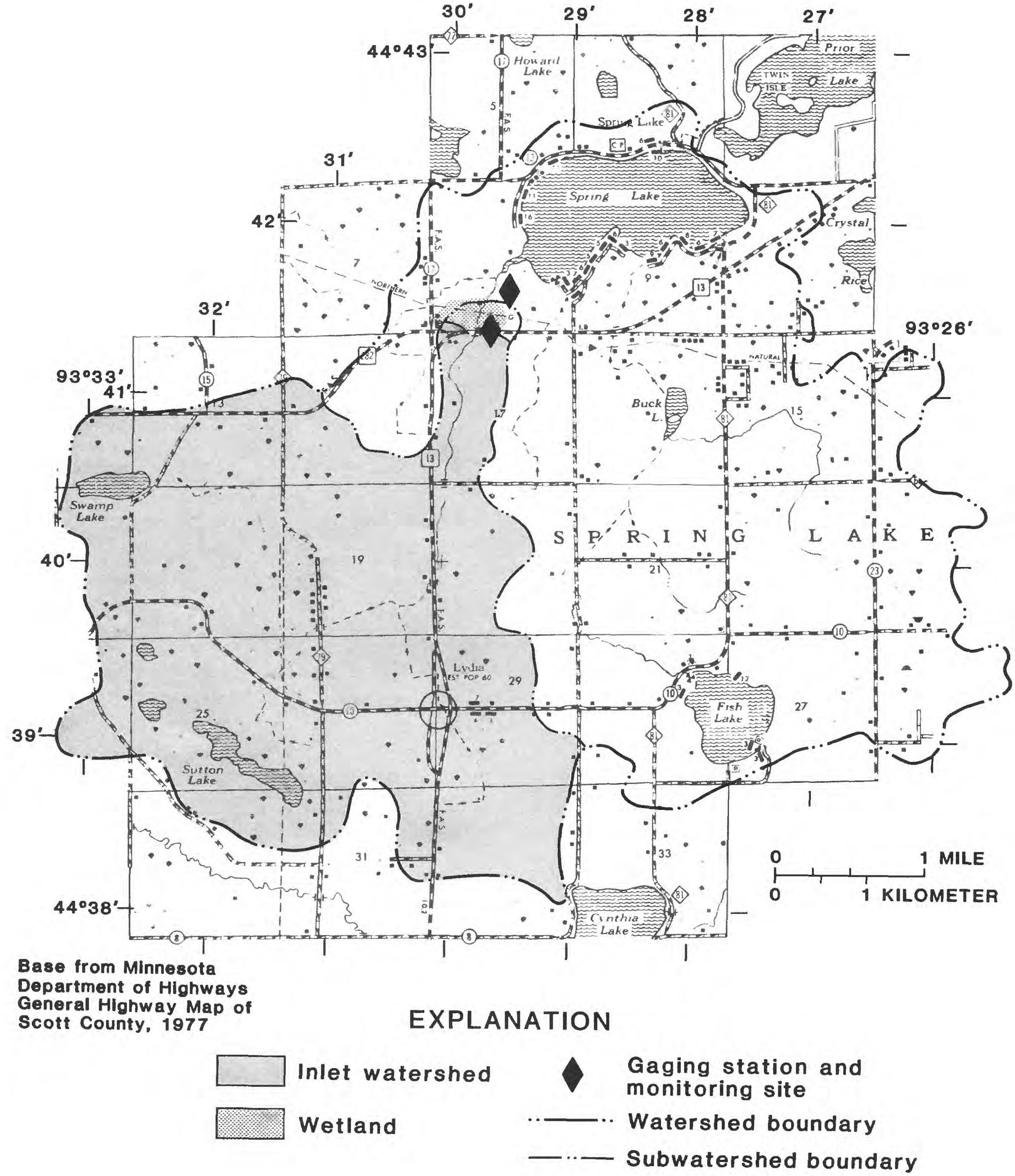


Figure 4.--Location of Lake Riley wetland, watershed, and data-collection sites



Base from Minnesota Department of Highways General Highway Map of Scott County, 1977

Figure 5.--Location of Spring Lake wetland, watershed, and data-collection sites

METHODS AND APPROACH

Inlets and outlets of the wetlands were gaged and sampled for quantity and quality of water throughout 1982. All major runoff events were sampled--seven at the Fish Lake wetland, five at the Lake Elmo wetland, five at the Lake Riley wetland, and five at the Spring Lake wetland. Stage recorders (15-minute cycle) were installed at all sites to measure discharge (fig. 6). Water-quality samples were collected by automatic samplers set at 60- or 120-minute collection cycles.

All samples were flow composited so that only one sample was analyzed per event. The flow-composited sample represents the flow-weighted mean concentration. Each sample was analyzed for concentrations (mg/L) of (1) total nonvolatile suspended solids, (2) total volatile suspended solids, (3) total phosphorus, (4) dissolved phosphorus, (5) dissolved nitrite plus nitrate nitrogen, (6) total ammonia nitrogen, and (7) total organic nitrogen. Total volume of flow was determined at the inlet and outlet using the area under the hydrograph. Total load of each constituent, in kilograms, was calculated by multiplying the flow-weighted mean concentration by the total flow volume, as described by Nelson and Brown (1983). All analyses were made by the Metropolitan Waste Control Commission (MWCC) laboratory at the Metropolitan Wastewater Treatment Plant in St. Paul, Minn. Quality-assurance samples for determining accuracy and precision of the analyses were shared with the U.S. Geological Survey Central Laboratory in Atlanta, Ga. A more detailed explanation of the sampling methods and the quality-assurance program is discussed in a data report by Nelson and Brown (1983).

EFFECTS OF WETLANDS ON QUALITY OF RUNOFF ENTERING LAKES

Comparisons between wetland inlet and outlet flow-weighted mean concentrations are discussed for the specific wetland watersheds and for differences between wetlands. Flow to the Lake Elmo, Lake Riley, and Spring Lake wetlands ceased after a storm on May 16 because the amount of precipitation for any given storm after May 16 was not enough to generate significant runoff. Runoff to the Fish Lake wetland continued into summer. Individual wetland characteristics are described and compared to influences of ecological and hydrological factors that affect the quality and quantity of the wetland effluent.

Fish Lake Wetland

Suspended Solids

Flow-weighted mean concentrations of total nonvolatile suspended solids and total volatile suspended solids generally decreased as runoff passed through the Fish Lake wetland, as indicated by the difference in inflow and outflow concentrations given in figure 7. Decreases in concentrations of nonvolatile and volatile suspended solids occurred during both increases and decreases in total discharge. When total discharge was increasing, concentrations of suspended solids were decreased by a combination of dilution and retention. When total discharge was decreasing, concentrations of suspended solids were decreased by retention only.

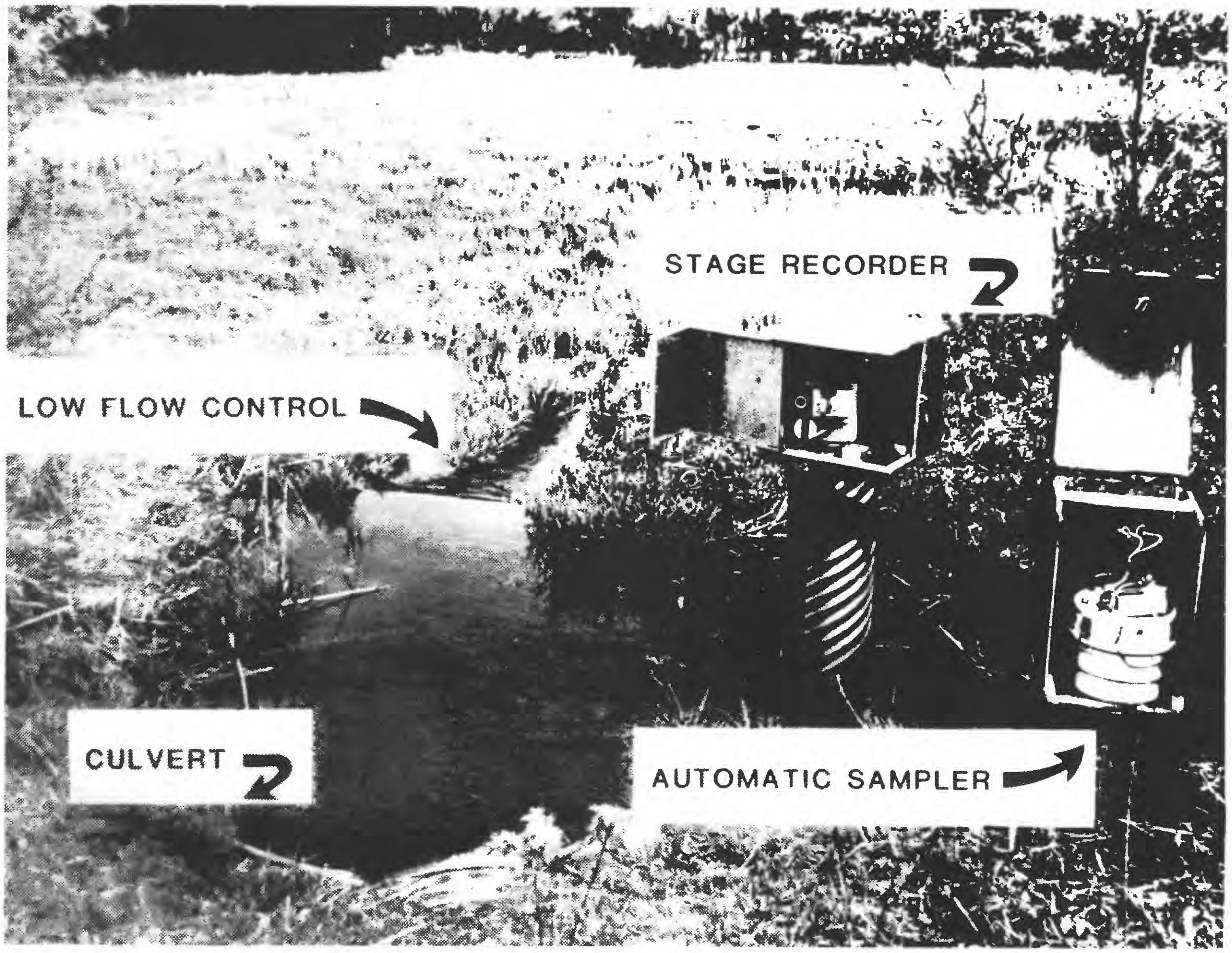


Figure 6.--Fish Lake wetland-inlet gaging site 1; interior view of a typical gaging-site installation

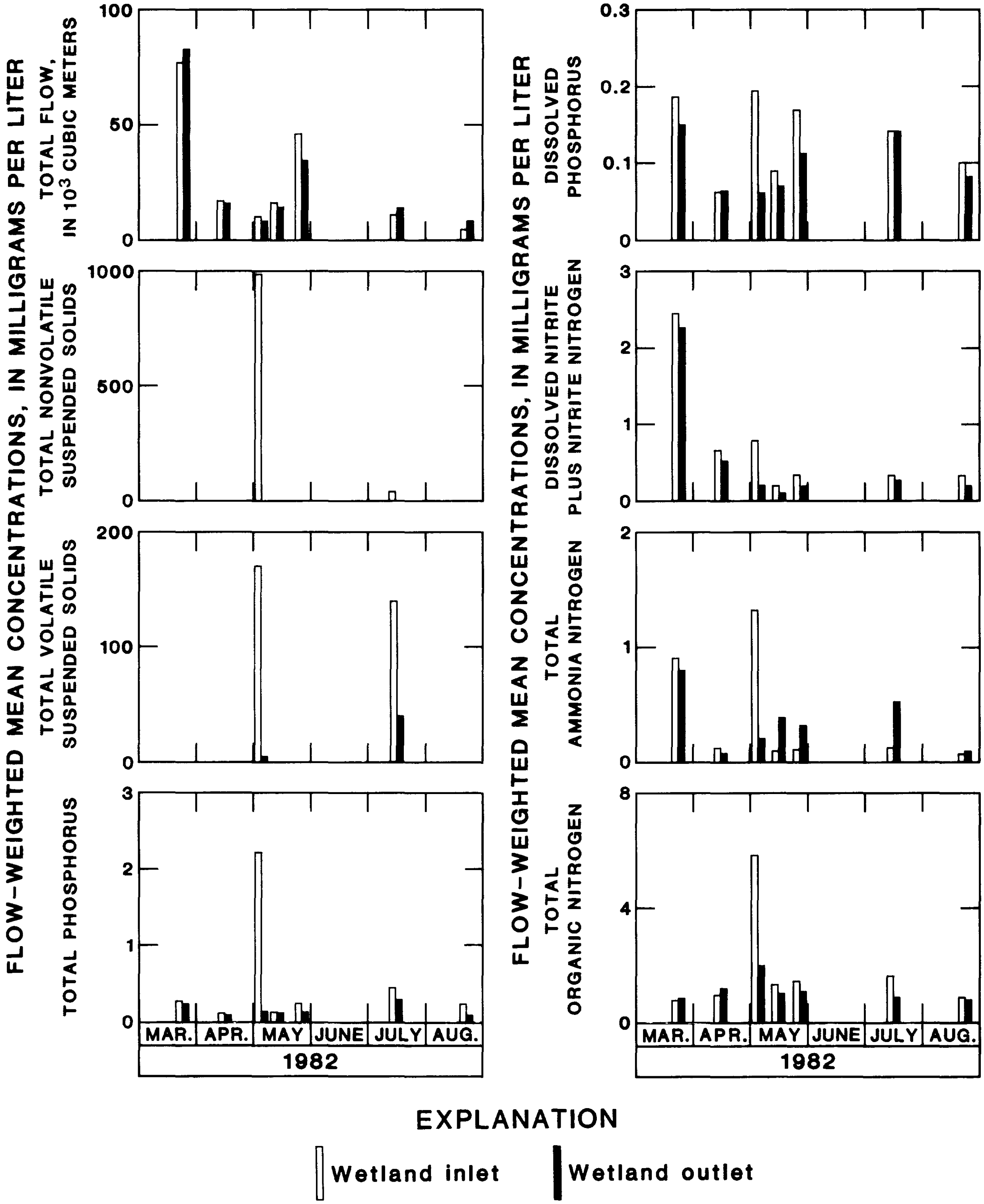


Figure 7.--Total flow and flow-weighted mean concentrations at the inlet and outlet of Fish Lake wetland

The decrease of solids in Fish Lake wetland results primarily from construction of the impoundment, which changed the hydrologic characteristics of the wetland. The impoundment created a depression wetland which, with the increased depth of water, promotes settling of suspended solids at rates that probably exceed those found in natural wetlands. The impoundment also causes the incoming water to spread evenly over the wetland. The whole wetland is then used, and, as a matter of course, the overall retention time of water in the wetland is increased, which increases sedimentation rates. In contrast, natural wetlands generally have well-defined channels that carry most of the runoff so that the area of wetland in contact with sediment-laden water is far smaller than the total area of the wetland.

Phosphorus

Flow-weighted mean concentrations of total and dissolved phosphorus in runoff generally were decreased during flow through the Fish Lake wetland (fig. 7). Annual efficiency of removal of phosphorus from water passing through a wetland depends primarily on the hydrologic characteristics of the wetland (Van der Valk and others, 1978). The hydrologic regime of the Fish Lake wetland may result in a higher efficiency of phosphorus removal than other wetlands because of the larger capacity for runoff retention. The difference between decreases of total phosphorus and dissolved phosphorus shown in figure 7 is primarily caused by the high mobility of dissolved phosphorus.

Nitrogen

Dissolved nitrite plus nitrate nitrogen concentrations in water passing through the Fish Lake wetland generally decreased, probably because of denitrification and assimilation by emergent plants, such as cattails, and their associated epiphytes (fig. 7). Both concentrations of ammonia and organic forms of nitrogen in runoff passing through the Fish Lake wetland increased and decreased depending on the event. These forms of nitrogen are suspected to be released from fresh-fallen litter and removed through nitrogen fixation and denitrification. Nitrogen fixation occurs through microbial and algal action, including symbiotic associations of microorganisms and higher plants. The variation of release or removal of ammonia and organic forms of nitrogen in the wetland depends primarily on the balance of release from litter and denitrification. Mineralization of organic nitrogen to ammonia nitrogen would explain the decrease in organic nitrogen and the increase in ammonia nitrogen.

Lake Elmo Wetland

Total discharge and flow-weighted mean concentration of suspended solids and nutrients in inflowing water at the Lake Elmo wetland had to be calculated from two inlets. Total discharge for inlets was the sum of total discharge at each of the two inlets. Flow-weighted mean concentrations were the mean concentration at the two inlets, calculated by the following equation:

$$C_m = C_1[Q_1/(Q_1 + Q_2)] + C_2[Q_2/(Q_1 + Q_2)]$$

where C_m = inlets mean concentration, in milligrams per liter;

C_1 = flow-weighted mean concentration at site 1 inlet, in milligrams per liter;

C_2 = flow-weighted mean concentraton at site 2 inlet, in milligrams per liter;

Q_1 = total discharge at site 1 inlet, in cubic meters; and

Q_2 = total discharge at site 2 inlet, in cubic meters.

The sum of total discharge entering the wetland during the study did not equal half the volume of the 61-hectare marsh. Therefore, it is likely that inlet and outlet samples do not represent the same time frame. Interpretation of inlet and outlet concentration comparisons is limited because the comparison may not be valid.

Suspended Solids

Flow-weighted mean concentrations of nonvolatile suspended solids and volatile suspended solids were decreased as water flowed through the wetland (fig. 8). These decreases in concentrations of suspended solids represent the magnitude of sedimentation in the wetlands even when the percent of total discharge increased as it did during the first two storms. Dilution apparently is not a factor, as the decreases in concentration were high during both increases and decreases in total discharge.

The marsh probably enhances the large decrease in suspended solids. This 60-hectare body of water provides a large area for sedimentation and the surrounding wetlands provide additional sediment entrapment and stabilization.

Phosphorus

Flow-weighted mean concentrations of total and dissolved phosphorus in runoff showed small increases and decreases between the inlet and outlet of the Lake Elmo wetland (fig. 8). Concentration of total phosphorus was decreased during snowmelt, but increased during the April storm, presumably the result of phosphorus being released from decaying plant material in the form of volatile solids. The decrease in concentration of total phosphorus apparently results from a combination of sedimentation of undissolved phosphorus and uptake of dissolved phosphorus.

The continuous decrease in concentration of dissolved phosphorus was most likely the result of uptake of dissolved phosphorus by wetland vegetation. A storm on May 16 may have generated above-normal quantities of dissolved phosphorus so that the supply exceeded demand by vegetation. Generally, wetlands will not export dissolved phosphorus because the demand or uptake by wetland vegetation is usually greater than the supply (Kadlec and Kadlec, 1978).

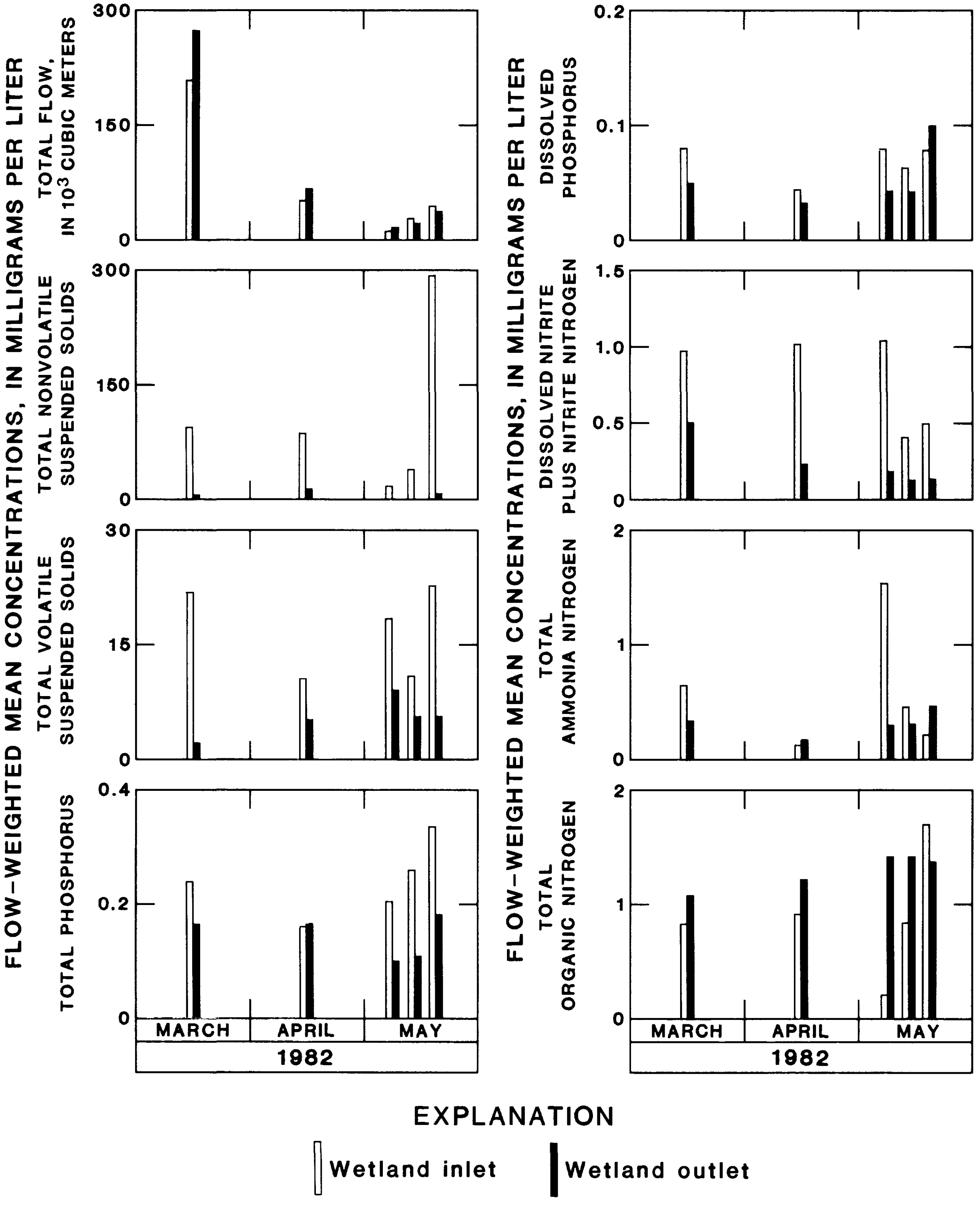


Figure 8.--Total flow and flow-weighted mean concentrations at the inlets and outlet of Lake Elmo wetland

Nitrogen

Concentrations of dissolved nitrite-plus-nitrate nitrogen and total ammonia nitrogen generally were decreased through the Lake Elmo wetland (fig. 8). Dissolved nitrite-plus-nitrate nitrogen was removed from the water passing through the wetland either by denitrification or assimilation. Ammonia and organic forms of nitrogen were most likely released by leaching of fresh litter and removed through nitrogen fixation and denitrification. The balance between the release and removal of ammonia and organic nitrogen is unstable and, overall, the Lake Elmo wetland watershed is a source for organic nitrogen and a sink for ammonia nitrogen.

Lake Riley Wetland

Suspended Solids

Concentrations of nonvolatile suspended solids were decreased only during the first May storm, which coincided with the peak decrease in concentration of volatile suspended solids (fig. 9). Previous to the first May storm, concentrations of nonvolatile and volatile suspended solids were not decreased or increased after runoff flowed through the wetland watershed. The next two storms in May showed increases in concentrations of nonvolatile suspended solids and stable or decreasing concentrations of volatile suspended solids in runoff after flowing through the wetland.

Increases in the concentration of nonvolatile suspended solids in water after flowing through the wetlands are not surprising. The concentration of nonvolatile suspended solids in the Lake Riley wetlands inlet was very low (1.25 milligrams per liter) because the inlet is an outlet of a lake (Lake Susan). Any input from the palustrine area (374 hectares) within the Lake Riley wetland would increase the low concentrations of nonvolatile suspended solids in the incoming water. The Lake Riley wetland area watershed is 22 percent aquatic, or lacustrine, and 78 percent palustrine; that is, meadow and woods with saturated soils. The suspended-solids input from the palustrine area cannot be determined because this area is part of the wetland. The input of suspended solids from the palustrine area of the wetland, however, can be estimated from suspended-solids inputs from areas with the same characteristics. Based on data collected during an urban-hydrology study (Payne and others, 1982), the concentrations of suspended solids between the wetland inlet and outlet should increase almost 10 fold. The lacustrine area of the wetland reduced the expected 10-fold increase to an increase of less than 1 fold. Therefore, the increase in suspended solids as water passes through the lacustrine area of the wetland actually represents a decrease of suspended-solids input from the palustrine area within the wetland.

Phosphorus

Flow-weighted mean concentrations of total and dissolved phosphorus consistently increased as runoff flowed through the Lake Riley wetland (fig. 9). Average concentrations at the inlet of the wetland were 0.09 milligrams per liter for total phosphorus and 0.05 milligrams per liter for dissolved phosphorus. An increase of 0.12 milligrams per liter in concentration of total

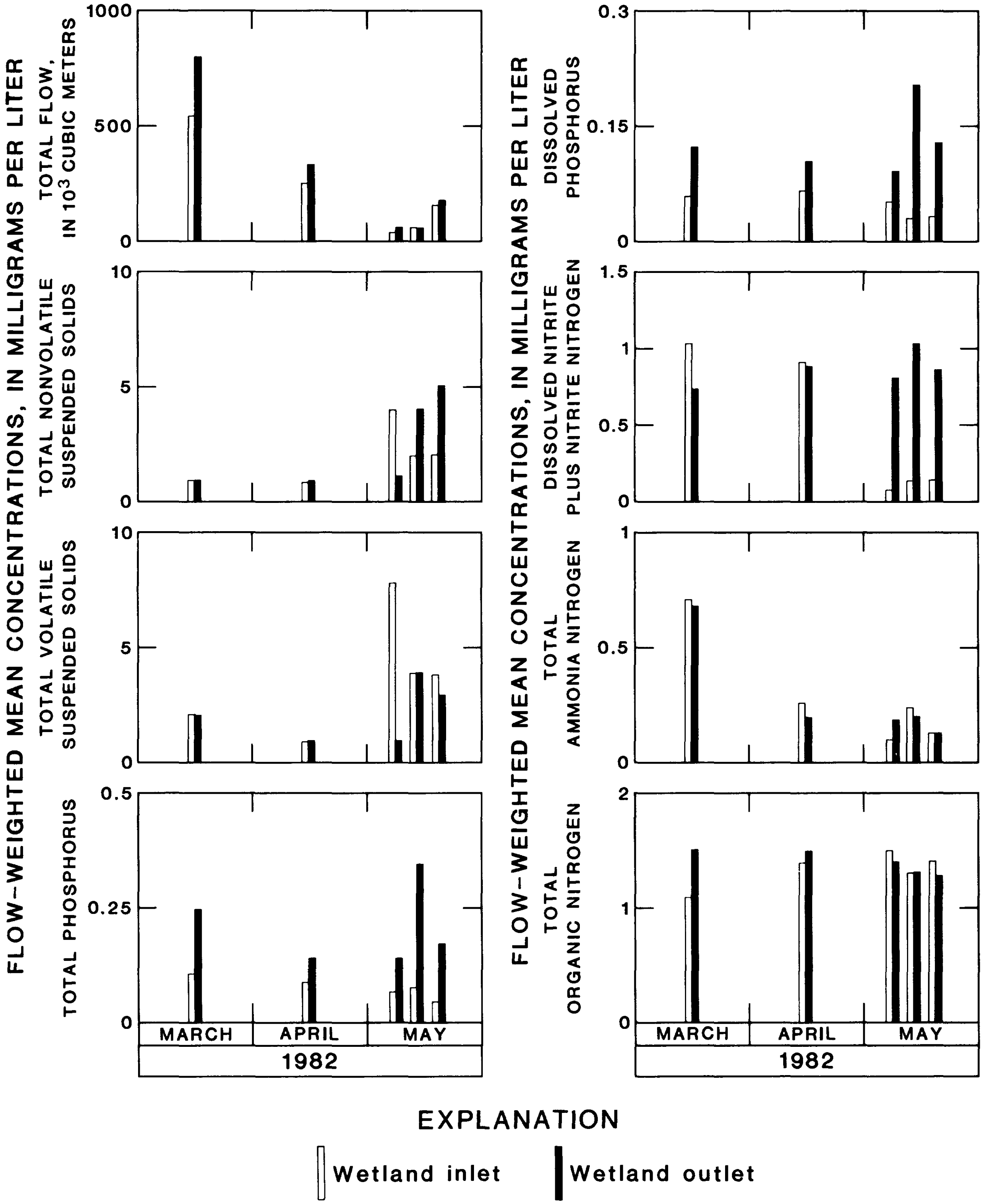


Figure 9.--Total flow and flow-weighted mean concentrations at the inlets and outlets of Lake Riley wetland

phosphorus and of 0.06 milligrams per liter in concentration of dissolved phosphorus in water passing through the wetland probably is not significant. The increase in concentration of phosphorus that potentially can be generated from the palustrine area of the wetland is 1.3 milligrams per liter for total phosphorus and 0.73 milligrams per liter for dissolved phosphorus (Payne and others, 1982). The increase in concentration of phosphorus apparently is the net result of phosphorus input to the lacustrine area from the palustrine area within the wetland and the removal of phosphorus through sedimentation and assimilation by plants in the lacustrine area.

Nitrogen

Flow-weighted mean concentrations of dissolved nitrite-plus-nitrate nitrogen increased, total ammonia nitrogen decreased, and total organic nitrogen increased as water passed through the Lake Riley wetland (fig. 9). Flow-weighted mean concentrations of nitrite-plus-nitrate nitrogen showed a decrease during snowmelt (March) and the April storm, but an increase during the last three storms. Concentrations of organic nitrogen changed throughout the year, whereas concentrations of ammonia nitrogen generally decreased except during the first storm in May.

Increases in concentration of nitrogen as the water passed through the wetland were assumed to be for reasons similar to those for phosphorus. The average concentration of nitrite-plus-nitrate nitrogen of 0.79 milligrams per liter at the wetland inlet doubled after the water flowed through the wetland. This increase in concentration is insignificant compared to the increase in concentration that probably would be generated after flowing through the Lake Riley wetland if the lacustrine area was not present; that is, 3.25 milligrams per liter or a 3-fold increase in concentration (Payne and others, 1982).

The annual average decrease in concentration of ammonia nitrogen as runoff flowed through the wetland was 0.05 milligrams per liter based on the five events sampled in 1982. However, this decrease in concentration of ammonia nitrogen also represents a decrease in ammonia nitrogen input from palustrine area within the wetland of 1.24 milligrams per liter, based on areas with similar characteristics as the palustrine area studied by Payne and others (1982). This decrease in concentration likely is the result of nitrification in the lacustrine area of the wetland.

The annual average increase in concentration of organic nitrogen between the inlet and outlet of the wetland is only 0.25 milligrams per liter. This increase is insignificant when compared to the estimated 5.9 milligrams per liter increase from the palustrine area within the wetland [based on areas with similar characteristics as the palustrine area studied by Payne and others (1982)]. Therefore, the wetlands do remove organic nitrogen, because input concentrations in water from the palustrine area are retained in the lacustrine area before the water leaves the wetland. The decrease in concentration of organic nitrogen most likely is by mineralization.

Spring Lake Wetland

Suspended Solids

Flow-weighted mean concentrations of total nonvolatile and total volatile suspended solids generally increased in water as it passed through the constructed wetland (fig. 10). Exceptions were the last two storms in May, when concentrations of nonvolatile suspended solids decreased.

The volume of water in the wetland is approximately 19,500 cubic meters. The volume of water coming out of the wetland during the first three storms was approximately 1,869,000 cubic meters, flushing the wetland 96 times in 54 days. This flushing eroded wetland sediments and, therefore, increased concentrations of nonvolatile and volatile suspended solids. The flushing was continuous and, once the wetland sediments were suspended, any increase in flow increased export of wetland sediments. There was a decrease in suspended solids in late May because the volume of water flowing through the wetland was a fraction of the volume observed in earlier storms. The lower volumes reduced flushing rates and allowed sedimentation to occur. Concentrations of volatile suspended solids increased because of flushing of both wetland sediments and aquatic vegetation. The wetland most likely was trapping sediment in previous years, but not during the study because the control structure was changed from a spillway to a ditch outlet just prior to the study.

Phosphorus

Flow-weighted mean concentrations of total and dissolved phosphorous generally were unchanged or reduced as runoff passed through the wetland (fig. 10). The decrease in concentration of phosphorous was presumed to be the result of either precipitation of phosphorous on organic matter or assimilation by plants or algae. The small increase in concentration of phosphorous likely was from either leaching of fresh litter or from phosphorus in resuspended sediments or exported aquatic plants. The decrease in concentration of phosphorus is directly related to the amount of runoff detention. The small increases in concentrations of total and dissolved phosphorus during the first two or three storms, or during high-flow periods, were caused, in part, by the limited amount of runoff detention in the wetland during these storms.

Nitrogen

Flow-weighted mean concentrations of dissolved nitrite-plus-nitrate nitrogen generally were unchanged during March and April and decreased during May with flow through the wetland (fig. 10). The concentration of nitrite-plus-nitrate nitrogen did not change significantly during the larger runoff events because any decrease through denitrification or plant uptake and increases from leaching or plant decomposition were restricted by the limited detention time. However, during smaller runoff events, the concentration of nitrite-plus-nitrate nitrogen decreased because the detention time was longer. Generally, the wetland was neither a source nor sink of nitrite-plus-nitrate nitrogen.

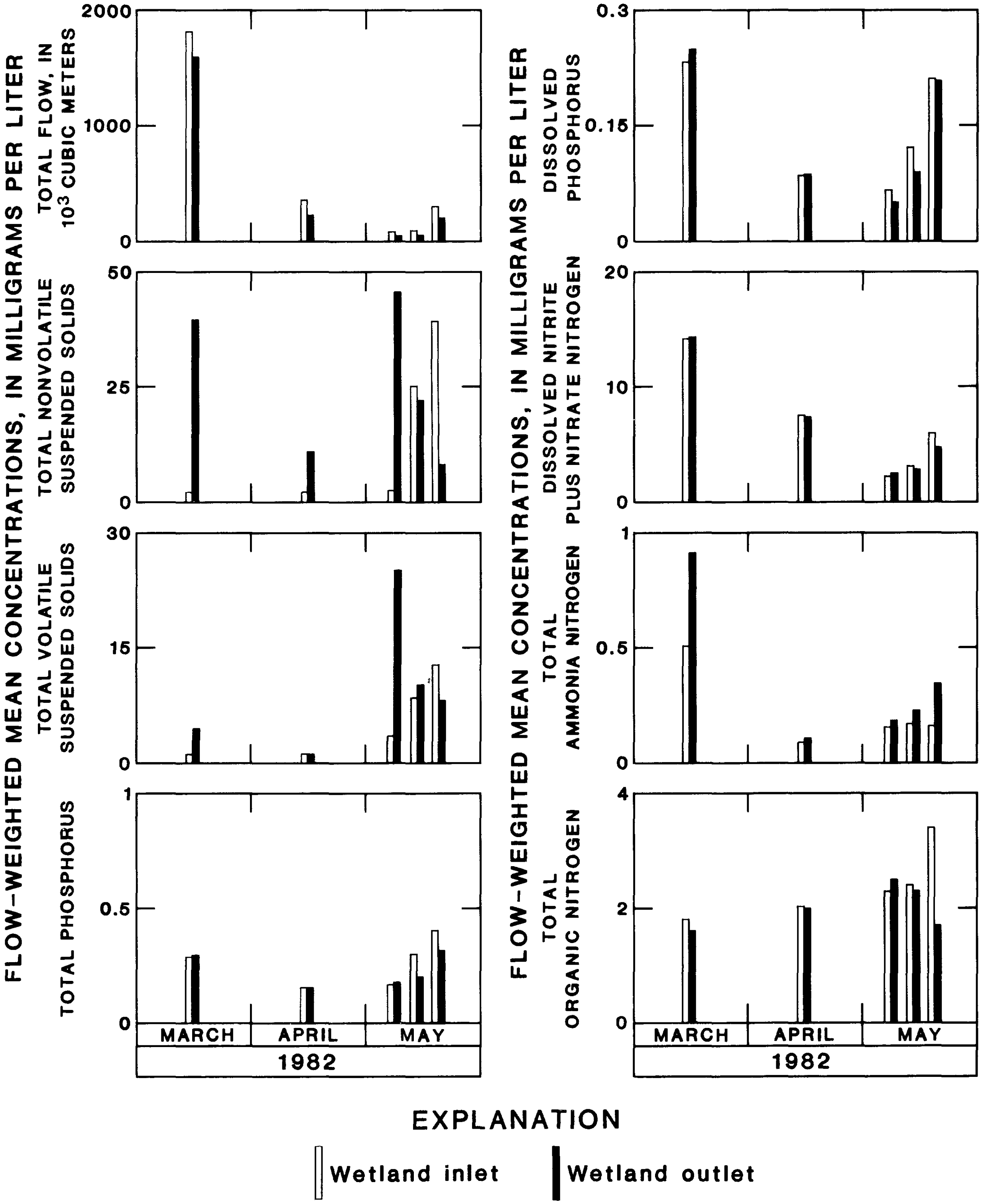


Figure 10.--Total flow and flow-weighted mean concentrations at the inlet and outlet of Spring Lake wetland

The concentration of ammonia nitrogen substantially increased as runoff flowed through the wetland during the first storm, but did not change substantially during other storms (fig. 10). The increase in ammonia nitrogen most likely was the result of mineralization or resuspension of anaerobic sediments. The increase in concentration of organic nitrogen during the third storm is likely the result of organic sediment being resuspended during flushing of the wetland (fig. 10). Decreased concentrations of organic nitrogen in the other four storms probably were the result of mineralization.

Comparison Between Wetlands

Comparisons between the effects of the wetlands on input of suspended solids and nutrients to lakes were made using the total discharge and annual average flow-weighted mean concentrations based on the five storms sampled during 1982 (fig. 11). The average flow-weighted mean concentrations were calculated by the equation

$$C_a = [C_1(Q_1/Q_t) + C_2(Q_2/Q_t) + \ldots C_n(Q_n/Q_t)]$$

where C_a = average flow-weighted mean concentration, in milligrams per liter;

C_1 = flow-weighted mean concentration for the first storm, in milligrams per liter;

Q_1 = total discharge for the first storm, in cubic meters; and

Q_t = total discharge for all storms sampled, in cubic meters.

Suspended Solids

The Fish Lake wetland had the greatest decrease in concentrations of nonvolatile and volatile suspended solids compared to the other three wetlands (fig. 11). The decrease in concentration of suspended solids in the Lake Elmo wetland was 50 to 80 percent of the decrease in the Fish Lake wetland. The Lake Riley wetland did not significantly affect suspended-solids concentrations, while Spring Lake wetland increased the concentration of suspended solids on the average. The Fish Lake wetland was more effective in decreasing the concentration of suspended solids because (1) the wetland had been modified by an impoundment to increase sedimentation and (2) the influent of one storm had extremely high concentrations of suspended solids that could be removed easily by sedimentation. The decrease in concentration of suspended solids in the Lake Elmo wetland was less as a result of input from the palustrine area within the Lake Elmo wetland.

The annual average decrease in concentration of suspended solids in the Lake Riley wetland is less than in the Lake Elmo wetland. However, the decrease of suspended solids in the Lake Riley wetland is misleading because the wetland watershed inlet is an outflow of a lake. The concentration of suspended solids in the lake outflow was low. Therefore, a decrease in concentration of

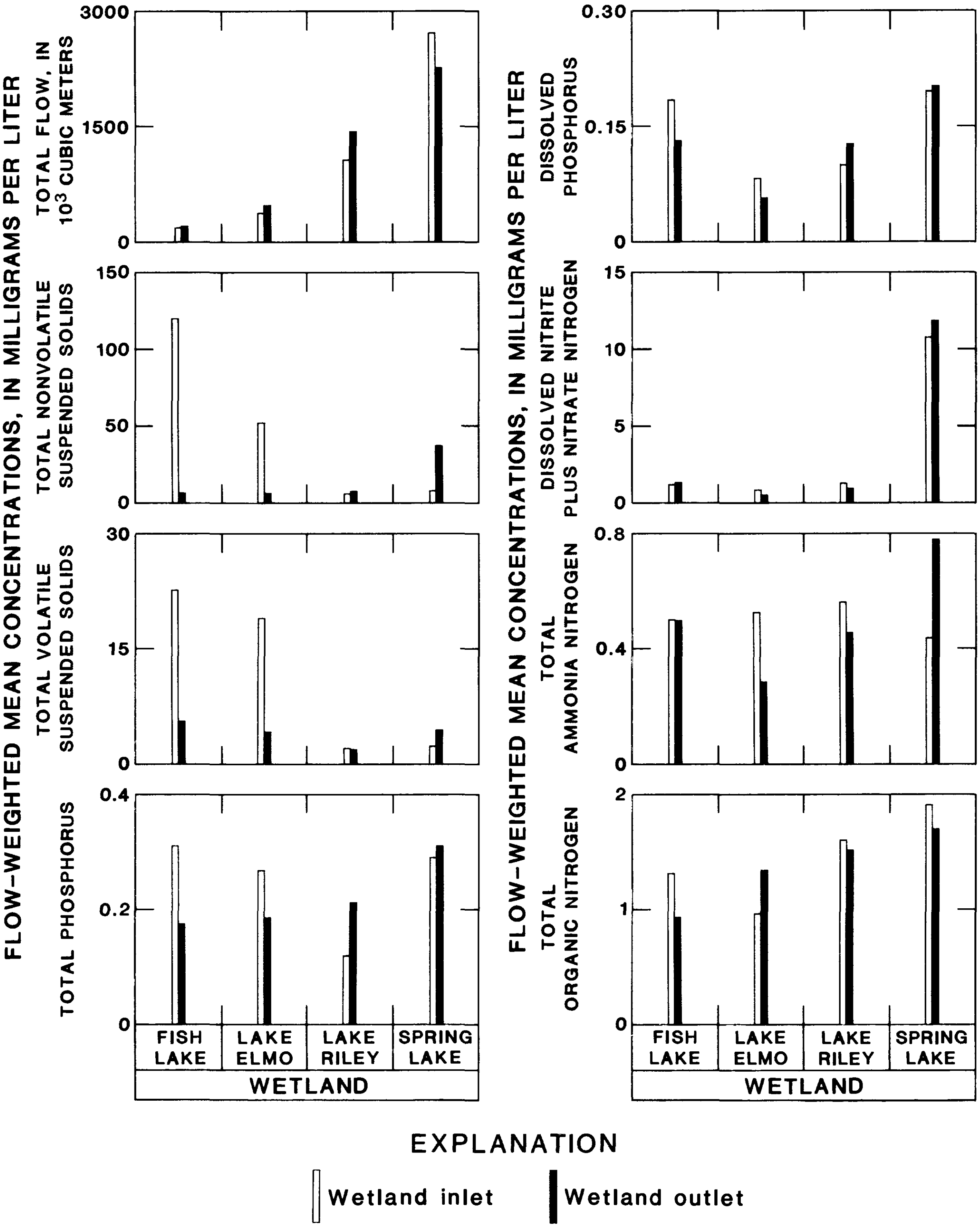


Figure 11.--Total flow and average flow-weighted mean concentrations for the storms sampled during 1982 at the inlets and outlets of study wetlands

suspended solids through the Lake Riley wetland would have to be attributed to nearly complete removal of incoming sediment from sources within the wetland. Because the ratio of lacustrine to palustrine area in the Lake Elmo (151/752 = 0.20) and Lake Riley (97/473 = 0.20) wetlands is similar, it can be assumed that the two wetlands decrease sediment concentrations similarly. If the assumption is valid, the difference in decreases between the two wetlands must be caused by differences in inlet concentrations, not wetland efficiency.

The concentration of suspended solids in runoff leaving the Spring Lake wetland increased because high flows eroded sediments from the wetland. The increase in concentration of suspended solids from the constructed wetland (Spring Lake wetland) and the decrease in the natural wetlands illustrate how areas designed to trap sediment can become a source. Natural-depression areas, such as Lake Elmo and Lake Riley wetlands, are effective sediment traps. Modified wetlands, such as Fish Lake wetland, are even more effective than natural wetlands in decreasing suspended solids. The constructed wetland studied had a surface-water-storage capacity insufficient for the amount of runoff to the pond, which caused increases in sediment that probably are not typical of constructed wetlands.

In general, the characteristics of a wetland that are most effective in decreasing suspended solids are (1) an impoundment or detention of runoff to increase sedimentation, (2) an undefined inflow channel to the wetland, which results in better dispersion of incoming sediments, and (3) a dense vegetative growth throughout the wetland to reduce flow velocity and wave action. These three characteristics probably are only a few of many that affect sedimentation rates, but the results of this study indicate that these three are significant. Additional studies of the entire wetland, not just the inlet and outlet, could identify other wetland characteristics that affect sedimentation.

Phosphorus

The concentrations of both total and dissolved phosphorus were decreased to a greater extent in the Fish Lake wetland than in the other three. The reasons are similar to those given for suspended solids except that the vegetation type (cattails) also was a significant factor in decreasing phosphorus. The decrease in the Lake Elmo wetland and the increases in the Lake Riley and Spring Lake wetlands probably are caused by the same factors mentioned for suspended solids.

Factors that probably were most effective in decreasing concentrations of both total and dissolved phosphorus in the four wetlands studied are (1) impoundment or retention of runoff to provide greater interaction between wetland vegetation and incoming nutrients, (2) an undefined inflow channel to stimulate dispersion within the wetland, and (3) vegetation, such as cattail, that is efficient in assimulating nutrients. These characteristics may or may not be important in themselves, but in combination they are primarily responsible for efficient removal of phosphorus in the Fish Lake wetland. Other factors also may be important, and further investigation of entire wetland systems could identify which wetland characteristics are most important in removing phosphorus from runoff.

Nitrogen

The concentration of nitrite-plus-nitrate nitrogen increased at the Spring Lake wetland, probably as a result of the same factors given for the increase in concentration of suspended solids; flushing of the wetland during early storms. The Fish Lake, Lake Elmo, and Lake Riley wetlands did not substantially affect concentrations of nitrite-plus-nitrate nitrogen.

The concentration of ammonia nitrogen was not affected in the Fish Lake wetland but decreased in the Lake Elmo and Lake Riley wetlands and increased in Spring Lake wetland. Organic nitrogen decreased in the Fish Lake, Lake Riley, and Spring Lake wetlands and increased in the Lake Elmo wetland. The decrease in ammonia nitrogen probably was the result of nitrification (increasing nitrate concentrations). The decrease in organic nitrogen probably was the result of mineralization (increasing ammonia concentration). Nitrogen is returned or released to the water by the wetland through various chemical transformations and, as a result, the decrease or increase in any particular form of nitrogen may cause a decrease or increase in another form of nitrogen. Further investigation is needed to understand the effects of denitrification and of mineralization of organic nitrogen in wetlands.

CONCLUSIONS

The natural wetlands studied improved quality of runoff entering lakes to some degree. The Fish Lake wetland was generally the most effective natural wetland in reducing the input of suspended solids and nutrients to lakes. The dense cattail vegetation in Fish Lake wetland and modification of the outlet allowed for unusually high rates of sediment and nutrient retention. The constructed wetland studied was ineffective in decreasing sediment and nutrient inputs to the lake. Further investigations of mineral cycling and sedimentation processes in the wetlands are needed to substantiate these conclusions and to understand the long-term effects of accelerated inputs of suspended solids and nutrients on wetland flora and fauna.

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