The Effects of Flow-Path Modification on Water-Quality Constituent Retention in an Urban Stormwater Detention Pond and Wetland System, Orlando, Florida

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CONVERSION FACTORS, VERTICAL DATUM, ABBREVIATIONS, AND ACRONYMS

Multiply	By	To obtain
	Length	centimeter
inch (in.)	2.54	
feet (ft)	0.3048	meters
	Area	
square foot (ft^2)	0.0929	square meter
	Volume	
cubic foot (ft^3)	0.028317	cubic meter
	Flow	
foot per year (ft/yr)	0.3048	meter per year
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
mile per hour (mph)	1.609	kilometer per hour

Equations for temperature conversion between degrees Celsius (°C) and degrees Fahrenheit (°F):

$$°C = 5/9\ (°F - 32)$$
$$°F = 9/5\ (°C) + 32$$

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929--a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Additional Abbreviations

eq	equation
hr	hour
L	liter
µS/cm	microsiemens per centimeter at 25 degrees Celsius
µg/L	micrograms per liter
mg/L	milligrams per liter
min	minute
Pt-Co Units	Platinum-Cobalt units
yr	year

Acronyms

CSTR	constantly stirred tank reacto
EMC	event mean concentration
FDOT	Florida Department of Transportation
MVUE	minimum variance unbiased estimate
NOAA	National Oceanic and Atmospheric Administration
NURP	Nationwide Urban Runoff Program
RE	retention efficiency
SR	State Road
TR	transport ratio
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey

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ABSTRACT

Changes in constituent retention in a wet stormwater-detention pond and wetland system in Orlando, Florida, were evaluated following the 1988 installation of a flow barrier which approximately doubled the flow path and increased detention time in the pond. The pond and wetland were arranged in series so that stormwater first enters the pond and overflows into the wetland before spilling over to the regional stream system. Several principal factors that contribute to constituent retention were examined, including changes in pond-water quality between storms, stormwater quality, and pond-water flushing during storms. A simple, analytical pond-water mixing model was used as the basis for interpreting changes in retention efficiencies caused by pond modification. Retention efficiencies were calculated by a modified event-mean concentration efficiency method using a minimum variance unbiased estimator approach.

The results of this study generally support the hypothesis that changes in the geometry of stormwater treatment systems can significantly affect the constituent retention efficiency of the pond and wetland system. However, the results also indicate that these changes in efficiency are caused not only by changes in residence time, but also by changes in stormwater mixing and pond water flushing during storms. Additionally, the use of average efficiencies as indications of treatment effectiveness may fail to account for biases associated with sample distribution and independent physical properties of the system, such as the range and concentrations of constituents in stormwater inflows and stormwater volume.

Changes in retention efficiencies varied among chemical constituents and were significantly different in the pond and wetland. Retention efficiency was related to inflow concentration for most constituents. Increased flushing of the pond after modification caused decreases in retention efficiencies for constituents that concentrate in the pond between storms (dissolved solids) and increases in retention efficiency for constituents that settle out of pond and wetland storage between storms. The greatest increase in retention efficiencies in the detention pond was observed for total lead, which increased from 19 percent before modification to 73 percent after modification. However, retention efficiencies for nutrients and suspended constituents decreased in the wetland after modification. This was probably because of the flushing of accumulated sediments as a result of a change in flow path through the wetland. As a result, the overall effect of modification on the system (pond and wetland retention efficiencies combined) was a reduction in retention efficiency for all but two constituents (total zinc and total ammonia nitrogen).

INTRODUCTION

Stormwater detention ponds and wetlands are increasingly used to control the contamination of surface water by a range of urban stormwater pollutants. Although differences in pond geometry are of little practical importance in flood control, these differences can affect the treatment effectiveness of stormwater detention systems for water-quality control. The effectiveness of stormwater treatment systems has been evaluated at a number of sites, but the effects of flowpath and stormwater flushing have been difficult to generalize because of site-specific differences in pond size, shape, operation, and stormflow characteristics.

In a previous study (1982-1985), the U.S. Geological Survey (USGS), in cooperation with the Florida Department of Transportation (FDOT), monitored the quality of stormwater entering and leaving an urban stormwater detention pond and wetland system in Orlando, Fla. (Martin and Smoot, 1986). In the original configuration of the treatment system, highway runoff first entered an excavated pond, then flowed out of the pond into a cypress wetland before exiting into the Little Wekiva River, a tributary of the St. Johns River (fig. 1). Discharge and stormwater quality were monitored at the inlet and outlet of the pond and at the outlet of the wetland during 13 storms. The fraction of constituent load retained by the system (retention efficiency) was individually determined for the pond and the wetland.

After publication of the work by Martin and Smoot (1986), a task force on urban hydrology under the auspices of the American Society of Civil Engineers, suggested several structural modifications to the system to improve (increase) constituent retention. Generally, the task force concluded that a greater percentage of particulate load would settle and be retained in the pond if the flow path and residence time through the pond were lengthened. To test this idea, the pond was modified in 1988 and another set of storms was monitored and sampled by the USGS in 1989 and 1990. During this period, pond hydraulics during storms and pond chemistry between storms also were studied to determine the physical and biological response of the system to the modification. This second phase of the study also was a cooperative effort by the USGS and FDOT.

Purpose and Scope

This report presents the results of studies of treatment effects and treatment-related processes in an Orlando detention pond and wetland system on constituent retention after structural modification of the pond. Because this work is a continuation of the original assessment of the system by Martin and Smoot (1986), many of their constituent-retention data (before modification) are included for comparison.

The discussion specifically addresses fractional changes in concentrations of selected suspended and dissolved constituents in stormwater as they move through the system, and how these changes (referred to collectively as "retention efficiencies") can be influenced by changes in the flow path or other properties of the system. In addition to an empirical and quantitative assessment of the effects of modifications, several other aspects of the system that may contribute to constituent retention and that may be influenced by pond modification are discussed. Principal topics include: (1) a comparison of stormwater-inflow quantity and quality before and after modification; (2) a qualitative assessment of mixing in the pond and its relation to storm intensity and volume; (3) an evaluation of changes in pond-water quality between storms and how these changes affect constituent retention; (4) an examination of the interrelations among constituent transport, stormwater inflow concentration (relative to in-pond concentration), and storm-water volume; and (5) an analysis of the influence of stormflow volume and other weighting factors in the determination of mean retention efficiencies.

A simple, analytical input-output model is presented to illustrate the fundamental relation of retention efficiencies to mean inflow constituent concentrations, mixing, and residence time. Retention efficiencies are computed for the pond and wetland based on mean-event concentration data and are averaged using a minimum variance unbiased estimate approach.

Previous Studies

The Orlando detention pond and wetland system has been the subject of several other stormwater-related studies in addition to the previous study by Martin and Smoot (1986). The quality of bed sediments in the Orlando detention pond and wetland system was surveyed by Schiffer (1989a). Another

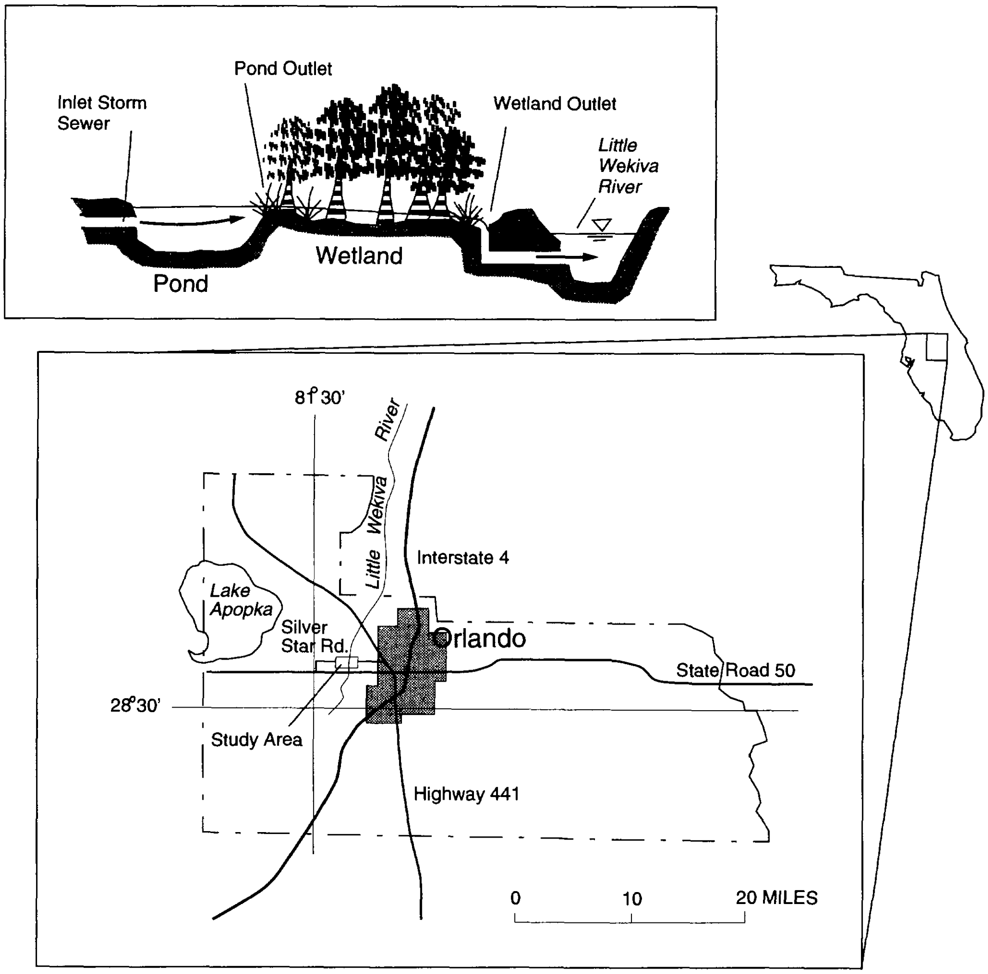

Figure 1. Schematic and location of the Orlando detention pond and wetland system (modified from Martin and Smoot, 1986).

wetland system study in the Orlando area by Schiffer (1989b) described the effects of the Orlando detention pond and wetland system and other stormwater detention facilities on the quality of ground water in the surficial aquifer system. Sloat (1990) measured the accumulation of sediment in the Orlando detention pond and eight other ponds throughout Florida and developed an equation to predict accumulation rates based on drainage area and pond-surface area. Observed sediment accumulation was also compared to predicted accumulation based on the U.S. Environmental Protection Agency (USEPA) design manual for detention ponds (USEPA, 1986; Driscoll, 1983). Yousef and others (1990) studied the quality of sediments in the Orlando pond and other ponds around the State, evaluating the toxicity of the sediments and the feasibility for disposal of dredged sediments in landfills or other surface applications.

An initial hydraulic analysis was done by Martin (1988) before the pond was modified. Rhodamine WT fluorescent dye was released and tracked through the system in a series of trials to measure traveltime and mixing in the pond. Because of the short duration of storms and the unsteady character of stormflow, high-flow conditions were simulated at a relatively steady state by pumping water from an adjacent watershed into the storm-sewer drainage network for the pond. Five individual dye runs at different levels of discharge were made before modification of the pond. Results of these studies were used to calculate the hydraulic residence time of stormwater within the pond and wetland as a function of detained storage and discharge.

In response to growing concerns about surface water-quality problems and to Section 208 of the Clean Water Act, the USEPA initiated studies in the late 1970's of urban stormwater quality under the Nationwide Urban Runoff Program (NURP) and began to develop "best management practices" for stormwater management programs (Luskow and others, 1981; Finnemore, 1982). These practices included a number of land-management techniques to control nonpoint-source pollution, one of which was the use of stormwater detention ponds. Since then, a handful of studies have measured or monitored constituent retention in detention ponds and small lakes throughout the country (McCuen, 1980; Oliver and Grigoropoulos, 1981; Randall, 1982a; Scherger and Davis, 1982; Ferrara and Witkowsky, 1983; Gietz, 1983; Hampson, 1986; Martin and Smoot, 1986; Striegl, 1987; Wanielista and others, 1988; Pope and Hess, 1989; Veenhuis and others, 1989; Wu and others, 1989). Although flow and removal processes have been thoroughly described for process-reaction tanks in steady-state treatment applications (Weber, 1972), little work has been done to relate constituent retention to mixing and other processes in stormwater treatment systems.

The results of these studies have been used to quantify the benefits of stormwater treatment, but typically are too site specific to provide a single and comprehensive assessment of the overall effectiveness of stormwater detention ponds. The lack of a single assessment can result from the diversity of approaches and concepts in these studies, but it also reflects the variation in design of the study ponds themselves, which until recently has received comparatively little attention. Physical, chemical, and hydraulic properties were not measured in most of these studies, but when they were, the reported retention efficiencies could not be convincingly related to measured properties. System geometry was unchanged in most reported studies and consequently cannot be connected with any measurable effect on retention. One study by Schueler and Helfrich (1989) evaluated the influence of storm size on retention efficiency and reported a significant inverse correlation.

Overall, the conceptual framework for detention-pond studies and models of water-quality treatment effects remains incomplete. Beyond a basic input-output analysis, there are few conceptual tools to help identify and explore the important processes and reactions dictating the efficiencies of these systems. A detention-pond efficiency model developed for the USEPA by Driscoll (1983), partially based on the concepts of Small and DiToro (1979), is a first probabilistic attempt to conceptualize stormwater-treatment effects in terms of storm characteristics (frequency, intensity, and duration, among others), and takes into account pond volume and sediment-size distribution. However, this model does not incorporate the effects of pond shape on mixing and efficiency, nor does it account in any way for changes in pond-water quality between storms.

Description of the Original and Modified Pond and Wetland System

The Orlando detention pond and wetland system was built by the FDOT in 1980 and receives stormwater runoff from State Road (SR) 438 on the west side of Orlando, Fla. (fig. 2). The system was designed to be conceptually similar to primary and secondary stages of wastewater treatment. In concept, the pond provides "primary" treatment of wastewater by allowing sediments to settle out of stormwater. Biological processes in the pond and wetland then provide a form of "secondary" treatment between storms. Stormwater enters at the southern end of the detention pond through a submerged, 5-ft diameter culvert. The water then flows over a shallow, earthen spillway at the northeastern corner of the pond and into the wetland where it flows northward to a compound weir built around a drop outlet to the Little Wekiva River. The arrows in figure 2 indicate a general path of flow through the system as it was originally designed.

The pond was excavated in a layer of impermeable clay to a depth of about 9 ft. The sides are sloped at a 2:1 ratio and are protected by sand-cement riprap. Small shrubs, cattails, and other emergent aquatic vegetation have grown up around the sides and in submerged shallow areas. The bottom is covered by about 1.0 ft of dark, organic-rich sediment that has accumulated at a rate of about 0.1 ft/yr during the 10 years since construction (Sloat, 1990). The wetland adjacent to the pond is a natural cypress swamp. The bed material is a sandy, loamy silt, covered by organic sediments of varying thickness. Standing vegetation in the wetland is dominated by a canopy of mature bald cypress in the center and willow on the edges. Below the cypress canopy is a sparse understory of water hyacinth, duckweed, cattails, various small trees, and blackberry. In the center and deepest areas of the wetland the understory is absent.

The drainage area for this system is about 41.6 acres. Land use in 1987 included 32 percent paved roadway, 28 percent forest (or undeveloped), 27 percent high-density residential development (apartments), and 13 percent low-density residential development. The principal roadway is SR 438, a four-lane highway posted at a speed of 45 mph that in 1984 had a traffic count of about 22,000 vehicles per day (Martin and Smoot, 1986). The area of commercial land use has increased with the construction of a number of retail business and parking areas since 1982 when the first studies on this system began. Although these land-use changes likely have affected runoff from the basin, the extent of change in land use has not been determined.

Drainage to the pond is provided by an underground storm-sewer system (fig. 2). Numerous drop inlets are connected to the main storm sewer which parallels SR 438 and extends about 3,700 ft upgradient (west of the pond). About 1,000 ft of the storm sewer system is completely or partially below the pond-water level and, as a result, is submerged between storms, thus creating about 16,000 ft^3 of wet storage upstream from the pond. The remaining length of this system is above the static-water level of the pond; however, based on observations of the water-surface elevation (reflecting the water table) in several ponds near the highway, much of it seems to be below the water table. As a result, ground water seeps into the storm-sewer system and continues to flow into the pond between storms.

Stormwater Detention Capacity

As a "wet-detention" system, the pond and wetland remain partially full between storms. The volume retained between storms is commonly referred to as dead storage. The water-surface area of the pond is about 8,600 ft^2 and the dead storage is about 54,000 ft^3 between storms. The pond volume during storms can increase to 81,000 ft^3 of combined live and dead storage. This combined stormwater storage capacity is sufficient to handle about 0.55 in.of sufficient to handle about 0.55 in. of runoff from the basin, of which about 0.36 in. (65 percent) is held in dead storage. Average depths in the pond range from about 8 ft between storms to 11 ft during storms. The tightness of the clay surrounding the pond and the low water-table gradients suggest little ground-water inflow or outflow between storms (Schiffer, 1989b).

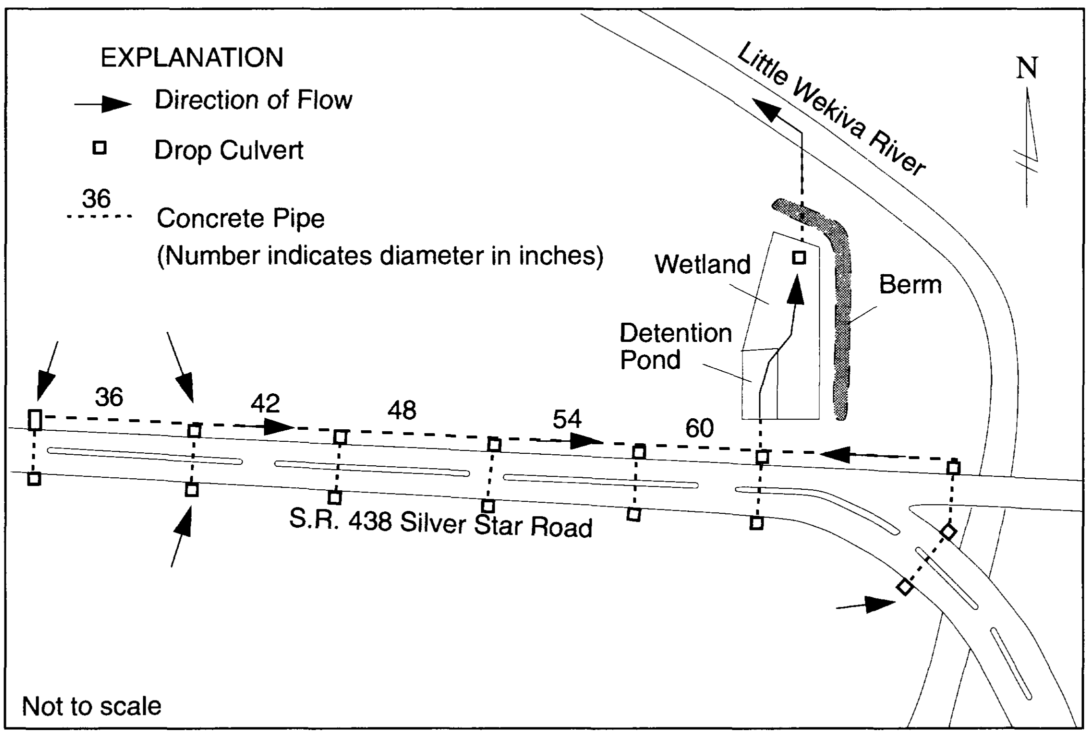

Figure 2. Plan view of the detention pond and wetland, and storm-sewer systems (modified from Martin and Smoot, 1986).

Although the wetland retains somewhat less water in dead storage than the pond does between storms, the wetland's live storage capacity is greater than that of the pond. The area of the wetland is about 32,000 ft^2, of which less than a third usually is submerged between storms. Water depths between storms range from 0 ft over much of the wetland, to 3 ft in depressions. Dead storage amounts to only about 20,000 ft^3 of water. During storms, water levels can rise 2 to 3 ft, and combined live and dead storage can increase to about 122,000 ft^3 (or about 0.8 in. of runoff from the drainage basin).

Live and dead storage contribute differently to the treatment effects of the system. Hydrographs for a typical summer storm illustrate the effects of storage on discharge intensity and detention time in the system. A hydrograph for the storm of August 20, 1982, (fig. 3) is a typical storm—near median size—and generated a total discharge volume of 48,500 ft^3, or about 90 percent of dead storage in the pond. Most of the stormwater entered the pond in about 40 min. Inflow to the pond peaked two-thirds of the way through the storm at about 28 ft^3/s, then rapidly decreased. The discharge peak at the pond-outflow point was attenuated by about one-third to about 18 ft^3/s; however, a time lag of only 8 min on the falling limb of the hydrograph indicates that live storage contributes little to stormwater detention time. Live storage has a relatively greater effect on detention time in the wetland, as shown by the wetland outflow hydrograph in which the discharge peak is attenuated to about 8 ft^3/s and the recession curve is more drawn out (extending to several hours).

Modifications

The detention pond was modified in 1988 to increase the flow path of stormwater in the system. Two principal changes were made. First, a curtain of rubberized fabric was installed from the south edge extending three-quarters of the way across the center of the pond (fig. 4). The curtain was draped from a steel cable stretching from end to end and was held down on the bottom by cement blocks. This effectively restricted stormwater from moving diagonally across the pond from the inlet to the outlet. The second change was the placement of a wall of concrete sacks along the northern and northeastern sides of the pond to prevent water from exiting as it had previously, at the low spot in the pond berm. This wall forced flowing water to move down the eastern side of the flow barrier and farther south along the edge of the pond prior to entering the wetland.

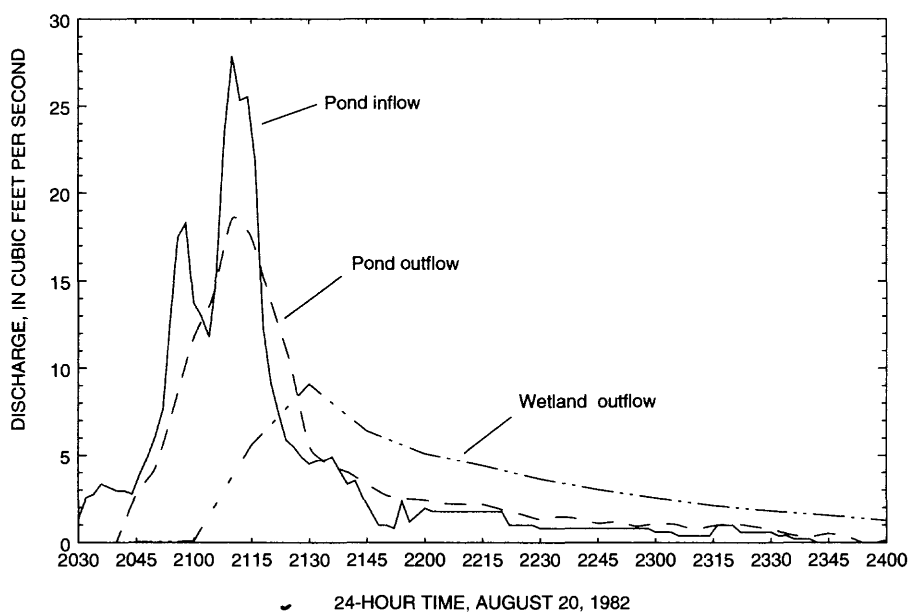

Figure 3. Discharge for a typical storm showing peak attenuation due to storage in the pond and wetland (modified from Martin and Smoot, 1986).

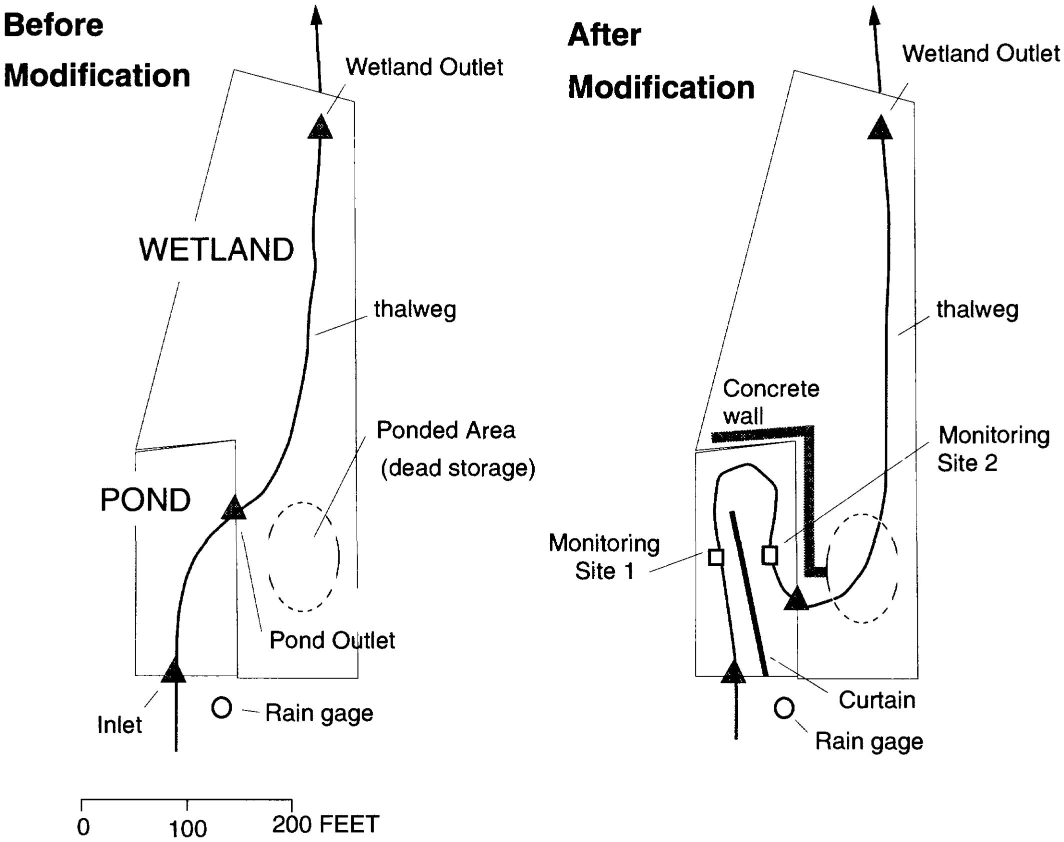

Figure 4. Plan view of pond and wetland before and after modification. (Thalweg shows rerouting of stormwater after modification.)

The modifications to the pond effectively redirected flow and lengthened the flow path in both the pond and wetland as shown in the after modification diagram in figure 4. From this figure, we might estimate the length of the flow path through the pond to be increased by a factor of 2; the increase in the length of the flow path in the wetland proportionately was less but can be as great as 30 percent. The depth of water and distribution of storage in the wetland is spatially uneven, and a large part of the dead storage is confined to a small area on the south end of the wetland, just east of the point where the water now enters from the pond. A small change in flow path through this area of the wetland can increase stormwater flushing of dead storage; however, the exact nature of this effect and the wetland storage in this area were not measured.

Instrumentation and Data Collection

Instruments used in the previous study were refurbished or reinstalled after the system was modified. A total of 22 storms were monitored and sampled between July 1989 and October 1990. Post-modification studies of stormwater mixing were done using a network of thermocouples to trace temperature fronts moving through the pond under dynamic-flow conditions. Dissolved oxygen, specific conductance, temperature, and pH were monitored in the pond between several storms in 1990 by pumping through hoses installed at several locations and depths in the pond. The evolution of the chemical composition of pond water between storms was determined in a single time series of four samples at several points in the pond collected over a 12-day period after a storm in February 1990.

Stormwater Discharge and Quality

Sample-collection frequency at the pond and wetland inlet and outlet varied during each storm in proportion to discharge. Velocity was monitored at the pond inlet using an electromagnetic velocity meter and inflow was computed by multiplying velocity by the cross-sectional area of the 5-ft diameter inlet pipe (19.6 ft^2). Outflow from the pond (inflow to the wetland) was computed from gaged inflow to the pond and the change in pond storage using a conservative flow-routing equation (Martin, 1988). Pond storage was computed from water-surface elevation and a stage-volume rating based on pond geometry. The pond water-surface elevation was monitored in stilling wells at the inlet and the outlet of the pond using a float-and-tape assembly driving an electrical potentiometer. Stage and velocity readings were made at 1-min intervals and recorded in 5-min averages by an electronic datalogger.

Outflow from the wetland was measured using a compound, sharp-crested weir built around a rectangular drop culvert at the wetland outlet. The water-surface elevation upstream from the weir was monitored using a float-and-tape assembly and a potentiometer; the data were recorded using an electronic datalogger at 5-min intervals. Discharge was computed for each 5-min interval using an analytical discharge rating for the weir. The rating was checked at low flows on several occasions and was accurate to within about 5 percent of measured discharges.

Stormwater samples were flow weighted. Dataloggers computed discharges at 1-min intervals and triggered automatic samplers at the inflow and outflow points of the pond and wetland. The first sample for each storm was collected at each location after the first 2,500 ft^3 of water passed the sampling point, and subsequent samples were collected at increments of 5,000 ft^3 of water. The samples from the pond inlet and outlet were collected in refrigerated plastic containers using vacuum-type automatic samplers housed in an instrument shed near the pond inlet. Samples of wetland outflow from the compound-weir outlet were collected in unrefrigerated plastic bottles using a peristaltic-type sampler. Sampling continued until flow receded to less than 10 percent of peak flow for the storm. Small storms were represented by as few as three samples.

Discrete flow-proportional samples were composited in equal parts at the site and subsamples were retained for chemical and physical analysis. Subsamples for analysis of major inorganic constituents and metals were acidified with nitric acid to a pH less than 2. Subsamples for analysis of nitrogen and phosphorus concentrations were preserved with mercuric chloride. All chemical and physical analyses were done by the USGS Analytical Laboratory in Ocala, Fla., using standard analytical techniques of the USGS described by Fishman and Friedman (1989).

Rainfall was monitored at the pond to identify changes in rainfall-runoff conditions and differences in the frequency distribution of storms sampled before and after pond modification. A tipping-bucket rain gage located near the pond inlet (fig. 4) recorded rainfall at 5-min intervals. A nonrecording, volumetric rain gage at the site was read at 2-week intervals. Rainfall recorded by the tipping-bucket gage was adjusted proportionately to match the observed rainfall in the volumetric gage for each 2-week period and was divided into individual storms greater than 0.1 in.

Stormwater Mixing

Thermal differences in pond-water temperature were monitored to evaluate the extent of stormwater mixing in the pond during storms. A network of thermocouples in the pond provided a relatively inexpensive means to study pond stratification and mixing in multiple dimensions during dynamic-flow conditions. Type-T (copper-constantan), high-precision thermocouple wire was placed along the bottom of the pond to six sites in the pond; these included one each at the inlet and outlet, and one at each of two depths (1.5 and 6.5 ft below the surface, identified as T and B, respectively), and at two locations along the modified flow path of the pond (fig. 5). Site 1 in figure 5 was located about 45 ft from the pond inlet. Site 2 was located a similar distance from the inlet, but on the opposite side of the fabric curtain, about 30 ft from the pond outlet. The thermocouples were monitored at 5-min intervals from February through the summer of 1990. Temperatures were automatically recorded by a datalogger using a standard type-T rating.

The accuracy of the thermocouples and the datalogger rating was checked before installation in the field and was within 0.5 C° over a range of 4 to 30 °C. Subsequent field checks at each thermocouple location indicated that thermocouple and standard lab thermometer temperatures agreed within 0.5 C°. Thermocouple precision was somewhat greater than accuracy. In a preinstallation test conducted for a period of several days, eight thermocouples reading side-by-side in a 2-L bea-

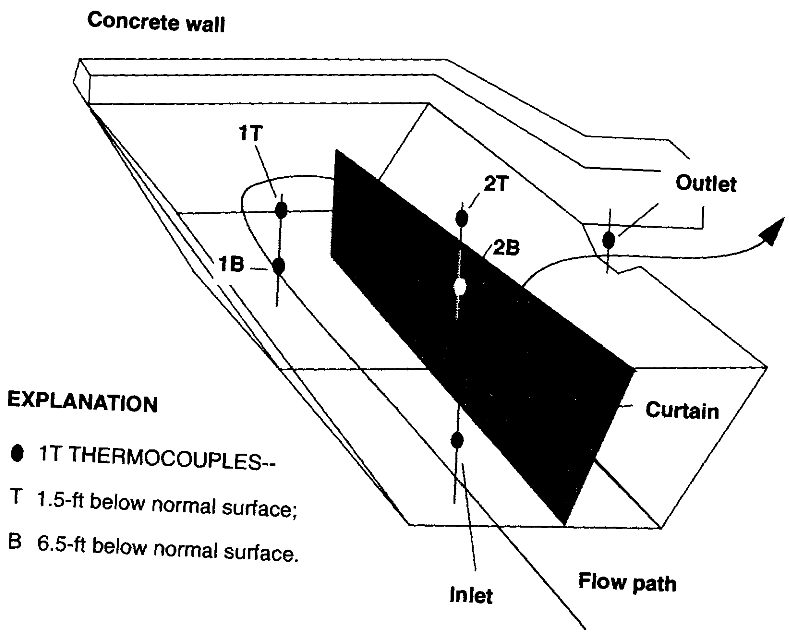

Figure 5. Location of thermocouple monitoring sites and between-storm sampling points in relation to the modified flow path.

ker of water consistently agreed within 0.1 C°. Measurements from thermocouples installed in the pond and set at the same depth under stratified conditions also generally agreed within about 0.1 C°.

Pond-Water Chemistry Between Storms

A system for monitoring pond-water chemistry between storms was installed in the pond in January 1990 to collect samples at selected locations and depths without causing vertical or horizontal mixing. Polypropylene hoses with a 3/8-in. inside diameter were installed from the instrument shed near the pond inlet to two depths at each of nine locations evenly distributed across the pond. Each location was equipped with hoses at two sampling depths, 1.5 and 6.5 ft below the normal surface elevation between storms. Concentration data for two of the locations (sites 1 and 2 in fig. 4) are included in this report. A peristaltic pump at the instrument shed was used to quiescently withdraw samples from each hose at the two sampling depths below the surface of the pond. The sample water was pumped through a 2-L glass container in which dissolved-oxygen concentration, specific conductance, temperature, and pH were measured. After a preliminary evaluation of changes in physical water-quality characteristics at these nine sites, four samples in a time-series were collected for chemical analysis from a subset of two sites after a large volume storm on February 23, 1991. The samples were collected from near the top and near the bottom of the pond (1.5 and 6.5 ft depths) at sites 1 and 2 at about noon on the 2nd, 4th, 7th, and 12th day after the storm. Temperature, pH, specific conductance, and dissolved oxygen also were measured at the sites.

Analytical Approach to Retention Efficiencies

The effects of detention were measured as fractional changes in stormwater constituent concentrations within the pond and wetland. Conceptually, changes in constituent concentrations can be observed over a scale of temporal resolutions including: individual plugs of water (discrete samples), individual storms (composited means), extended periods of stormwater and base flow. The following analysis is related primarily to storm-averaged data.

Measures of Efficiency and Transport

Retention efficiencies (*REs*) are common measures of constituent retention and are based on concepts developed in work on sedimentation. The basic efficiency computation in fractional form can be expressed by the equation:

$$RE = \frac{\text{Inflow} - \text{Outflow}}{\text{Inflow}}, \qquad (1)$$

where Inflow and Outflow represent concentrations or loads entering and leaving the system. Retention efficiency is related to transport ratio by the following:

$$RE = 1 - TR. \qquad (2)$$

Transport ratio (*TR*) is the fraction of inflow constituent load, or concentration "transported" through the system:

$$TR = \frac{\text{Outflow}}{\text{Inflow}}. \qquad (3)$$

Though retention efficiencies are the primary focus of this report, transport ratios are substituted in the analysis later in the report to facilitate numerical computations. The range and distribution of *TR*s (positive and log-normal) have proven better suited to certain kinds of mathematical evaluation and analysis. Where discharge is strictly conservative (inflow=outflow), retention efficiencies are equivalent whether computed on concentrations or loads. However, even where discharge is not strictly conserved, an efficiency computed on concentration can be the more definitive measure of processes affecting retention—particularly where the study interest is in discerning a change in retentive properties of a defined system. Flow in this pond and wetland system has proven to be generally conservative. Given this, and the nature of the study, the retention efficiency analysis presented here is based on concentration data. The importance of discharge in determining a weighted-mean efficiency is discussed in greater detail later in this report.

An Input-Output Model of Retention Efficiency

Retention efficiencies are determined by fundamental and physical relation to constituent concentrations in stormwater, constituent concentrations within receiving pond water prior to an inflow event, residence time in the pond during an event, and the mixing and flushing of pond water and stormwater. The interrelated effects of these conditions introduce variability into retention efficiencies measurements that confound the identification of patterns and trends. A simple black-box mixing model (fig. 6) is presented here to illustrate the basic properties of retention efficiencies in relation to these causative factors. This model will provide the physical basis for an in-depth analysis of retention efficiencies in relation to inflow concentrations, stormwater volumes, and through-flushing later in this report.

Retention efficiencies can be expressed as a mass-balance of loads where the flushing of pond water during an event and the attenuation of stormwater constituent concentrations are reduced to constants:

$$RE = 1 - \frac{L_s + L_p}{L_{in}}, \qquad (4)$$

where

L_s is the load leaving the pond that originated in stormwater,

L_p is the load leaving the pond that originated in the pond before the storm, and

L_{in} is the load entering the pond in stormwater.

The fraction of pond water contributing to outflow from the system can be expressed by a pond-flushing coefficient (*m*):

$$m = \frac{V_p}{V_{out}}, \qquad (5)$$

where

V_p is the volume of antecedent pond water discharged from the pond during a storm, and

V_{out} is the total volume of flow through the pond.

By substituting equation 5 into equation 4 and simplifying, *RE* can be expressed by equation 6:

$$RE = 1 - \frac{V_{out}(1 - m) \times C_{in}(1 - R) + V_p \times C_p}{V_{in} \times C_{in}}, \qquad (6)$$

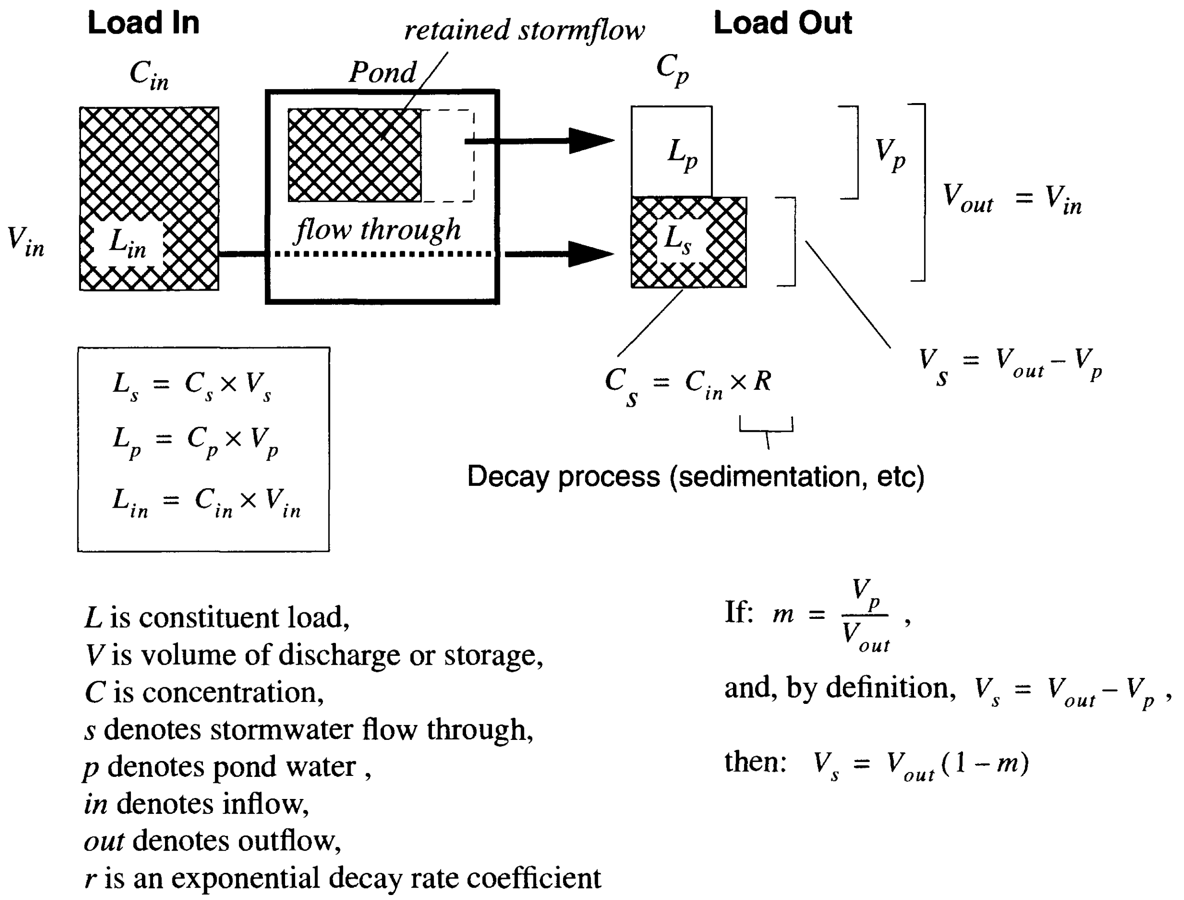

Figure 6. Schematic of stormwater and pond-water mixing model. (Constituent retention is a function of the proportionate mixing of dissimilar waters, and the rates of decay processes (sedimentation, sorption, and assimilation).)

where

C_p is the average constituent concentration in the pond before a storm,

C_{in} is the average constituent concentration in stormwater inflow,

V_{in} is the volume of stormwater inflow, and

R is defined as the capture rate and is the fraction of constituent load retained per unit of inflow load.

And the system is assumed to be discharge conservative ($V_{in} = V_{out}$).

Collecting terms, the equation describing the nature of *RE*s in a mass-balance system can be simplified from equation 6 to:

$$RE = 1 - \frac{C_p}{C_{in}} \times m + (1 - m)(1 - R) . \qquad (7)$$

This model generally illustrates the reciprocal relation of transport ratio (1-*RE*) to inflow concentration, and the proportional relation of transport ratio to pond-water flushing. For a completely conservative constituent, *R* equals .0, and *RE* is a function only of the ratio of pond-water to stormwater constituent concentrations and the relative proportions of pond water and stormwater leaving the pond. For small storms, where little or no mixing occurs, *m* equals 1 and *RE* is related strictly to the ratio of pond-water to stormwater constituent concentrations. In contrast, during large storms or when a pond short circuits, *m* is reduced as water passes directly from inflow to outflow, by-passing dead storage. When *m* approaches zero, *RE* is strictly related to the magnitude of *R*.

A Minimum Variance, Unbiased Estimate of Mean Retention Efficiency

Individual retention efficiencies for discrete storms are commonly averaged to evaluate the overall or long-term effects of detention on stormwater quality. Several common approaches have been used to evaluate average efficiencies (Martin, 1988). The most conservative approach in terms of the variance of the mean retention efficiency estimate is the equal-discharge weighting approach (USEPA, 1983). This has been called the EMC approach because it is calculated as the ratio of average inflow to outflow event-mean concentrations (EMCs). The EMC is a flow-composited mean concentration for each storm. In computing retention efficiencies on concentrations instead of loads, the EMC approach assumes equal-discharge weight for each retention efficiency estimate. This tends to increase the precision of the estimate (Neter and Wasserman, 1974). The simple arithmetic EMC efficiency, however, is not a minimum variance unbiased estimate (MVUE) of mean retention efficiencies and tends to vary to a greater extent on the low side of true mean efficiency.

The simple EMC retention efficiency approach (USEPA, 1983) is given in equation 8:

$$E_{EMC} = 1 - \frac{\left(\dfrac{\sum_{i=1}^{n}(Co_i)}{n}\right)}{\left(\dfrac{\sum_{i=1}^{n}(Ci_i)}{n}\right)}, \qquad (8)$$

where

E_{EMC} is retention efficiency computed from average EMCs,

Ci_i is inflow EMC for storm i,

Co_i is outflow EMC for storm i,

n is number of storms sampled, and

$_i$ indicates the individual storms sampled.

By rearranging equation 8 to equation 9, it can be shown that the EMC retention efficiency is equivalent to a mean of individual storm-averaged transport ratios weighted by inflow EMCs.

$$E_{EMC} = 1 - \sum_{i=1}^{n}\left(\frac{Co_i}{Ci_i} \times \frac{Ci_i}{\sum_{i=1}^{n} Ci_i}\right), \qquad (9)$$

where

E_{EMC} is retention efficiency computed from average EMCs,

Ci_i is inflow EMC for storm i,

Co_i is outflow EMC for storm i,

n is number of storms sampled, and

$_i$ indicates the individual storms sampled.

The simple arithmetic averaging of EMCs in equation 8 assumes that the distributions of EMCs are normal. In practice, it has been shown that many of the chemical constituents monitored in water-quality studies do not fit assumptions of normality and log-transformations of water-quality data have become common place in scientific literature. Because many water-quality constituents appear to fit a log-normal distribution, MVUEs based on log-transformed data have been developed and widely used to provide more robust measures of central tendency while correcting for log-transformation bias (Gilbert, 1987).

A modified approach to equation 8 to account for the potential lack of normality in EMC can be adapted from the concept of a MUVE. A simplified approximation of the MVUE of the mean of a lognormal distribution of the variable is expressed by equation 10 (Gilbert, 1987):

$$\hat{\mu} = 10^{\left(\bar{Y} + \frac{S_y^2}{2}\right)}, \qquad (10)$$

where

$\hat{\mu}$ is the minimum variance unbiased estimate (MVUE) of the mean of x,

$\bar{Y}$ is the mean log(x), and

S_y^2 is the variance of log (x).

The bias correction term is a simplification of the exact solution which is an infinite series. A more rigorous solution uses an estimate of the correction term based on sample size (Aitchison and Brown, 1969).

By substituting equation 10 for the numerator and denominator in equation 8, the equation for the MVUE of efficiency takes the form

$$E_{MVUE} = 1 - \frac{\left(10^{\bar{Y}_{Co} + \frac{S^2_{y_{Co}}}{2}}\right)}{\left(10^{\bar{Y}_{Ci} + \frac{S^2_{y_{Ci}}}{2}}\right)}, \qquad (11)$$

or

$$E_{MVUE} = 1 - \left(\frac{10^{(\bar{Y}_{Co})}}{10^{(\bar{Y}_{Ci})}} \times 10^{\left(\frac{S^2_{y_{Co}} - S^2_{y_{Ci}}}{2}\right)}\right), \qquad (12)$$

where

E_{MVUE} is the minimum variance unbiased estimate of EMC retention efficiency,
$\bar{Y}_{Co}$ is the mean $\log_{10}$ (outflow EMCs),
$\bar{Y}_{Ci}$ is the mean $\log_{10}$ (inflow EMCs),
$S^2_{y_{Co}}$ is the variance of log (outflow EMCs), and
$S^2_{y_{Ci}}$ is the variance of log (inflow EMCs).

When the variances of the log-transformed inflow and outflow EMCs are equal, the bias correction term in equation 12 resolves to a factor of 1 and ceases to be important. Equal variance in log-transformed data implies that population distributions vary in equal proportions to their means. That is, sample distributions with higher average concentrations also have larger variances. The assumption of equal variance is readily accepted in statistical inference testing and is reasonable, if not essential, for any meaningful analysis of average retention efficiencies. By assuming equal variances, equation 12 can be further simplified to a simple geometric mean of individual storm retention efficiencies as shown in equation 13:

$$E_{MVUE} = 1 - 10^{\left(\frac{\sum_{i=1}^{n} \log\left(\frac{Co_i}{Ci_i}\right)}{n}\right)}. \qquad (13)$$

From equation 13, the geometric mean of individual storm efficiencies is shown to be a MVUE of average retention efficiency of the system which is equivalent to EMC efficiencies expressed in equations 8 and 9. Because the MVUE approach was judged to be generally a more robust method for small sample sizes, it was the approach adopted in this report.

STORMFLOW HYDROLOGY

Discharge record at the wetland outlet was complete for the period July 1989 to October 1990, except for 10 days in August 1989. Because the discharge record generally was more consistent and reliable for the wetland outlet than for the other discharge-gaging sites, wetland discharge was used to compute overall storm volume for each storm in the period. Sustained ground-water inflows maintained minimal flows and dead storage throughout the period of study. Storm-discharge hydrographs were separated from an estimated base flow of 0.03 ft^3/s at the wetland outlet. Inflow and outflow from the pond were measured as a basis for compositing storm samples, and were generally in agreement with total volumes of outflow from the wetland on a storm-to-storm basis.

Rainfall and Runoff During the Study Period

The intensity of stormwater discharge and the size of storms vary seasonally with the changing frequency of frontal and convective storms. Frontal storms, which are common in late autumn, winter, and early spring, tend to be of fairly long duration and lower intensity. These storms may last several hours to several days, and can generate large inflow volumes, but generally produce low inflow rates. Convective storms, in contrast, are intense, short-lived thunder showers typical in summer and early autumn. These storms may last only 5 to 50 min, but produce higher inflow rates than do frontal storms. Although convective storms generally are more frequent than frontal storms, and on average are smaller, they generate somewhat more annual stormwater discharge than do frontal storms.

Although the single largest daily discharge during a sampled storm was from a large frontal storm on

February 23, 1990, large-volume storms were more common in the summer. Daily discharge from the wetland and cumulative runoff from the drainage basin from July 1989 to October 1990 are shown in figure 7. During this period, 69 storms produced about 20 in. of runoff in the basin. This represents about 16 in. of runoff annually, most of which occurred from June through September.

A change in the relation of rainfall to runoff after pond modification can result from land-use changes in the drainage basin. Generally, runoff for storms after modification was about 38 percent of rainfall; runoff before modification was about 32 percent of rainfall (fig. 8). This change, which cannot be related to the modification of the pond, probably is caused by increases in the hydraulically effective

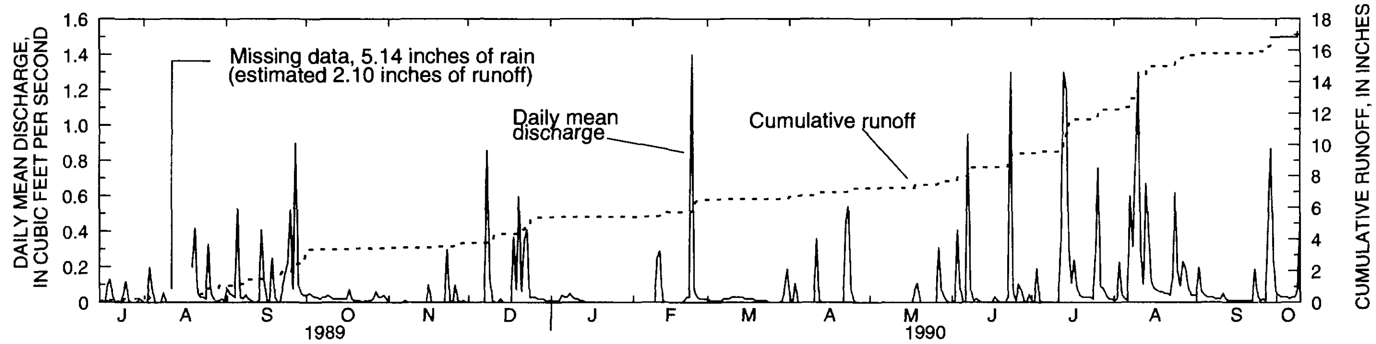

Figure 7. Daily mean discharge and cumulative stormwater runoff at the wetland outlet. (Runoff is greatest in the period from June to September.)

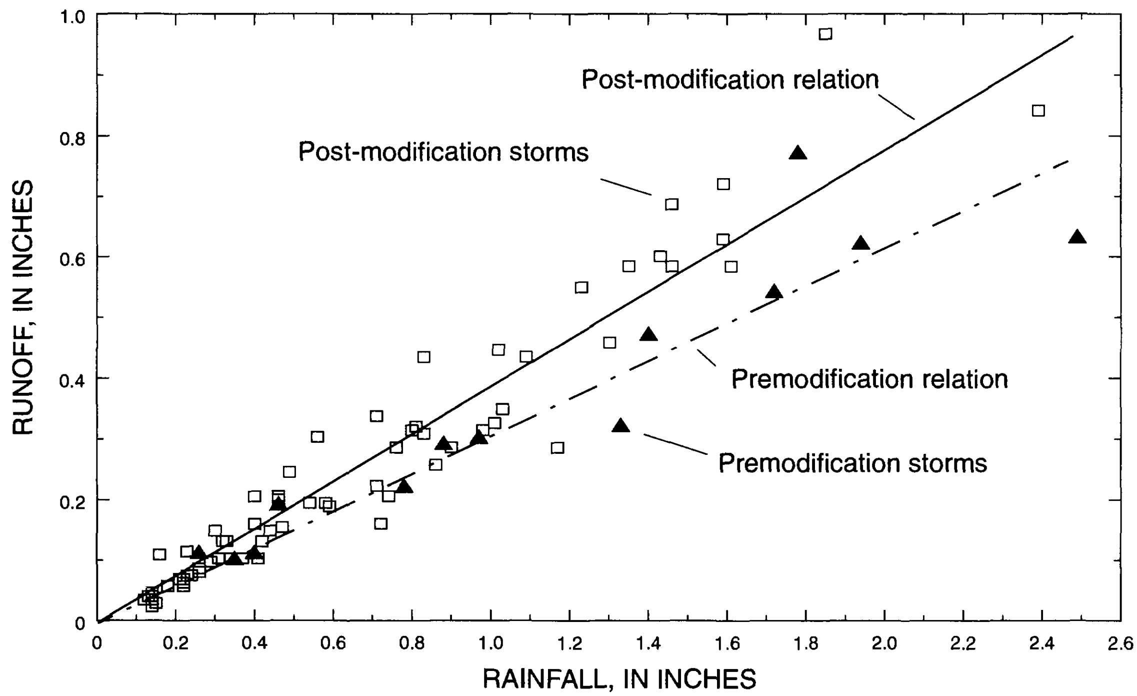

Figure 8. The relation of stormwater runoff to rainfall. (The change in relation after modification may be caused by changes in land use.)

impervious area associated with increasing urban development in the drainage basin observed during both studies (before and after modification).

Storm Volume and Distribution of Sampled Storms

The size-frequency distributions of sampled storms were similar before and after modification. Mean rainfall for after-modification storms (0.92 in.) was less than that for before-modification storms (1.13 in.). However, the mean storm runoff for the two sets of storms was nearly equal because of the increase in the ratio of runoff to rainfall over the period of the study. Twenty-two of the 69 after-modification storms gaged were sampled for constituent retention. Runoff from sampled storms ranged from 0.07 to 0.97 in. (table 1). Pond volume (or pond-water flushing) for sampled storms ranged from about 19 to about 235 percent of dead storage in the pond (54,000 ft^3). Runoff for the average-sized storm sampled was 0.37 in. (about 55,000 ft^3) which is approximately equal to the dead storage of the pond. None of the recorded storms exceeded the live and dead storage of the combined pond and wetland system.

Table 1. Descriptive information for storms sampled after pond modification

[ft^3/s, cubic feet per second; ft^3, cubic feet; --, no data]

Date	Rank[a]	Rain (inches)	Runoff (inches)	Rain-fall/ runoff ratio	Wet-land outflow (inches)	Storm volume		Previ-ous dry time (days)
						(ft^3)	(per-cent)[b]	
July 18, 1989	1	0.21	0.069	0.327	0.12	10,400	19.2	--
July 19, 1989	2	.23	.074	.323	.13	11,200	20.8	1
Aug. 25, 1989	7	.54	.195	.360	.34	29,400	54.4	5
Sept. 5, 1989	8	.90	.286	.318	.50	43,200	80	4
Sept. 18, 1989	5	.40	.160	.401	.28	24,200	44.8	4
Sept. 22, 1989	15	1.03	.349	.339	.61	52,700	97.6	4
Sept. 25, 1989	12	.80	.315	.393	.55	47,500	88	1
Feb. 23, 1990	21	2.39	.841	.352	1.47	127,000	235	13
Mar. 31, 1990	3	.37	.103	.278	18	15,600	28.8	1
Apr. 23, 1990	9	.76	.286	.376	.50	43,200	80	12
May 27, 1990	6	.59	.189	.320	.33	28,500	52.8	9
June 3, 1990	10	1.17	.286	.245	.50	43,200	80	6
June 7, 1990	18	1.35	.584	.432	1.02	88,100	163	4
June 23, 1990	19	1.59	.629	.396	1.10	95,000	76	1
June 26, 1990	4	.34	.103	.303	.18	15,600	28.8	3
July 13, 1990	20	1.59	.721	.453	1.26	108,900	202	1
Aug. 9, 1990	17	1.02	.446	.438	.78	67,400	125	2
Aug. 10, 1990	22	1.85	.967	.523	1.69	146,000	270	1
Aug. 13, 1990	16	.83	.435	.524	.76	65,700	122	3
Aug. 24, 1990	14	.71	.338	.475	.59	51,000	94.4	1
Sept. 28, 1990	11	.83	.309	.372	.54	46,700	86.4	5
Oct. 10, 1990	13	.81	.320	.396	.56	48,400	89.6	10
Mean	--	.92	.364	.373	.64	55,300	102	4.33
Before-modification mean (Martin and Smoot, 1986)		1.13	.350	.318[c]	--	53,000	98.2	--

[a]Ranked by runoff from smallest to largest.

[b]Storm volume as a percentage of pond volume.

[c]Rainfall-runoff ratio was significantly higher during after-modification phase of study (a=0.05, students t-test on log-ratios).

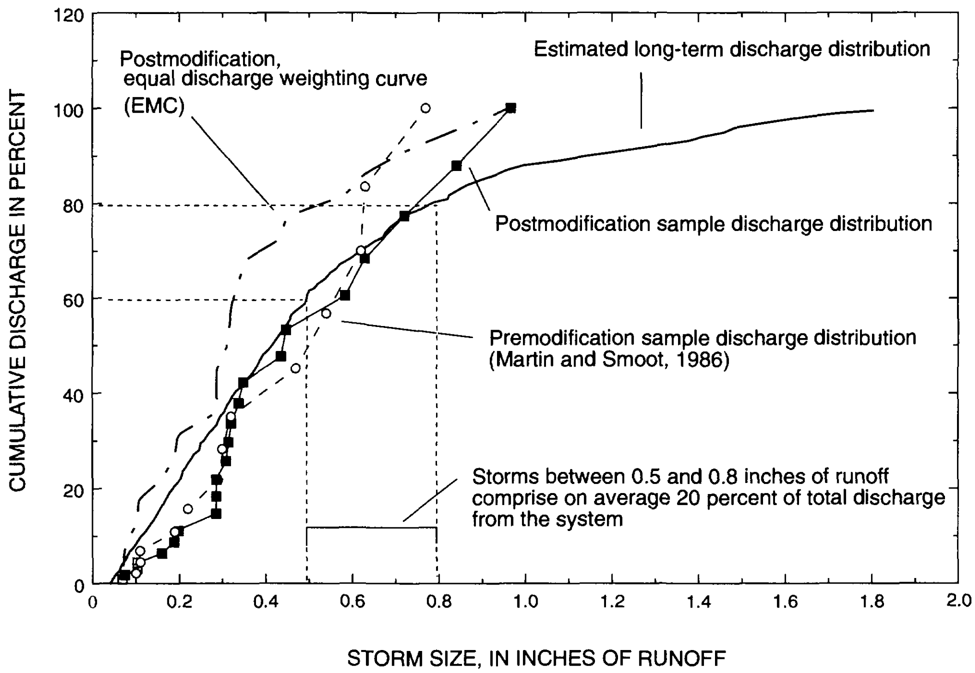

Figure 9. Long-term and sample cumulative-discharge distributions. (The slope of the curve indicates the relative contribution by storms of a given size class. The equal discharge line shows an equivalent curve when all storms are held to be of the same volume as in the computation of the EMC retention efficiencies.)

The relation of storm size to stormwater contribution is illustrated in a cumulative-runoff plot (fig. 9). A long-term (17 yr) average cumulative-runoff curve was estimated from rainfall data collected at the National Oceanographic and Atmospheric Administration (NOAA) rain gage in Orlando. Storms with rainfall greater than 0.1 in. during this period were listed in order from smallest to largest and summed, the incremental sums were then divided by the total accumulated rainfall. Equivalent stormwater-runoff volumes were computed for this distribution using the after-modification relation of rainfall to runoff observed for the study basin. Cumulative discharge curves also are shown for before- and after-modification sample sets based on measured storm volumes for each storm sampled. The match of the cumulative before- and after-modification curves and the long-term average curve indicates the representativeness of the two sample distributions for long-term conditions. For both sample distributions, storms producing less than 0.3 in. of runoff (where the slope of the sample curves is lower than that of the long-term curve) are under represented relative to long-term distributions. However, sample storms greater than 0.65 in. of runoff are overrepresented relative to typical volume contribution.

Though the E_{MVUE} approach applied in this paper is not weighted for discharge, the sample frequency distributions for storm volume do affect the representativeness of mean efficiencies. Discharge-weighted mean efficiencies based on load give more weight to large storms than to small storms on the premise that large storms contribute more to overall loading. However, large storms should not necessarily be sampled more frequently, nor given greater weight than small storms based simply on storm volume or load. Although small storms generally contribute less load than large storms individually, small storms are typically more frequent and contribute an equal or greater portion of total discharge and load. If storms of all sizes were sampled in correct proportion to their frequency distributions and in sufficient numbers, the volume distribution over the range of storm sizes would correctly represent the true volume distribution, and a load-based average retention efficiency would provide an unbiased estimate of the true population mean. Within the set of storms sampled for this study, large storms were overrepresented based on volume.

As a result, a mean *RE* for this system based on load cannot be presupposed to be any better a representation of the true mean than the E_{MVUE} based on concentration.

MIXING OF STORMWATER WITH DETENTION-POND WATER

Generally, the outcome of stormwater treatment in wet ponds may be seen as the product of four functional attributes of the system. These are (1) process rates (sedimentation, oxidation, etc.) in stormwater as it is conveyed through the system, (2) the residence time of stormwater in the system, (3) the extent of mixing of stormwater and pond water during storms (affecting both residence time and pond-water flushing), and (4) the quality of water resident in the pond at the beginning of the storm relative to the quality of incoming stormwater. Process rates generally are very difficult to determine in an uncontrolled environment and may be themselves dependent on the pattern of mixing and the quality of the water in the pond before a flow event. However, mixing and resident-water quality may to some extent be directly observed.

Mixing in process-reaction tanks generally is similar to one of two hydraulic flow regimes—plug flow and completely mixed flow. Plug flow is the movement of discrete "plugs" of water from the inlet of a tank (or pond) to the outlet without substantial mixing or diffusion. Completely mixed flow, as the term implies, is a randomized process in which water entering the tank mixes immediately and completely with water residing in the tank.

In practice, mixing and water movement in detention ponds usually falls somewhere between these two extremes. Martin (1988) reported that before modification the flow through the study pond was neither completely mixed flow nor plug flow. Depending on inflow rate and transient storage within the pond, stormwater appeared to flow along preferential pathways that effectively bypassed or short-circuited a complete flushing of the pond. Although some mixing probably occurred in secondary circulation cells formed by preferential currents, substantial parts of the dead storage of the pond were not mixed or flushed by incoming stormwater. The result was a reduction in the average residence time and effective volume of the pond.

Stormwater Movement for Typical Storms

Generally, the extent of stormwater mixing in the pond is seasonally related to stormwater volume, inflow rates, and pond and stormwater temperatures. Cooler inflow temperatures allow stormwater to be trapped near the bottom of the pond (fig. 10). High inflow rates may overcome vertical temperature gradients and cause mixing, but as inflow rates recede, thermal gradients usually are reestablished. The pond is free to mix vertically only when inflow temperatures are fairly uniform and similar to pond temperatures—a condition most commonly associated with warmer inflow in summer. Because both temperature and inflow rates tend to increase from winter to summer, mixing in the pond can span a continuum from extremes of sheet flow and filling vertical plug from the bottom in winter (cool water and low inflow rates) to plug flow in summer (warmer water and high inflow rates).

Vertical gradients of more than 5 °C are common between storms. Temperatures can drop more than 4 °C in about 18 hrs at the surface of the pond. This rate (about 0.22 C° per hour) is indicative of the ambient diffusion heat from the system and, as such, provides the standard against which stormflow-related changes in temperature can be compared.

A series of temperature plots (figs. 11-13) for three selected storms illustrate how temperature, inflow intensity, and storm volume typically affect mixing and residence time in the pond. Storm intensity in figures 12 and 13 is represented by instantaneous and cumulative discharge hydrographs. The location of thermocouples is shown in figure 5.

Persistent vertical-temperature gradients during and after small storms suggest that flow is not completely mixed and that most of the stormwater entering the pond is retained. The March 30, 1990, storm was small, and of low intensity and short duration. Total inflow was only about 17.5 percent of the volume of the pond. A drop in temperature at the pond outlet shortly after inflow began (fig. 11) was probably a response to water near the outlet moving from the middle to near the surface of the pond. Had stormwater been the cause of the temperature change, it would have arrived later and resulted in greater cooling. A slight decrease in temperature near the surface of the pond could have been caused by limited vertical mixing, but also might be explained by the inflow of cool water near the bottom of the pond and upward vertical displacement of the temperature gradient.

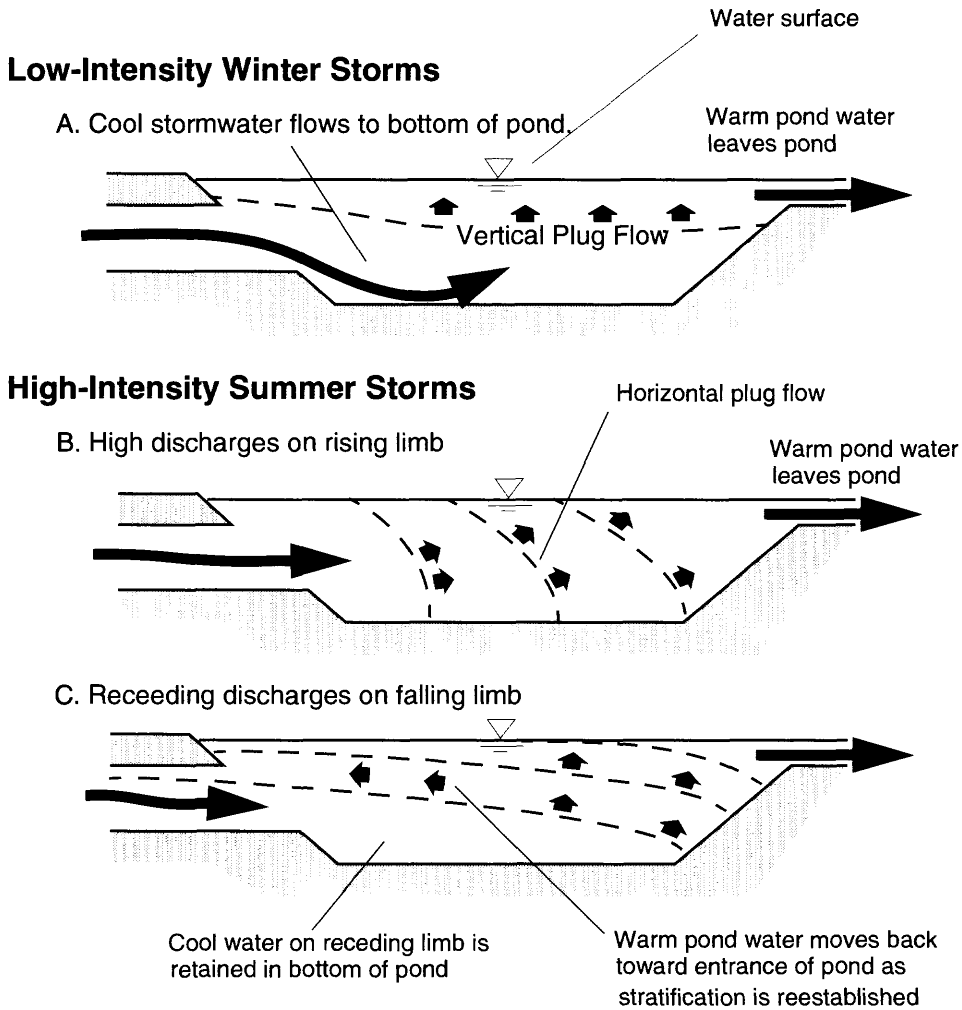

Figure 10. Movement of water through the pond during low- and high-intensity storms.

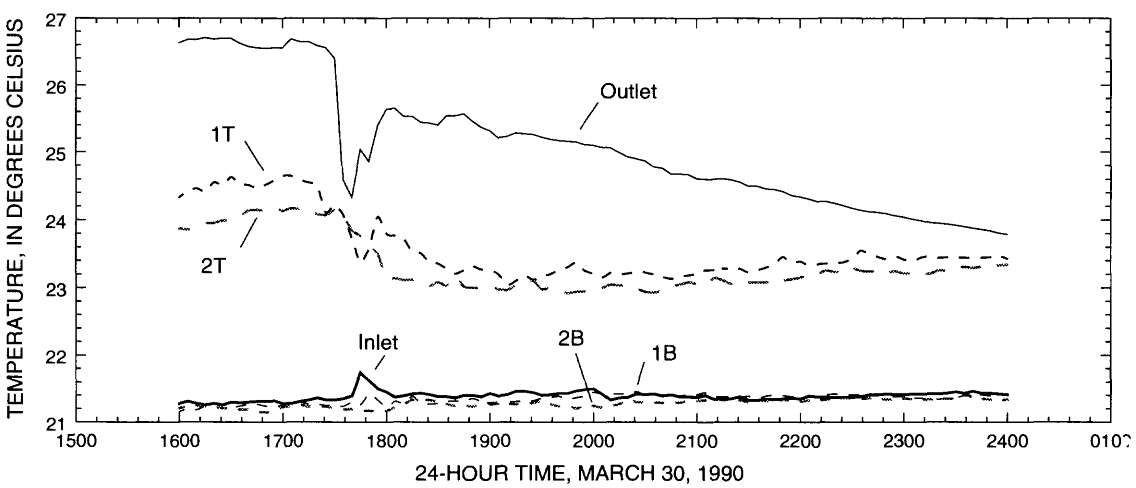

Figure 11. Temperatures in the pond during the storm of March 30, 1990, showing relative stability in temperature gradients. (See fig. 5 for site locations.)

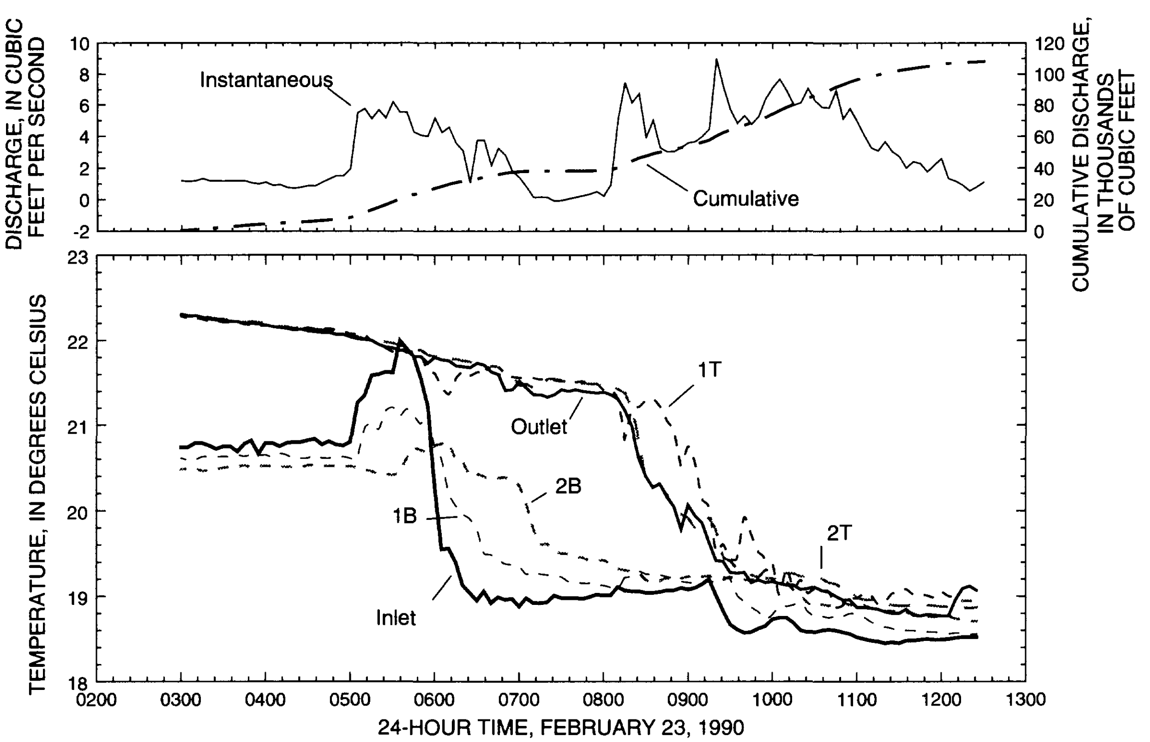

Figure 12. Discharge and temperature patterns in the pond for a typical winter storm that occurred on February 23, 1990.

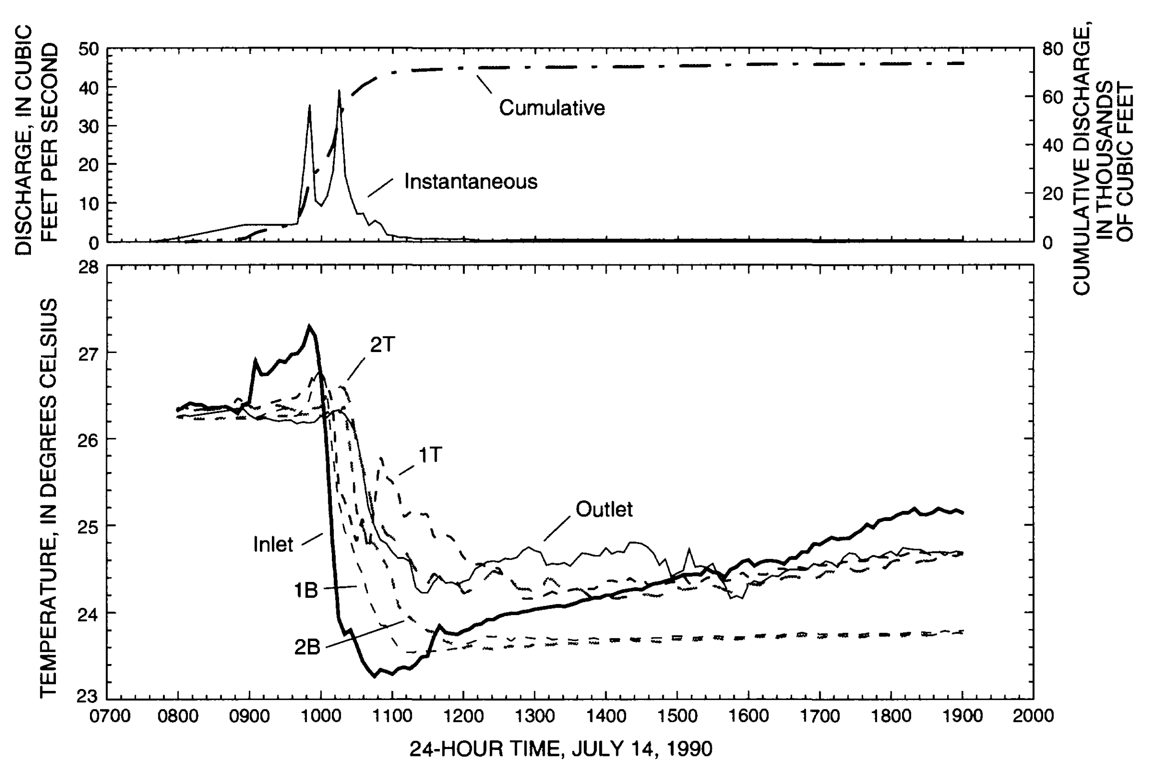

Figure 13. Discharge and temperature patterns in the pond for a typical summer storm that occurred on July 14, 1990.

Thermal fronts moving through the pond during larger storms are indicative of traveltime and mixing in the pond. As an example, before the large storm of February 23 (fig. 12), pond temperatures were uniformly stratified—about 20.6 °C at the inlet and bottom thermocouples (6.5 ft below the surface), and about 22.3 °C near the top (1.5 ft below the surface) and outlet thermocouples. During the first hour of flow (from 5:00 to 6:00 a.m.), the inlet temperature increased about 1.5 °C. This was in response to the inflow of warmer water that had been stored in the sewer system upstream from the pond combined with warm stormwater carrying residual heat from the pavement early in the storm. After the first hour, the inflow temperature dropped sharply by about 3 °C—as unmixed storm runoff began entering the pond. This pattern of increasing, then sharply decreasing, temperatures in stormwater inflow—typical of this and most other storms—can be seen to move through the pond over time in much the same way as might a dye or some other tracer; and as such, provides a reasonable measure of traveltime through the pond.

The propagation of this thermal front through the pond in the February 23 storm suggests that for typical winter storms (low inflow rates, long duration), inflow momentum may fail to overcome thermal energy gradients established between and during storms. Consequently, inflow is forced into a kind of layered, vertical plug flow similar to that described for some lakes by Fischer and others (1979)and shown schematically in figure 10. This phenomenon is illustrated in figure 12 by the arrival of the thermal front at the lower thermocouple on the outflow side of the curtain (2B) at about 1 hr and 20 min into the storm, long before its arrival at the upper thermocouple on the inflow side of the curtain (1T) at about 3 hrs into the storm. This progression of the thermal front in order from inlet to 1B, 2B, 2T, outlet, and finally, 1T, can only be explained by vertical plug flow—displacing dead storage in the pond from the bottom up. The lag in temperature drop near the surface on the inflow side of the curtain (the last to drop) may indicate unmixed pond water on the inlet side of the curtain trapped by up-welling stormwater as it leaves the pond on the outlet side of the curtain.

Storms producing greater inflow rates demonstrate characteristics of both vertical and horizontal plug flow. Before the storm of July 14, 1990 (fig. 13), temperatures were nearly uniform for all thermocouples (no obvious stratification). As stormwater entered the pond, the temperature at the inlet increased then decreased sharply for similar reasons noted for the February 23 storm. Warm water arrived at 1B and 1T (inflow side) about 45 min after the beginning of inflow, and at 2B and 2T (outflow side) about 15 min later. The arrival of the warm front at both levels in the pond at about the same time suggests that this initial volume of water remained uniformly distributed in the vertical as it moved through the pond, approximating plug flow (fig. 10). The attenuation of peak temperature in water moving from the inlet to 1T, indicates some horizontal advective mixing. By the time the warm water reached 2T, the difference in peak stormwater temperature and prestorm pond temperature had dropped by about two-thirds. This drop from about 27.3 to 26.6 °C represents an attenuation rate of about 1.5 °C per hour.

Just after 10:00 a.m., cool water entered the pond and moved fairly quickly through to the outlet (about 20 min traveltime). From the timing of the thermal front as it arrived at each thermocouple, flow appears to have been vertically coherent, and characteristic of plug flow. The increasing lag time from bottom to top thermocouples as the front progressed from set 1B/1T to 2B/2T, indicates a tendency for the thermal front to spread as it moves—as does a slight change in the rate of temperature decline (fig. 13). After inflow peaked at about 10:15 a.m. and the pond began to drain, the spread of the temperature traces indicates a tendency for the thermal front to first slow, and then to begin to level out into a more vertical form of plug flow similar to the lower intensity February storm (fig. 12). The last and coolest water entering the pond was then trapped near the bottom of the pond (1B and 2B at 11:00 a.m.) by thermal stratification initiated by the thermal layering of inflow during the storm. As in the February storm (fig. 12), an increase in temperature at 1T as the pond began to drain may indicate the redistribution of water trapped in the inlet side of the curtain. As the temperature of stormwater increases in summer months (approaching pond-water temperatures), the effect of temperature on flow and stratification during storms seems to decrease.

Effects of Storm Volume and Flow Regime on Flushing Rate

The effects of flow regime and storm volume on retention efficiencies are illustrated by their relations to the stormwater-mixing model (eq 8). The theoretical relation of pond-water flushing (m) to flow regime and storm volume is shown in figure 14. At the extremes of plug flow, m is equal to 1 for all storm volumes less than pond dead storage. Outflow for storms in this size category is composed entirely of antecedent pond water and represents a maximum treatment level for the system. For larger storms, average detention time (and treatment efficiency) decreases as the proportion of stormwater to pond water in outflow increases.

Modifications to decrease mixing and short-circuiting in the system should increase detention times and treatment effects by increasing the "effective" dead storage of the pond. Effective dead storage is that portion of dead storage typically involved in plug flow or constantly stirred tank reactor (CSTR) mixing. When a pond short-circuits, some portion of the pond is by-passed. As a result, effective dead storage in somewhat less than the geometric content of the pond between storms. Generally, stormwater retention times are shorter for CSTR-dominated systems and short-circuiting plug flow systems. Although differences in detention time due to mixing regime are small for very large storms (greater than several times the dead-storage capacity of the system), these differences can be significant for smaller storms and tend to be greatest for storms equal in volume to the dead-storage capacity of the system (design storms). The extent of the observable treatment differences resulting from different flow regimes will also depend to a great extent on the pond-water treatment efficiency between storms.

CHANGES IN POND-WATER QUALITY BETWEEN STORMS

The chemical quality of water in the system evolves between storms as the result of several processes. By changing the constituent concentrations in

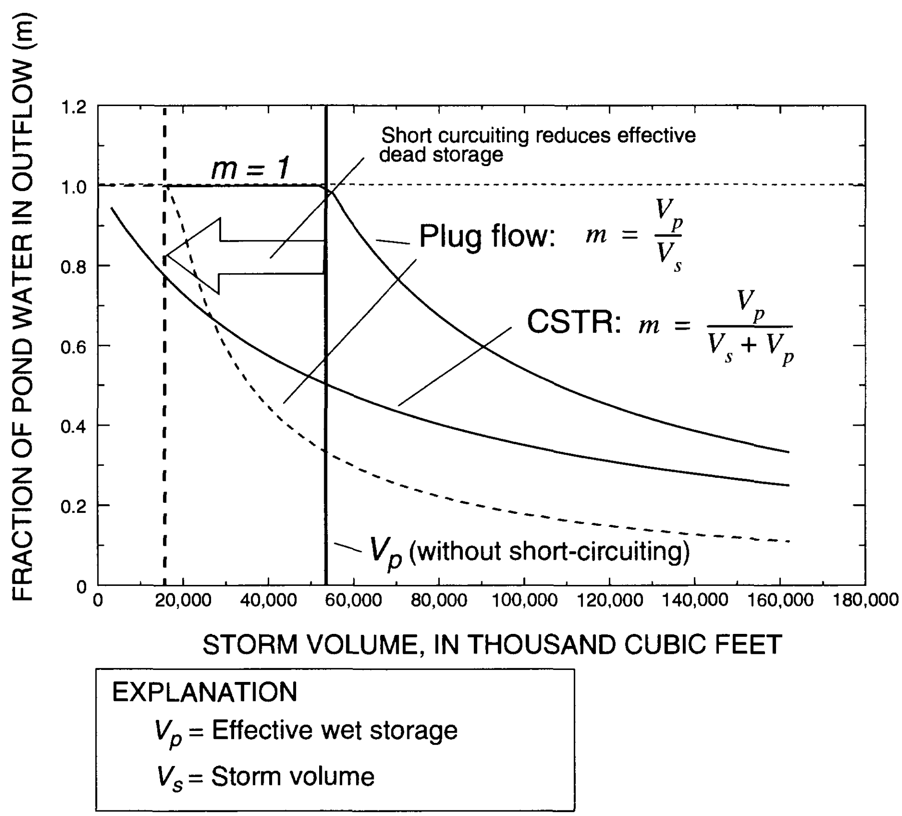

Figure 14. The theoretical relation of pond-water flushing to stormwater volume under various flow regimes.

pond water between storms (C_p in eq 6), these processes directly affect the treatment efficiency of the system.

The storm sampled on February 23, 1990, was one of the largest storms recorded in this study and produced a total discharge volume of 127,000 ft^3. This is equivalent in size to about 2.5 times the dead storage of the pond and appeared to completely flush the antecedent storage of the pond. The chemical properties of the water that remained in the pond after the storm was significantly different from that measured on several other surveys of physical properties between storms; this flushing event provided an opportunity to observe the evolution of the chemical composition of the pond water after a storm.

Typical Patterns of Change

Changes in constituent concentrations over a 12-day period following the February storm show several patterns indicative of processes affecting water-quality constituents and contributing to constituent retention efficiencies. The first notable pattern was one of increasing concentrations. This is most likely geochemically based and the result of either ground-water inflow or the chemical equilibration of the pond with bed materials. It is typically observed in dissolved inorganic constituents—dissolved solids, calcium, chloride, and specific conductance (fig. 15).

The cause of the increased dissolved inorganic concentrations and conductivity in the pond probably

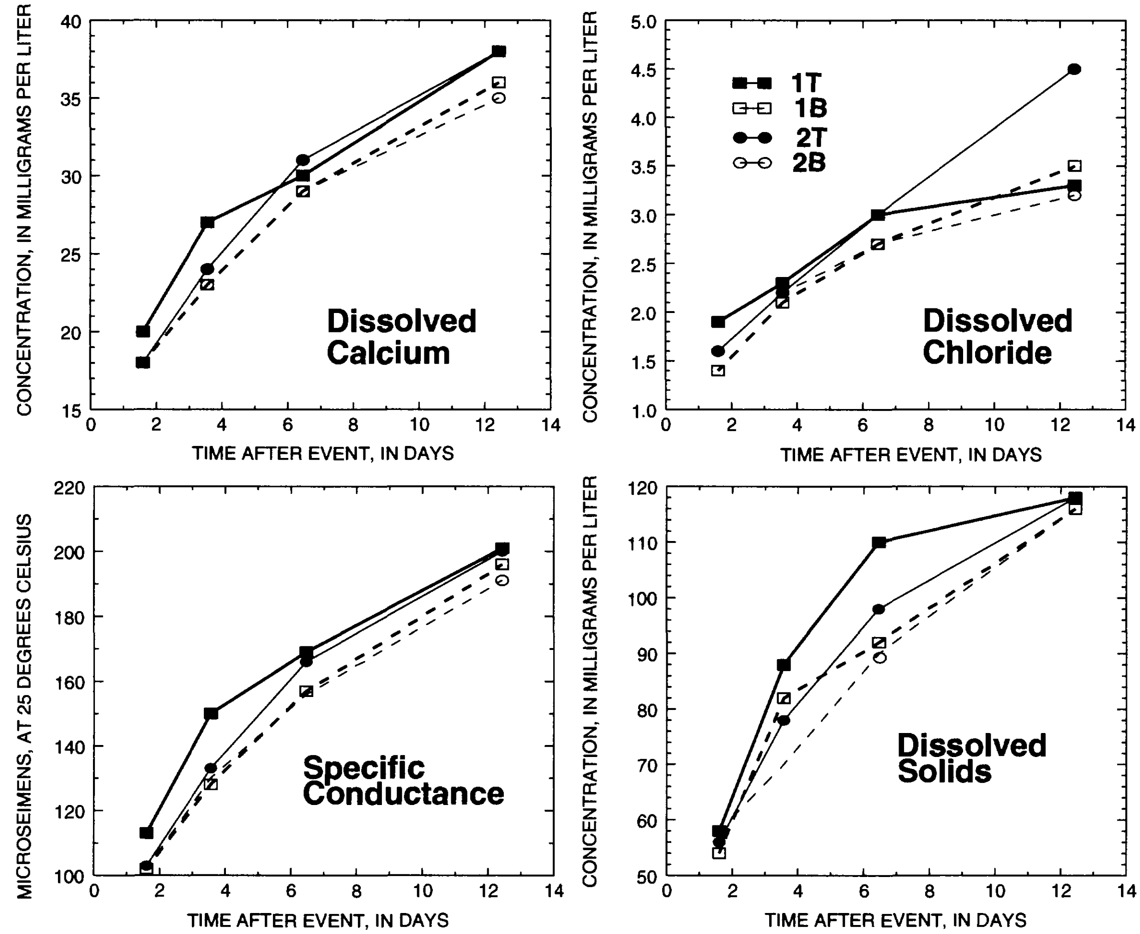

Figure 15. Patterns of change in conservative, dissolved constituents over a 12-day period after the storm of February 23, 1990.

is ground-water inflow from the submerged storm-sewer system feeding the pond. Schiffer (1989b) found the specific conductivity of ground water around the pond to be on the order of 250 to 300 μS/cm. This is consistent with changing conductivities in the pond which are shown to increase from between 20 to 60 μS/cm on the first day after the storm to about 195 μS/cm after the storm. Outflow, routinely measured at about 0.1 ft^3/s and most likely contributed by ground water, was sufficient to replace the dead storage of the pond over a period of 3 to 5 days. Constituent concentrations increased most rapidly near the surface of the pond and on the inlet side of the curtain. This would seam to indicate a source in the submerged stormwater drainage system upstream.

A second general pattern of change observed between storms is a decrease in suspended constituent concentrations, exemplified by changes in total lead and zinc (fig. 16). This pattern suggests a physical process of sedimentation. Concentrations of total lead decreased by about one-half between successive samples and dropped overall from about 4 or 6 μg/L 2 days after the storm to less than 1 μg/L (the analytical detection limit) 12 days after the storm. Throughout the 12-day period, lead concentrations generally were somewhat higher in the lower level of the pond, reflecting the downward settling of the constituent.

Unlike the changes in dissolved solids, lead concentrations did not appear to be influenced by the location of the sampling point with respect to the curtain. Concentrations of dissolved lead were at or below detection limits in all samples collected from the pond during the 12-day sampling period. Consequently, the changes in lead were almost entirely associated with changes in the suspended fraction. Generally, the same pattern occurred for other metals sampled including zinc, copper, and aluminum (copper and aluminum are not shown in fig. 16).

Biological processes in the pond seem to produce a third set of identifiable patterns in concentrations associated with chemical transformations among nutrient and organic constituents. An increase in nitrate-plus-nitrite nitrogen and ammonium nitrogen in the pond within the first few days after the storm (fig. 17), for example, may be a response to an initial increase in the rate of nitrogen mineralization (decomposition of organic nitrogen to ammonium) and nitrification (sequential oxidation of ammonium to nitrite then nitrate) in the absence of significant assimilation. Mineralization and nitrification occur in strict sequence and rely on specific bacteria and environmental conditions. Consequently, the concentrations of ammonium and nitrate nitrogen in the pond can change dramatically over time depending on micro floral and fauna population dynamics, temperature, and oxidizing and reducing conditions. The episodic increase in ammonium nitrogen concentrations in the upper part of the pond was not evident at the bottom. This was probably in response to warmer temperatures and higher dissolved oxygen concentrations at the surface. Consequently, greater ammonium production at the surface may be partly explained by the availability of organic nitrogen for mineralization.

Organic constituents tend to behave in similar ways, although a lack of uniformity among constituents and locations in the pond points toward a multitude of interacting processes. During the first 7 days, total phosphorus decreased in concentration throughout the pond except in the upper level on the inflow side of the curtain. By the twelfth day, this trend had reversed and phosphorus concentrations show an increase. The initial decrease in phosphorus concentration was similar to that seen for suspended solids, lead, and zinc, and may indicate the effects of particulate settling. Phosphorus also may have flocculated (perhaps with iron) and settled out of solution as dissolved oxygen and pH increased after the storm.

The subsequent increase in phosphorus (also seen with other solids involving carbon and nitrogen) might be due to biological assimilation and dissolved-oxygen stratification. At the surface, where dissolved oxygen concentrations eventually reached and surpassed saturation (about 9 mg/L, indicating algal growth and activity), increasing phosphorus also can be related to algal growth and incorporation in increased algal biomass. At the bottom of the pond, where dissolved oxygen concentration dropped below 2 mg/L, the increase in phosphorus coincides with an increase in iron and a decrease in pH, suspended solids, and organic nitrogen, all of which indicate a reducing environment in which phosphorus is readily dissolved.

Although the processes effecting changes in constituent concentrations between storms may themselves change with season, the general trends and patterns of change observed in these data probably are a good representation of the overall nature of change in this system and are typical of other similar systems as well. Hampson (1986) studied changes in concentrations between storms in two detention ponds in Jack-

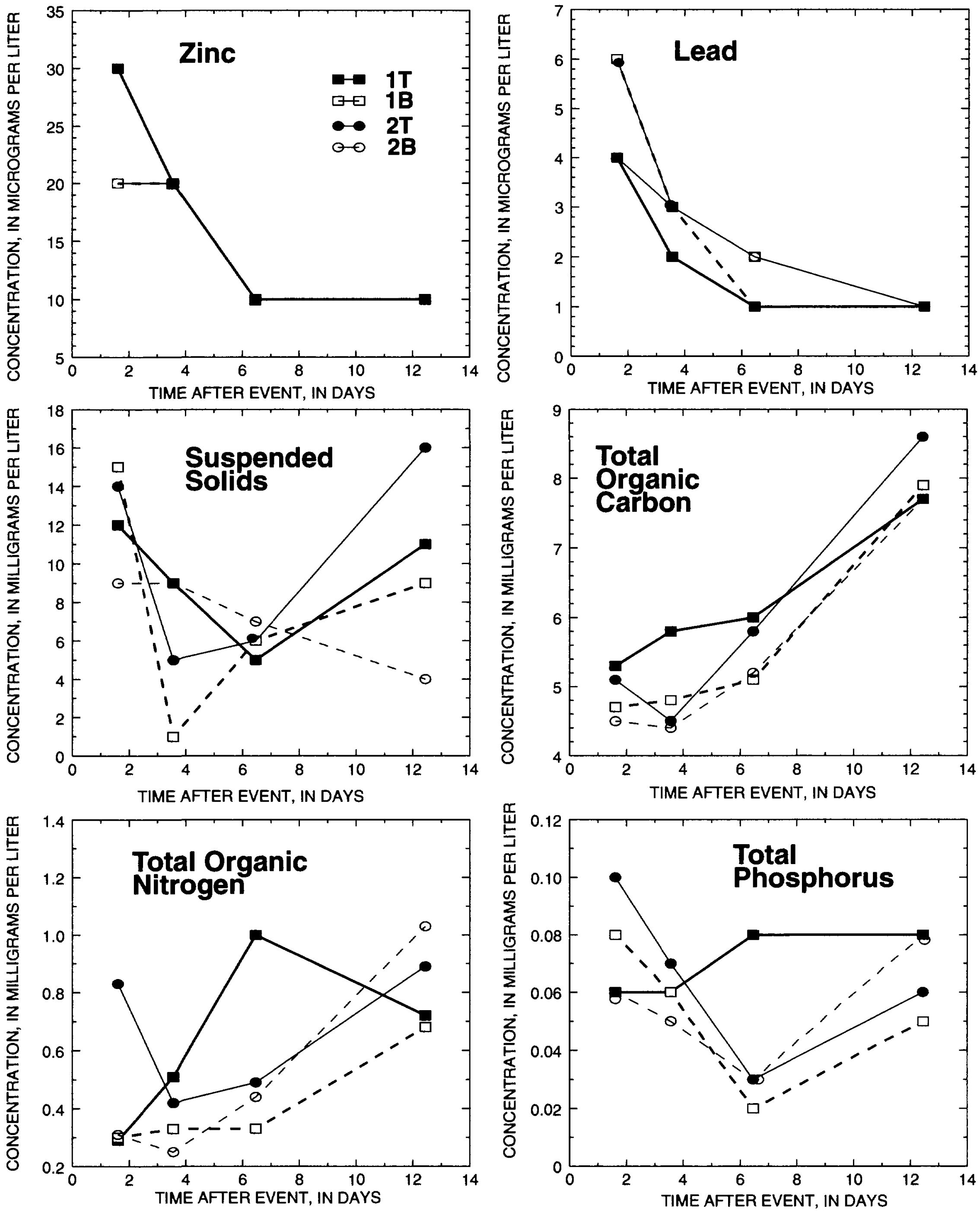

Figure 16. Patterns of change in suspended constituents over a 12-day period after the storm of February 23, 1997.

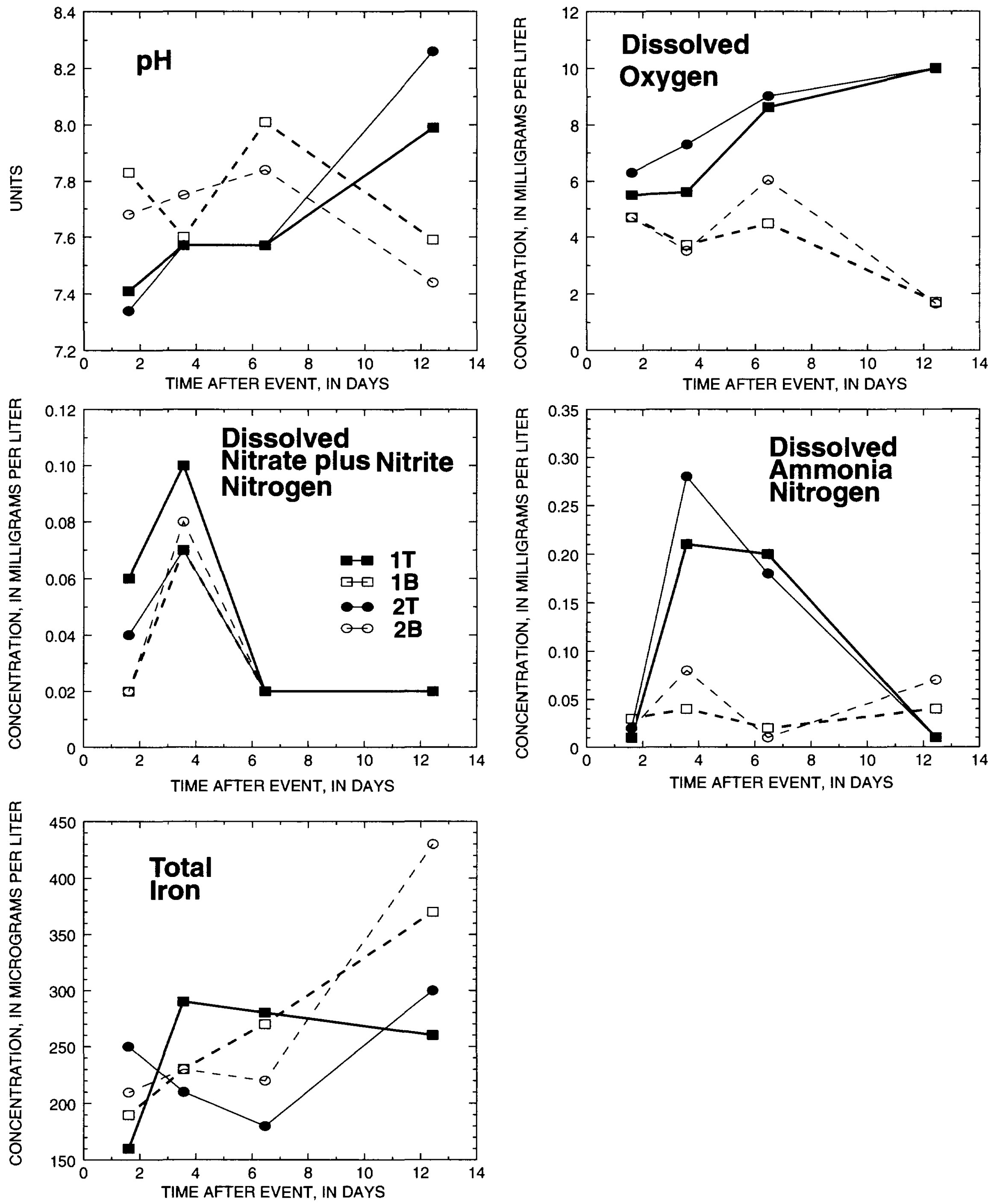

Figure 17. Patterns of change in reactive, dissolved constituents over a 12-day period after the storm of February 23, 1990.

sonville, Fla., and, using factor analysis, identified four factors–groups of chemical constituents–that generally can be equated with the processes enumerated here. The seasonal climatic effects of temperature, sunlight, and stormflow on this system have not been determined, but probably serve to slow or hasten process rates. It is also likely that most of these processes are active in the wetland system as well.

The Effects of Water-Quality Evolution on Retention Efficiency

The evolution of pond and wetland water quality between storms can be expected to have a direct effect on constituent retention efficiencies. Constituents that show a uniform increase in concentration over time (dissolved solids and total organic carbon) would indicate a system in which pond-water concentrations are generally greater than stormwater concentrations. Under these conditions, the flushing of pond water during storms will tend to produce low or negative retention efficiencies. Constituents that decrease in concentrations between storms (suspended metals) tend to show positive retention efficiencies. Likewise, constituents that increase and decrease following storms—such as reactive species of nitrogen and phosphorus—could be expected to vary in retention efficiencies depending on the time between successive storms.

The effect of changing concentrations in the pond between storms can be illustrated by the relation of transport ratios(*TR*) to the ratio of inflow EMCs to antecedent pond-water concentrations derived from equation 8. This relation is shown in figure 18 for a range of flushing rates (*m*) and capture rates (*R*). Generally, *TRs* are highest when ratios of inflow EMCs to antecedent concentrations are lowest, a condition that prevails for constituents that tend to increase in the pond between storms. From this relation, an increase in pond-water flushing (*m*) can actually reduce the retention efficiency of the system for these constituents. Constituents that settle out of the pond water, or that are otherwise removed between storms, produce higher inflow to in-pond concentration ratios for a given stormwater EMC, and therefore show an overall decrease in *TRs* as flushing increases. In terms of the model curves in figure 18, an increase in flushing rate (*m*) should have the effect of increasing the slope of the relation of *TR* to inflow-EMC in-pond concentration ratio in figure 18, pivoting at the plotted *TR* of 1 and the sample-average ratio of inflow EMC to in-pond concentrations. An increase in capture rate (*R*) associated with increased detention time during storms might further increase retention and would be shown in figure 18 by a general downward offset of the *TR* curve

EFFECTS OF POND MODIFICATION ON WATER-QUALITY CONSTITUENT RETENTION

The findings of this study generally show that flow-path geometry and flow-path modification do influence retention efficiencies for both suspended and dissolved constituents in this wet-detention system. This can be seen in changes in the relation of constituent transport ratios to storm volume and to inflow EMCs after pond modification and appears to be the direct result of a change in system geometry.

Average Event-Mean Concentrations Before and After Pond Modification

The mean, standard deviation and change in EMCs before and after pond modification are presented in table 2. The statistical significance of the change in EMCs (before and after modification) was determined using a nonparametric (Mann-Whitney) test.

Average EMCs of seven constituents in inflow to the pond were significantly different (α=0.05) in pre- and post-modification samples. Six constituents decreased in concentration–dissolved solids, dissolved magnesium, dissolved sodium, dissolved chloride, total lead, and total organic carbon; only one, total nitrate-plus-nitrite nitrogen, increased in concentration. Differences in average EMCs entering the wetland before and after pond modification were similar to those observed for the pond. Average EMCs were decreased for seven constituents in the post-modification sample. These were: dissolved magnesium, sodium, chloride, total lead and zinc, dissolved zinc, and total organic carbon. Only total nitrate-plus-nitrite nitrogen increased in concentration. At the wetland outlet, all significant differences in average EMCs before and after pond modification indicate increases. Though concentrations of suspended solids were higher in all post-modification sample sets, this difference was most significant at the wetland outlet. Signif-

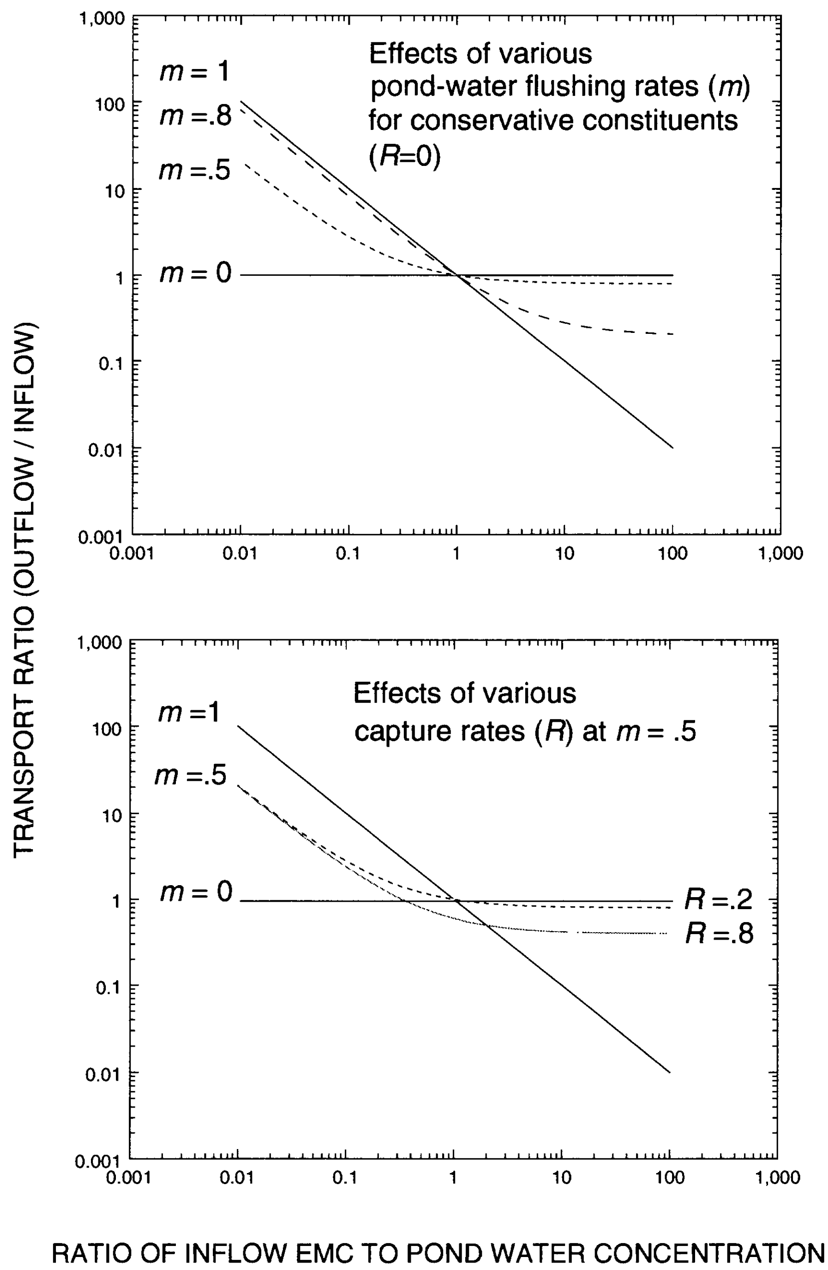

Figure 18. The relation of transport ratio to antecedent pond-water constituent concentrations, inflow constituent concentrations, pond-water flushing rate (*m*), and capture rate (*R*) from equation 8.

icant increases in EMCs for total organic nitrogen, total nitrogen, and total phosphorus at the wetland outlet may be associated with suspended organics.

Significant differences in pond and wetland inflow EMCs before and after modification are likely the result of changes in the drainage basin and changes in the retention efficiency of the pond. Figures 19-21 show the relation of inflow EMCs to storm volume for selected constituents before and after pond modification. EMCs show a relatively normal distribution when plotted on a log scale illustrating the general log-normal distribution of EMCs and supporting the use of E_{MVUE}.

The volume distribution of sampled storms probably has little effect on changes observed in most constituents. The change in total organic carbon may

Table 2. Mean, standard deviation, and change in event mean concentrations before and after pond modification

[Before-modification data from Martin and Smoot, 1986. Significance levels for efficiencies before and after modification indicate significance of the test for Ha: efficiencies not equal to zero. * indicates significance at α=0.1; ** indicates significance at α=0.05. All concentrations are in milligrams per liter, except where noted. S.D., standard deviation; Pt-Co Units, platinum-cobalt units; --, no data; µS/cm, microsiemens per centimeter at 25 degrees Celsius; µg/L, micrograms per liter]

Constituent	Entering pond					Leaving pond					Leaving wetland				
	Before modification		After modification		Change	Before modification		After modification		Change	Before modification		After modification		Change
	Mean	S.D.	Mean	S.D.	Mean	Mean	S.D.	Mean	S.D.	Mean	Mean	S.D.	Mean	S.D.	Mean
Color (Pt-Co units)	--	--	57	28	--	--	--	70	28	--	--	--	71	16	--
Specific conductivity (µS/cm)	--	--	180	59	--	--	--	194	45	--	--	--	200	43	--
pH (units)	--	--	7.4	.3	--	--	--	7.5	.3	--	--	--	7.4	.3	--
Total solids	186	50	159	48	-27	166	46	149	35	-17	145	56	181	47	36
Dissolved solids	154	55	117	47	-37 **	150	47	130	36	-20	135	58	138	32	3
Suspended solids	32	41	45	37	13	16	12	19	15	3	10	5	42	27	32 **
Dissolved silica	--	--	3.1	1.4	--	--	--	3.8	1.2	--	--	--	4.0	1.1	--
Dissolved calcium	34.9	12.9	32.4	11.5	-2.5	35.3	9.4	35.8	8.8	.5	33.2	9.5	36.2	7.8	3.0
Dissolved magnesium	1.8	.7	1.1	.5	-.7 **	1.8	.7	1.3	.4	-.5	1.7	.5	1.6	.7	-.1
Dissolved sodium	3.6	1.5	2.0	1.1	-1.6 **	3.4	1.4	2.4	.9	-1.0	3.6	1.5	3.7	4.5	.1
Dissolved potassium	1.7	.5	1.4	.5	-.3	1.6	2.4	1.6	.4	.0	1.8	.6	2.0	.5	.2
Dissolved chloride	5.7	2.5	3.7	2.6	-2.0 **	5.6	2.4	4.4	2.2	-1.2	6.5	2.8	5.5	2.7	-1.0
Dissolved sulfate	7.8	2.7	4.9	2.4	-2.9	8.3	3.4	5.3	2.2	-3	8.8	3.9	6.1	2.9	-2.7
Dissolved bicarbonate	110.0	40.4	94.2	32.5	-15.8	110.1	30.5	101.7	24.2	-8.4	99.9	26.8	100.1	22.2	.2
Total lead (µg/L)	62	65	19	21	-43 **	43	38	16	10	-37 **	16	12	13	11	-3
Total zinc (µg/L)	84	55	65	47	-19	98	95	32	20	-66 **	34	11	39	26	5
Dissolved zinc (µg/L)	35	28	21	6	-14	64	93	11	3	-53 **	12	5	16	20	4
Total copper (µg/L)	--	--	7	4	--	--	--	5	4	--	--	--	7	6	--
Dissolved copper (µg/L)	--	--	4	4	--	--	--	3	4	--	--	--	6	7	--
Total iron (µg/L)	--	--	850	480	--	--	--	500	240	--	--	--	730	320	--
Dissolved iron (µg/L)	--	--	382	380	--	--	--	16	75	--	--	--	110	39	--
Total aluminum (µg/L)	--	--	264	210	--	--	--	14	120	--	--	--	270	220	--
Total manganese (µg/L)	--	--	30	16	--	--	--	21	8	--	--	--	17	8	--
Total organic carbon	17.3	5.6	10.0	4.6	-7.3 **	16.9	6.2	11.9	3.6	5.0 *	15.6	5.5	12.3	2.1	-3.3
Total ammonia nitrogen	.13	.08	.09	.10	-.04	.06	.07	.09	.13	.03	.12	.15	.09	.21	-.03
Total nitrate+nitrite N	.10	.07	.31	.32	.21 **	.09	.11	.31	.39	.22 *	.18	.19	.63	.76	.45
Total organic nitrogen	1.13	.35	1.25	.77	.12	1.07	.29	.99	.42	-.08	.92	.31	1.47	.63	.55 **
Dissolved organic nitrogen	.57	.23	.45	.19	-.12	.54	.22	.45	.14	-.09	.47	.20	.62	.43	.15
Total nitrogen	1.37	.43	1.64	.75	.27	1.23	.37	1.39	.51	.16	1.22	.36	2.19	.98	.97 **
Total phosphorus	.16	.09	.17	.09	.01	.11	.04	.12	.06	.01	.11	.04	.19	.08	.08 **
Dissolved phosphorus	.06	.05	.05	.02	-.01	.03	.02	.03	.02	-.00	.04	.02	.05	.02	.01
Total orthophosphorus	.07	.05	.05	.02	-.02	.05	.02	.05	.03	.00	.05	.01	.07	.04	.02

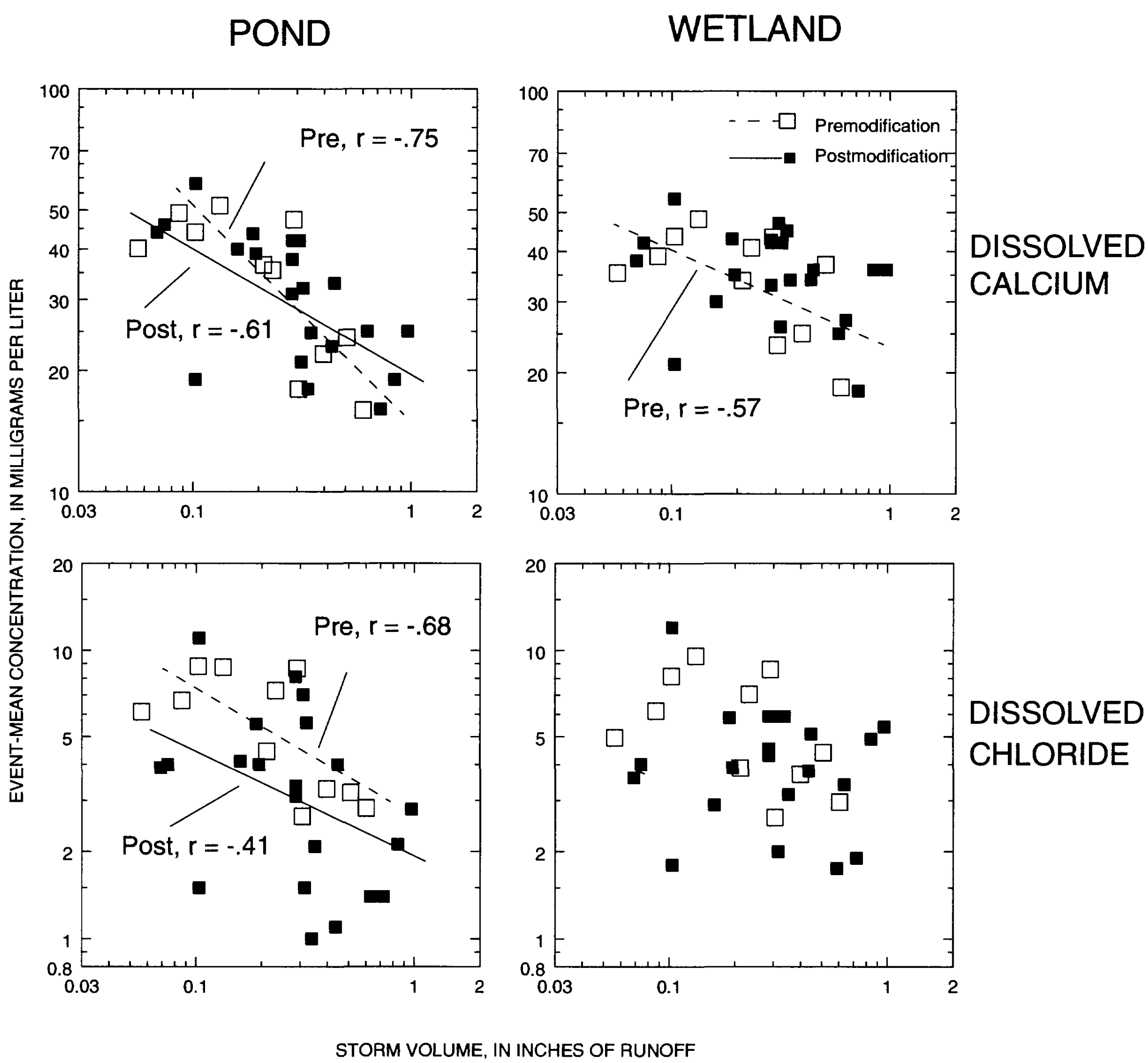

Figure 19. The relation of event-mean inflow concentration to storm volume for selected conservative inorganic constituents. (Correlation coefficients and linear trend lines are shown for significant correlations (α = 0.1).)

reflect changes in land use in the basin and an increase in development. Runoff from impervious, paved surfaces can dilute the organic carbon in water draining from lawns or other organic-rich sources. Runoff from impervious surfaces can in turn increase nitrates by picking up atmospheric and automobile exhaust deposits.

The decrease in lead concentrations in pond-inflow EMCs from a mean of 62 µg/L to only 19 µg/L probably is the result of the reduction of lead in automobile fuel. Concentrations of suspended solids and other metals such as zinc did not change over the same period, indicating that the amount or density of lead sorpted to suspended particulates has significantly decreased. All analyses for dissolved lead in the present study were below detection limits whereas mean EMCs for dissolved lead were recorded at 11 µg/L in the data collected earlier in the 1980's by Martin and Smoot (1986).

Decreases in dissolved inorganics (magnesium, sodium, and chloride) at the pond outlet after modification are likely an artifact of decreased pond inflow EMCs. The change in zinc concentrations in water leaving the pond after modification seems to indicate an increase in zinc retention by the pond.

Most of the dissolved and suspended inorganic constituents monitored in this study showed some correlation between EMCs and storm volume. The dis-

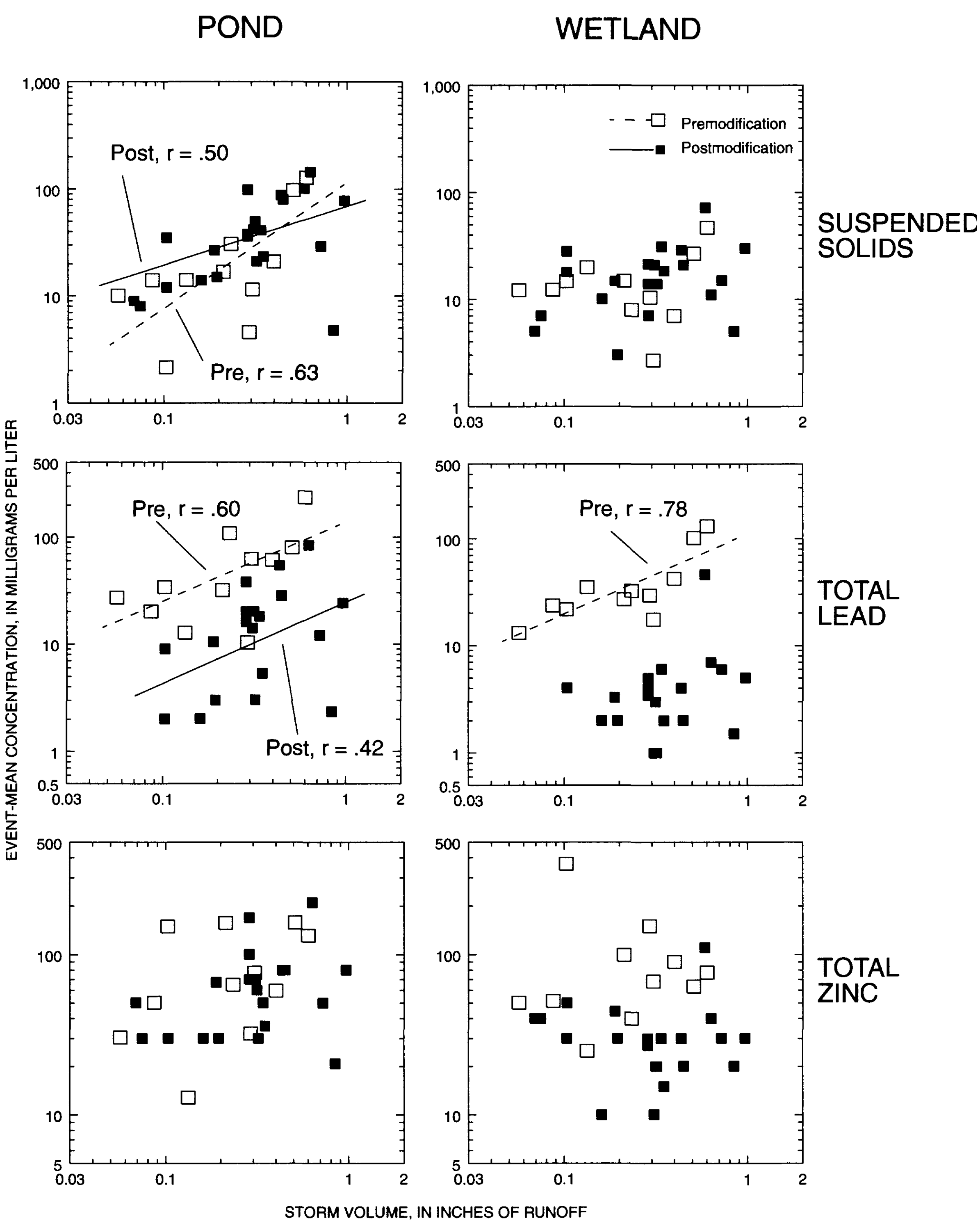

Figure 20. The relation of event-mean inflow concentration to storm volume for selected suspended constituents. (Correlation coefficients and linear trend lines are shown for significant correlations ($\alpha = 0.1$).)

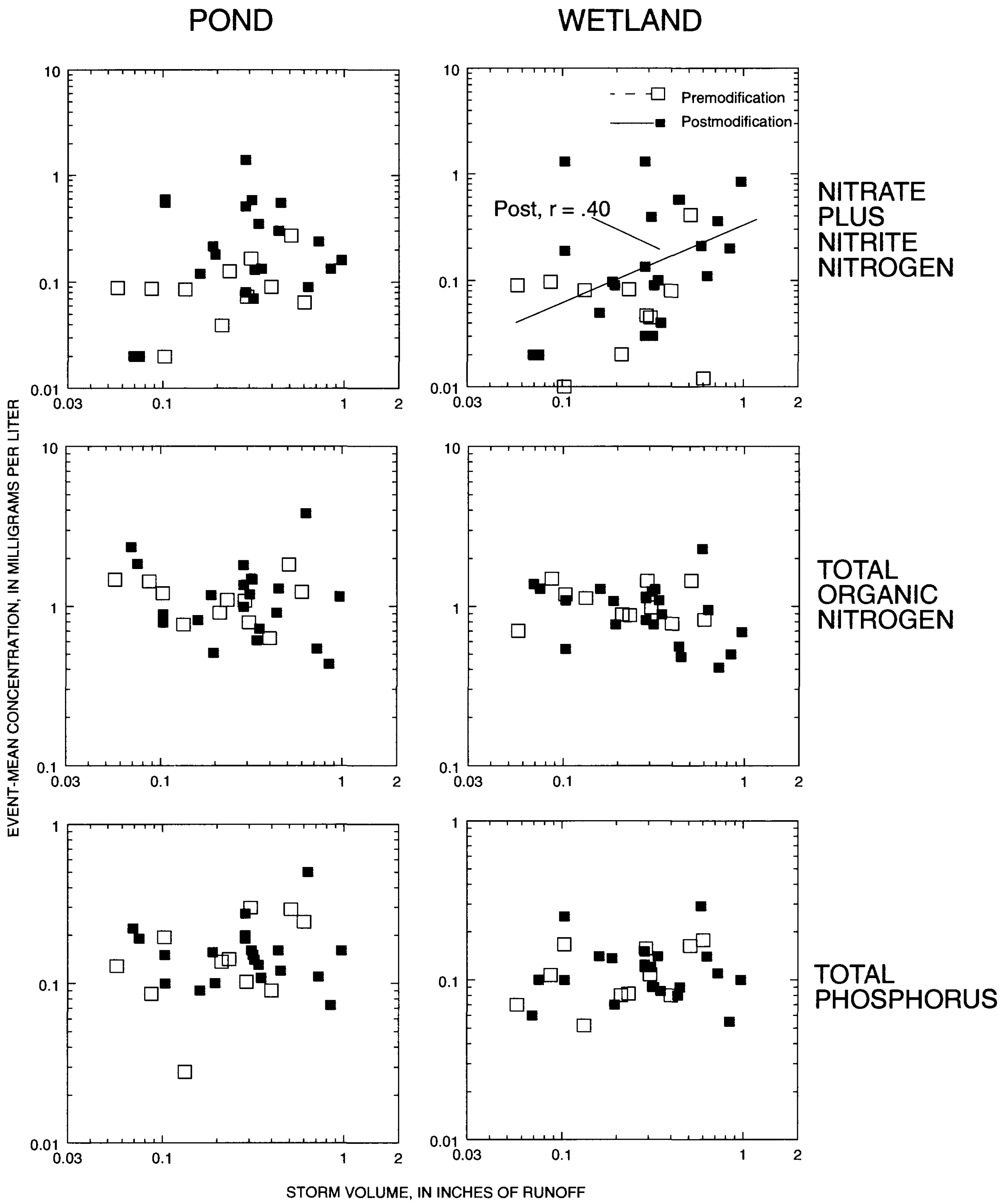

Figure 21. The relation of event-mean inflow concentration to storm volume for selected nutrient constituents. (Correlation coefficients and linear trend lines are shown for significant correlations ($\alpha = 0.1$).)

solved constituents were generally negatively correlated with storm volume while suspended constituents were positively correlated with storm volume (figs. 19-21). These correlations can generally be explained by a combination of runoff processes in the basin, and mixing processes in upstream storage. In the case of the pond, upstream storage is provided by 12,000 ft^3 of submerged storm sewer. In the case of the wetland, upstream storage includes both the pond's dead storage and storage in the storm-sewer system.

Changes in constituent concentration following the storm of February 23 illustrated a tendency for water in storage to increase in concentrations of dissolved inorganic constituents, and to decrease in concentrations of suspended metal constituents between storms. If we presume that stormwater runoff contains concentrations of dissolved solids lower than those in storage, and concentrations of suspended metals higher than those in storage, then the correlation of EMCs to storm volume is a direct reflection of the proportion of storage water and stormwater sampled in each event. EMC for small storms are dominated by samples of storage, consequently dissolved-solids concentrations are high and suspended-metals concentrations are low. EMCs for storms of increasing size are increasingly dominated by stormwater samples so dissolved solids concentrations decrease while suspended solids concentrations increase.

The relation of inflow EMCs to storm volume for nutrient species such as nitrate and ammonium is not significant. This is probably due to the lack of any consistent trend in nutrient constituent concentrations between storms. Nitrate-plus-nitrite nitrogen EMCs were somewhat positively correlated with storm volume–through this correlation was significant only in the pond outflow EMCs. After the storm of February 23, nitrate-plus-nitrite nitrogen responded in a way similar to suspended metals in the pond and decreased to detection levels within several days after the event.

Mean Retention Efficiencies and the Effects of Pond Modification

E_{MVUE}s computed for the pond and wetland for periods before and after pond modification are presented in table 3. The statistical significance of these average retention efficiencies was determined using a Wilcoxon signed-rank test and indicates the probability that each average efficiency is not equal to 0. The statistical significance of changes in E_{MUVE}s was also determined using a nonparametric Mann-Whitney U test on ranked *TRs* and indicates the probability that the observed change in E_{MUVE}s could have occurred at random (table 3).

The decreases observed in E_{MVUE}s for dissolved solids are the likely result of increased plug flow and pond-water flushing after modification. E_{MVUE}s for dissolved solids and major inorganics in the pond decreased following pond modification; all were nearly 0 before modification and decreased significantly to average about -0.25 percent afterward. Most wetland retention efficiencies for dissolved solids also decreased, although as an aggregate they remained significantly greater than before modification. In spite of the decrease in retention efficiency in the pond after modification, wetland inflow EMCs for dissolved inorganics were lower on average after the curtain was installed. This was due to significantly lower concentrations entering the pond. Though the decrease in E_{MVUE}s for dissolved inorganic constituents does not indicate a deterioration of water-quality after modification, it does serve to illustrate a fundamental change in the physical properties of the pond.

An increase in E_{MUVE}s for suspended constituents in the pond after modification was probably due to increased flushing of low-concentration pond water and an increase in sedimentation during storms. The retention of lead and zinc before pond modification was 19 and -15 percent, respectively, and increased after modification to 73 and 52 percent, respectively. E_{MVUE}s for other suspended solids and suspended nutrients also increased in the pond after modification. Suspended solids E_{MVUE} increased from 25 percent to 54 percent, total organic nitrogen E_{MVUE} increased from 4 percent to 20 percent, and total phosphorus E_{MVUE} increased from 21 percent to 30 percent. Although all these increases were not statistically significant, the commonality of processes affecting these constituents and suspended metals suggests a common response to pond modifications consistent with increased flushing of low concentrations in pond water.

Pond E_{MVUE}s for reactive dissolved-nutrient species—ammonium nitrogen, nitrate nitrogen, dissolved phosphorus and orthophosphorus—were all positive before pond modification, and decreased after modification. The most significant decrease was in retention of ammonium nitrogen, from 66 percent down to only 17 percent. This decrease in *RE* for ammonium probably was not the result of a change in

Table 3. Minimum variance, unbiased estimates of mean retention efficiencies

[Before-modification data from Martin and Smoot, 1986. Significance levels for retention efficiencies before and after modification indicate significance of the test for Ha: efficiencies not equal to zero. * indicates significance at α=0.1; ** indicates significance at α=0.05. All concentrations are in milligrams per liter, except where noted. Pt-Co Units, platinum-cobalt units; --, no data; µS/cm, microsiemens per centimeter at 25 degrees Celsius; µg/L, micrograms per liter]

Constituent	Pond retention efficiency (percent)			Wetland retention efficiency (percent)			System retention efficiency (percent)		
	Modification			Modification			Modification		
	Before	After	Change	Before	After	Change	Before	After	Change
Color (Pt-Co units)	--	-32**	--	--	-1	--	--	-33	--
Specific conductivity (µS/cm)	--	-12*	--	--	0	--	--	-12	--
pH (units)	--	-0	--	--	0	--	--	0	--
Total solids	10**	4	-6	20**	-19**	-39**	28	-14	-42
Dissolved solids	1	-19**	-20*	17**	- 4	-21**	18	-24	-42
Suspended solids	25	54**	29	40	-170**	-0**	55	-24	-79
Dissolved silica	--	-34**	--	--	-2	--	--	-37	
Dissolved calcium	-5	-16**	-11	8**	1	-7	3	-15	-18
Dissolved magnesium	2	-27**	-29**	5	-17**	-22**	7	-49	-55
Dissolved sodium	2	-32**	-34**	- 3	-24**	-21	-1	-64	-63
Dissolved potassium	7	-21**	-28**	-10**	-19**	-09	-2	-44	-42
Dissolved chloride	0	-38**	-38**	-9**	-21**	-12	-9	-67	-58
Dissolved sulfate	-4	-15*	-11	4	-12**	-16*	0	-29	-29
Dissolved bicarbonate	-3	-12*	-09	11**	4	-7*	8	-8	-16
Total lead (µg/L	19	73**	54**	68**	-187**	-255**	74	23	-52
Total zinc (µg/L)	-15	52**	67**	47**	-14	- 61**	39	45	6
Dissolved zinc (µg/L)	-32	48**	80**	60**	-15	-75**	47	40	-7
Total copper (µg/L)	--	42**	--	--	-67**	--	--	3	--
Dissolved copper (µg/L)	--	24	--	--	- 33	--	--	-1	--
Total iron (µg/L)	--	42*	--	--	- 41**	--	--	18	--
Dissolved iron (µg/L)	--	45	--	--	26**	--	--	59	--
Total aluminum (µg/L)	--	48**	--	--	-61**	--	--	16	--
Total manganese (µg/L)	--	24*	--	--	23	--	--	41	--
Total organic carbon	4	-30**	-34**	1	-1	-2	5	-31	-36
Total ammonia nitrogen	66*	17	-49*	-59	40	99	46	50	4
Total nitrate+nitrite N	35*	24	-11	-51	-193**	-142	2	-123	-125
Total organic nitrogen	4	20	16	17**	-34**	-51**	20	-7	-28
Dissolved organic nitrogen	7	-3	-10	17	-22**	-39*	23	-26	-48
Total nitrogen	10	16	06	5	-49**	-54**	15	-25	-40
Total phosphorus	21	30*	9	1	-55**	-56*	22	-9	-30
Dissolved phosphorus	40	35*	-5	-10	-46**	-36	34	5	-29
Total orthophosphorus	30	26	- 4	-44	-67**	-23	-1	-24	-23

the rate of its attenuation in the pond, but rather reflects lower average inflow EMCs for storms sampled after pond modification (table 2).

In contrast to the pond, E_{MVUE}s decreased for all suspended constituents in the wetland after pond modification. Some of the decrease in efficiency can be attributable to an increase in efficiency in the pond after modification, which, by decreasing concentrations entering the wetland relative to antecedent concentrations, increased the transport ratio from the wetland. Some of this decrease in E_{MVUE}s for suspended constituents may also be attributable to flushing and resuspension of organic particulates or inorganic flocculents from wetland sediments.

Wetland E_{MVUE}s decreased for all constituents after pond modification except for ammonium nitrogen. Nitrate nitrogen retention decreased from -51 percent to -190 percent–second in decrease only to lead E_{MVUE} which dropped from 68 percent to -187 percent. Orthophosphorus E_{MVUE} decreased from

-44 percent to -67 percent. Generally, the decrease in constituent retention for most constituents in the wetland probably was caused by the flushing of accumulated sediments as a result of the redirection of flow.

The Effects of Inflow Concentration and Storm Volume on Constituent Retention

Transport ratios are plotted against inflow EMCs for selected constituents in figures 22-24. Transport ratios are shown here as a transformation of retention efficiency to log space and can be seen as the inverse of *RE*. In the hypothetical case where pond-water concentrations (C_p) and pond-water flushing (m) are the same for all storms, these plots are comparable to the theoretical plots in figure 18 and show by inference the general response of retention efficiencies to inflow concentration, pond-water flushing and constituent capture rate.

Generally, retention efficiencies in both the pond and the wetland appear to be strongly dependent on inflow EMCs. This is demonstrated by the negative correlation of many constituent transport ratios with inflow EMC and illustrates the importance of considering inflow EMCs in design criteria. Though this correlation is not unexpected, given the reciprocal relation of transport ratios (Outflow EMC/Inflow EMC) to Inflow EMC, it can easily be overlooked and shows the importance of obtaining representative sample distributions in the determination of average retention efficiencies.

For conservative dissolved constituents, the line indicating the general trend of the relation of transport ratio to inflow EMC appears to be relatively flat before pond modification and to increase in slope after modification. This is consistent with the short-circuiting reported by Martin (1988). After modification, an increase in flushing rate (m) and a general decrease in inflow EMCs produces higher transport ratios (more negative retention efficiencies) for constituents that increase in concentration in the pond between storms. The slope of the transport ratio-inflow EMC relation for chloride and calcium, shown in figure 22, falls between the hypothetical curves for m=0.2 and m=0.8, and can be approximated by a curve having an m of about 0.5 (fig. 18), roughly indicating an average flushing rate of about one-half the pond volume for each storm.

For a conservative constituent, the concentration at which transport ratio-inflow EMC relation equals 1 approximates the average antecedent pond-water constituent concentration. At a transport ratio of 1 or the trend line for chloride after pond modification (fig. 22), inflow EMC equals about 5.5 mg/L. The pattern of changes after the storm of February 23 suggests that concentrations of dissolved chloride in a completely flushed pond will increase to about 5.5 mg/L over a period of several weeks. This is a considerably longer time than the average of 4 days between storms observed in the current study period. With an average pond-water flushing rate of only about 50 percent, however, dissolved chloride may be sustained at somewhat higher in-pond concentrations than those observed immediately after the February storm.

Transport ratios for suspended metals (as represented by lead and zinc) showed a general shift downward and to the left after modifications (fig. 23). This was consistent with an increase in capture rate (R) associated with longer detention times, but also suggests a general decrease in antecedent pond-water concentrations—especially for lead—which is not strictly an effect of modification. Decreases in average antecedent pond-water concentrations can result from decreased inflow EMCs which produce lower concentrations in pond water immediately after storms. This effect tends to confound the identification of treatment effects due to modification. An increase in the downward slope of the relation of transport ratios to inflow EMCs; however, does indicate some real increase in retention efficiency due to increased pond-water flushing after modification.

Little change is indicated in the transport ratios for total suspended solids in the pond after modification, and the pattern of the relation to inflow EMC was more typical of that for conservative constituents than for suspended metals (lead and zinc). This can be due to the dual organic and inorganic nature of suspended solids and a compensating tendency for particulate inorganics that settle between storms, to be replaced in the water column by particulate organic solids as the result of biological activity between storms.

Transport ratios were not correlated with inflow EMCs for reactive nutrient species (nitrate-plus-nitrite nitrogen, ammonium nitrogen, and orthophosphorus). This is probably due to the variability of reactive nutrient-concentration data. On the other hand, the relations of transport ratios to inflow EMCs for total nitrogen and total phosphorus were significant. The relatively tight range of data around the correlation trend line for total phosphorous and total organic

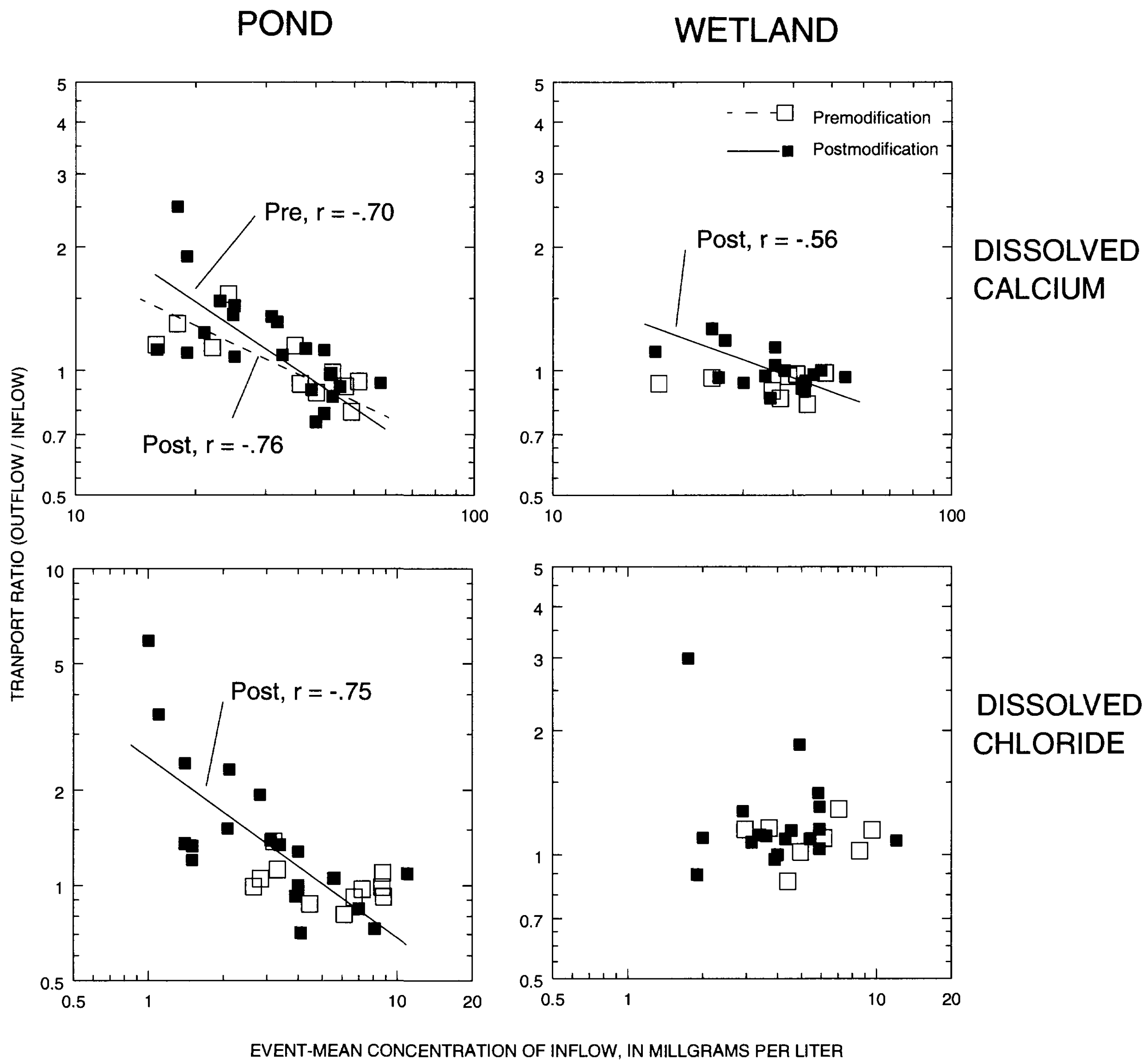

Figure 22. The relation of transport ratio to event-mean inflow concentration for selected conservative inorganic constituents. (Correlation coefficients and linear trend lines are shown for significant correlations ($\alpha = 0.1$).)

nitrogen in figure 24 reflects the relatively stable chemical speciation of these constituents and limited variability in concentration in pond water between storms.

For the wetland, transport ratios for conservative constituents followed about the same general pattern as that for the pond, indicating an increase in flushing as a result of sand-bagging the northeastern corner of the pond, and redirection of flow around to the southern part of the wetland. An increase in transport ratios for suspended metals (lead and zinc) in the wetland after pond modification (fig. 23) can be attributed to a decrease in inflow EMCs from the pond (lowering C_i relative to between-storm constituent concentrations, but may also indicate a resuspension of sediments in the wetland). The release of lead by the wetland can be a temporary response to the rerouting of water through areas of the wetland that previously had accumulated lead. If this is the case, lead retention might be expected to stabilize with time. Other suspended solids in the wetland also show an increase in transport ratios that can only be attributed to a resuspension and flushing of solids from the wetland.

Transport ratios for the pond and wetland vary with storm volume and the relation of storm volume to

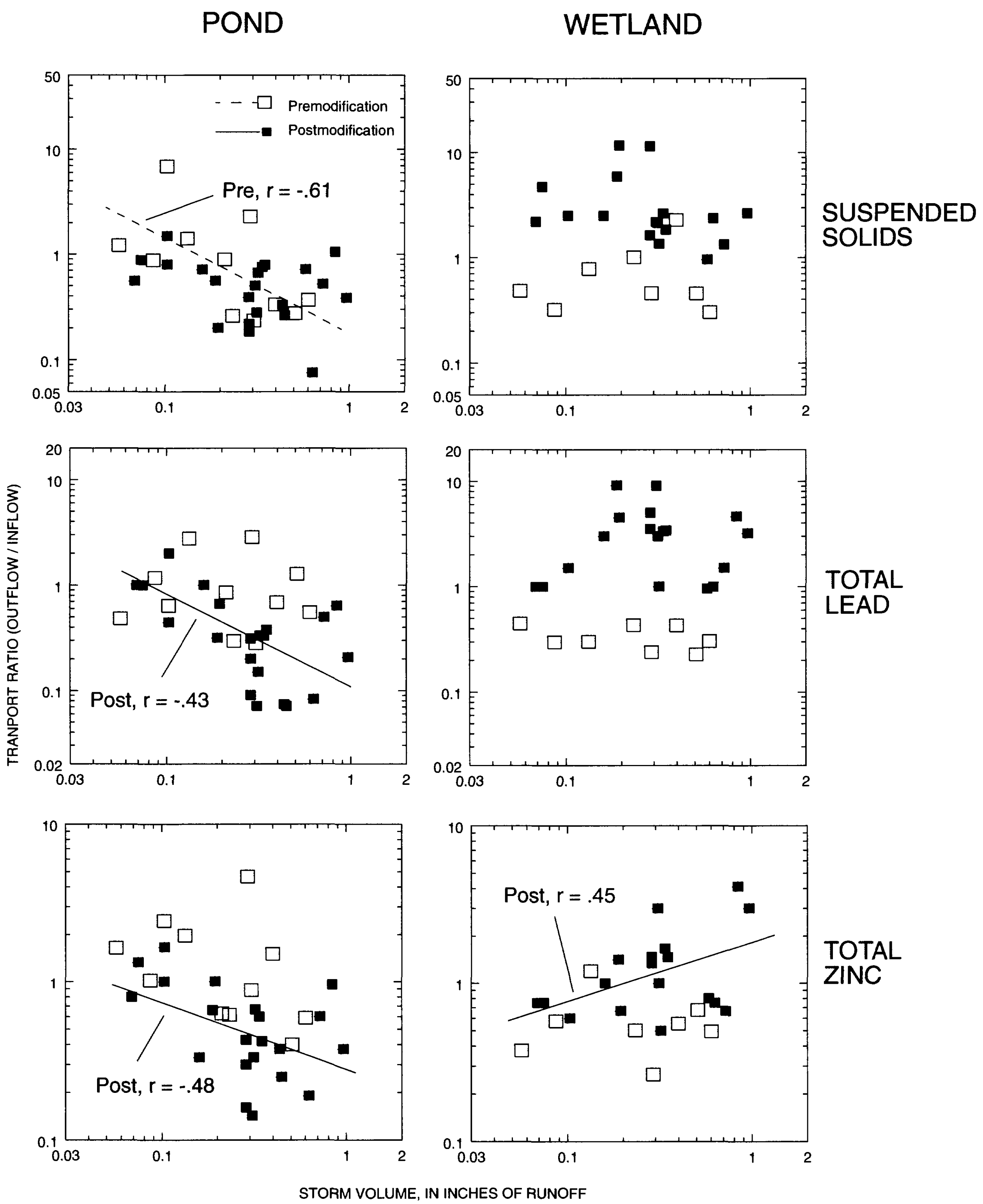

Figure 23. The relation of transport ratio to event-mean inflow concentration for selected suspended constituents. (Correlation coefficients and linear trend lines are shown for significant correlations ($\alpha = 0.1$).)

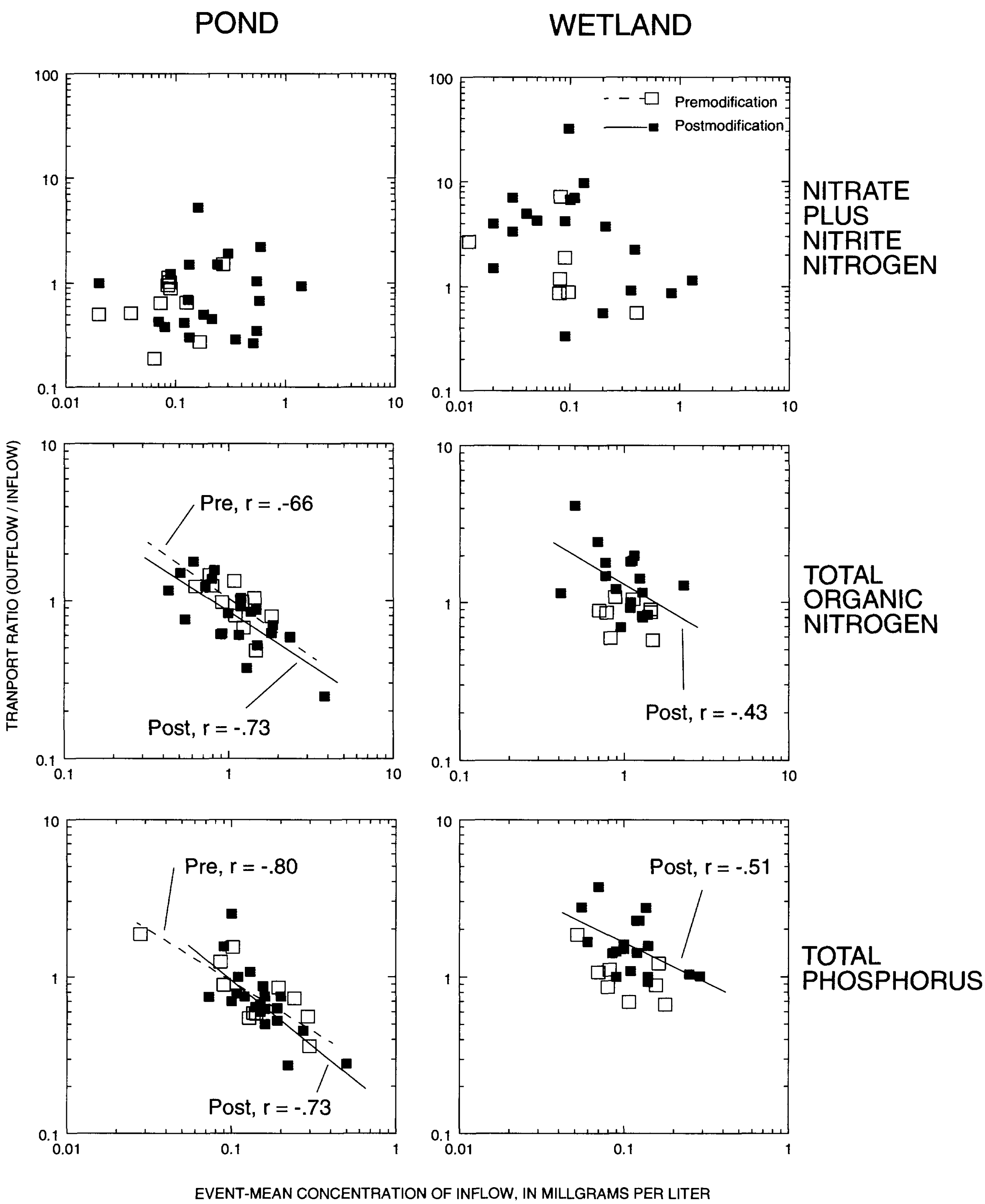

Figure 24. The relation of transport ratio to event-mean inflow concentration for selected nutrient constituents. (Correlation coefficients and linear trend lines are shown for significant correlations ($\alpha = 0.1$).)

both inflow EMCs and mixing regime. The departure of transport ratios from a smooth linear relation (figs. 25-27) reflects the extent to which stormwater inflow remains in coherent plugs as it moves through the pond and wetland. As inflow plugs disperse and mix in the pond (CSTR flow), outflow concentrations tend to approach an average of the pond-water and inflow-water concentrations in direct proportion to pond-water flushing (*m*). This should produce a relatively smooth and continuous relation (attenuating departures from the line of relation.) When stormwater plugs move coherently through the pond, the proportion of pond water flushed during the storm is strictly related to the inflow volume of the storm (fig. 14), and the effective volume of the pond. The discrete nature of plug flow tends to amplify departures and discontinuity in the relation of transport ratio to storm volume.

The relation of transport ratios to storm volume for the pond (figs. 25-27) generally indicates a system dominated by plug flow. Transport ratios are posi-

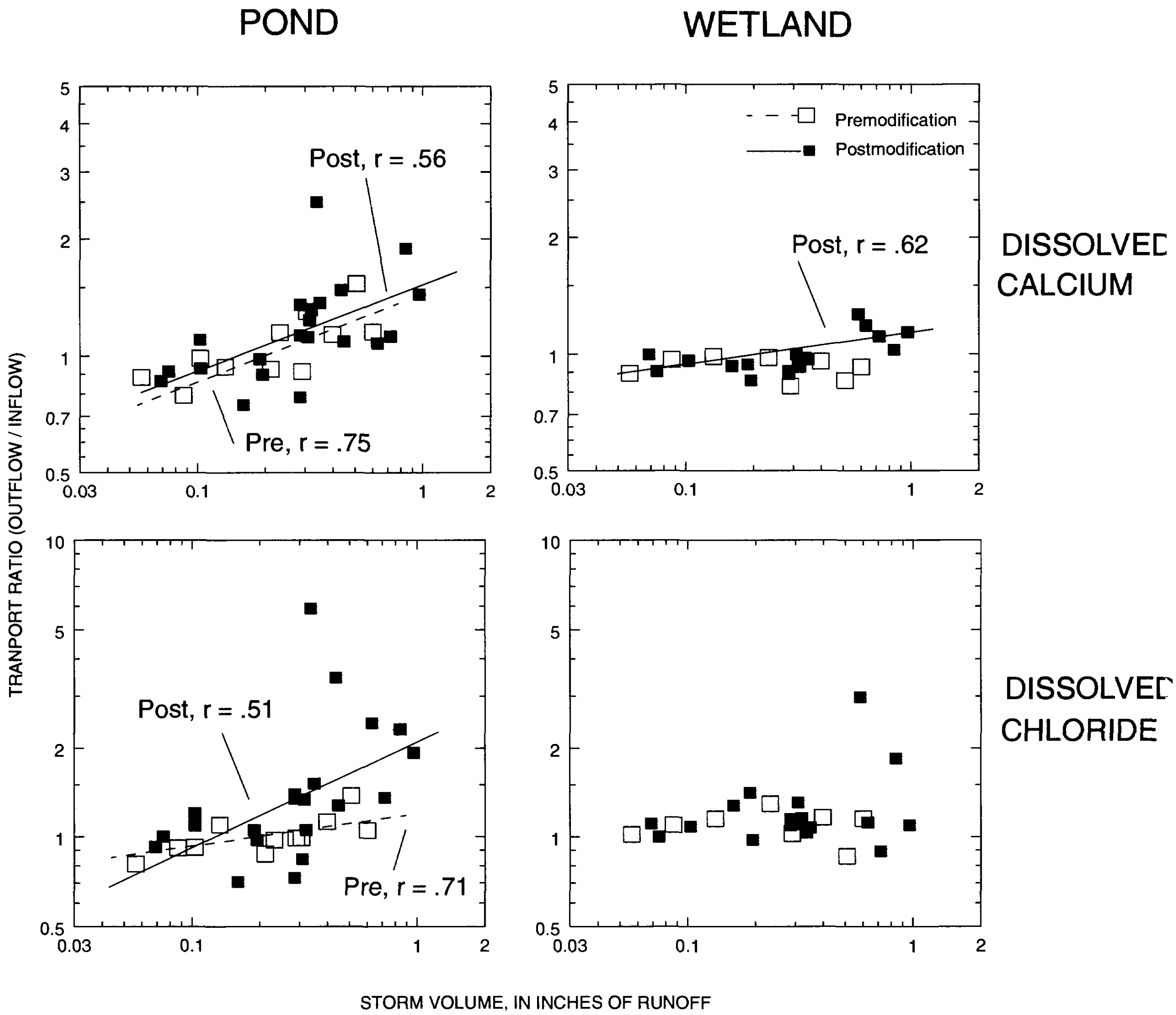

Figure 25. The relation of transport ratio to storm volume for selected conservative inorganic constituents. (Correlation coefficients and linear trend lines are shown for significant correlations ($\alpha = 0.1$).)

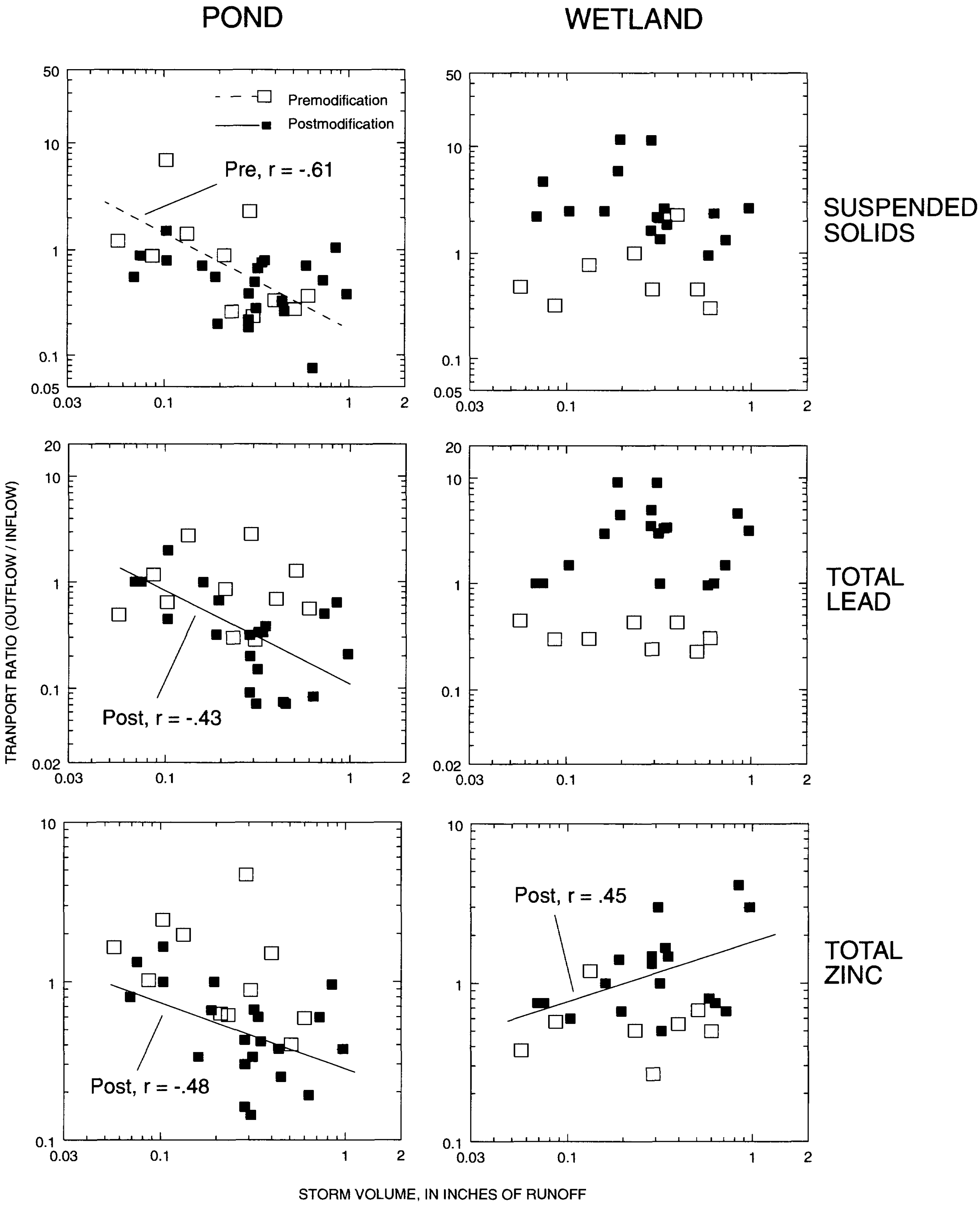

Figure 26. The relation of transport ratio to storm volume for selected suspended constituents. (Correlation coefficients and linear trend lines are shown for significant correlations ($\alpha = 0.1$).)

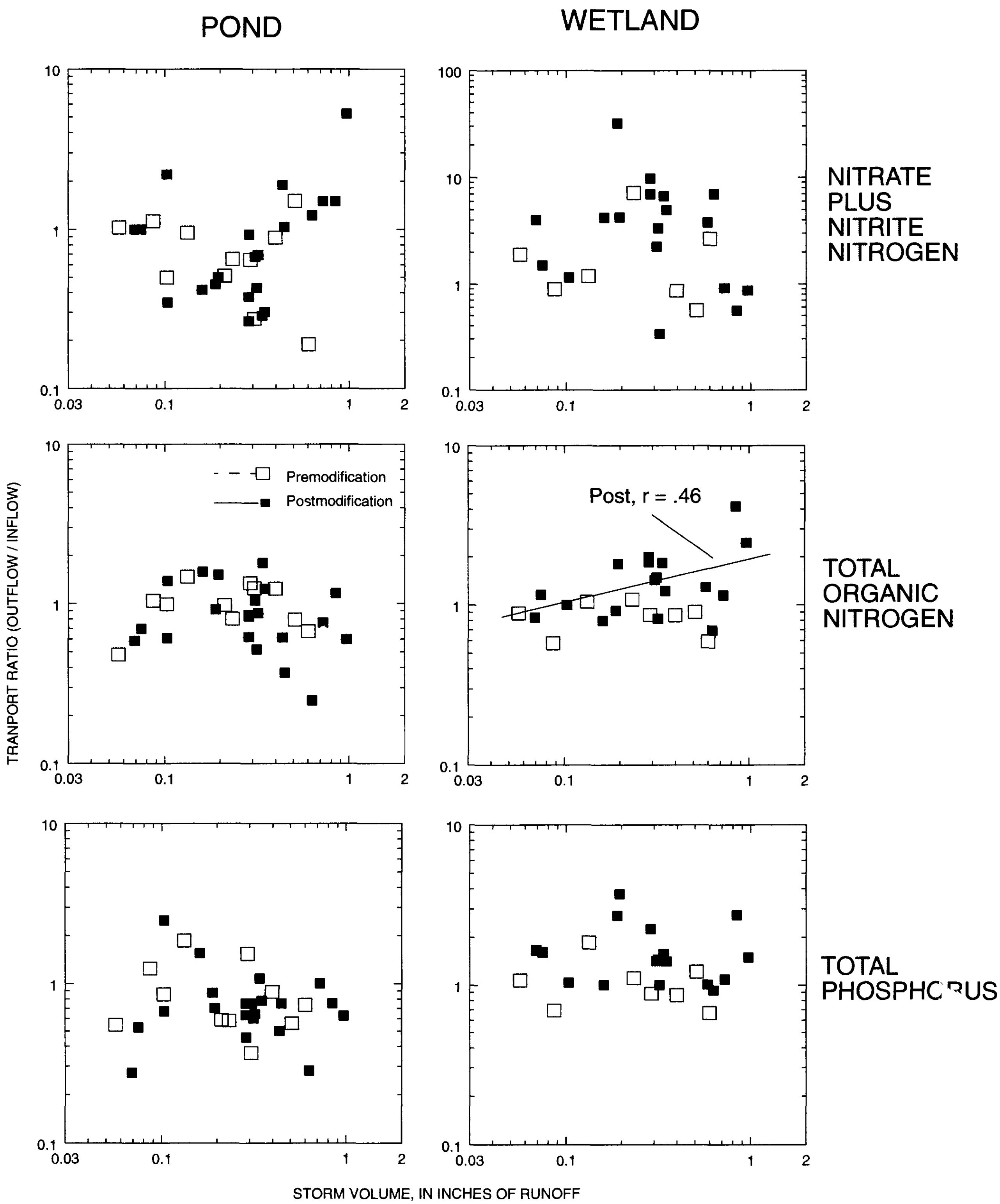

Figure 27. The relation of transport ratio to storm volume for selected nutrient constituents. (Correlation coefficients and linear trend lines are shown for significant correlations ($\alpha = 0.1$).)

tively and linearly related to storm volume for conservative inorganic constituents (chloride and calcium, fig. 25); thus transport ratios are greater for large storms and lesser for small storms. This can be generally related to the trend toward lower inflow EMCs for dissolved-solids constituents in large storms. The water entering the pond at the beginning of a storm contains relatively higher constituent concentrations than those of the water flushed out of the pond. In small storms, stormwater remains in the pond and transport ratios tend toward a value less than 1. In larger storms (0.1 to 0.3 in.), inflow EMCs for dissolved solids decrease with the passing of the initial flush and transport ratios increase. In still larger storms (greater than 0.3 in), the initial high-concentration flush reaches the pond outlet (at about 0.35 in. of runoff), causing an increase in outflow EMCs and an upward jump in transport ratios. For very large storms, outflow EMCs tend to decrease again after the passage of the initial flush, producing a downward curve in transport ratios.

Among suspended constituents (lead, zinc, and solids), the correlation of transport ratios to storm volume after modification generally was negative, but shows an upward inflection on large storms (fig. 26). Transport ratios were largest for small storms and decreased as storm size increased. At the beginning of a storm, inflow concentrations of suspended constituents generally are low. As a result, inflow EMCs for small storms are slightly lower than outflow EMCs. Later in a storm event, stormwater runoff generally carries higher concentrations of suspended constituent. As these inflow concentrations increase with larger storms (fig. 20), outflow concentration remains fairly constant. As a result, transport ratios decrease as storm size increases. For very large storms (greater than one-pond volume) high concentration stormwater flows through the pond and outflow EMCs and transport ratios increase toward a value of 1.

Transport ratios for nitrate nitrogen, organic nitrogen, and phosphorus show a slight tendency toward curvature–but do not show a significant linear correlation with storm size. The relation of transport ratio to storm volume in the pond for total organic nitrogen is the inverse of the relation of inflow EMCs to storm volume (fig. 27). Although inflow EMCs generally decrease with storm size for small storms, transport ratios tend to increase as inflow EMCs increase for larger storms; as a result, transport ratios generally decrease over the full range of storms.

In the wetland, transport ratios for lead and suspended solids show no strong relation to storm volume. In contrast, the correlation of zinc transport ratios to storm volume was significant and distinctly positive. This would support the idea that accumulated sediments were being flushed from the wetland on large storm events.

SUMMARY AND CONCLUSIONS

This report has evaluated the effects of flowpath modification on an urban stormwater detention pond and wetland system in Orlando, Fla. Three general conclusions can be drawn from its findings. First, flow path and flow regime do affect constituent retention efficiency in wet-detention, stormwater-treatment systems, and as a consequence, modifications causing changes in flow characteristics can produce significant changes in treatment effects. Second, the direction of change (whether it be increasing or decreasing level of treatment) as a result of modification is also highly dependent on the chemical characteristics of individual constituents and the properties of storms. Third, because treatment effects are strongly related to constituent and storm properties, an accurate evaluation of average retention efficiencies in studies of stormwater detention systems requires that the full range of storm conditions (volume, intensity and times between storms) be sampled in proper proportion to their occurance.

Measurements of temperature at several locations during selected storms showed the nature of flow in the system and demonstrated that pond-water flushing and mixing vary with the temperatures of pond water and stormwater and the velocity of stormwater inflows. The movement of water in the pond during storms generally indicated a pattern of plug flow that was somewhat seasonally dependent on storm intensity (rapidity of inflow) and stormwater temperature. Vertical temperature gradients during and after the storms indicated that flow progresses through the system in horizontal plugs during periods of rapid inflow, but changes to stratified sheets that can be likened to vertical plug flow as inflow rates diminished. The installation of the curtain through the pond appears to have increased the general flushing of the pond by inhibiting the short circuiting observed for periods of rapid inflow. This was also supported by the relations of transport ratios to storm volume, and the changes in transport relations after pond modification.

The chemical evolution of pond water between storms showed several typical patterns of change between storms for each of several groups of constituents with similar chemical properties. Dissolved inorganics, for example, increased in concentration as they equilibrated with ground-water inflow. Suspended metals decreased in concentration as particulates settled. Reactive nutrients decreased and increased at various points in time depending on microbial activity and redox reactions.

Average retention efficiencies were strongly effected by changes in pond-water chemistry between storms. Generally, constituents that tend to increase in concentration between storms were retained with less efficiency than those that settled or decreased in concentration between storms. Although this difference in retention efficiencies was apparent before modification, it became even more pronounced after modification due to an increase in plug flow and pond-water flushing. Mean retention efficiencies for dissolved solids and major inorganic constituents significantly decreased in both the pond and the wetland as a result of modification. Retention efficiencies for lead, zinc, other suspended solids, and nutrient species associated with suspended solids significantly increased in the pond after modification. Retention efficiencies for dissolved and reactive nutrient species (ammonium nitrogen, nitrate nitrogen, dissolved phosphorus, and orthophosphorus) though positive after modification, generally were lower than before modification. And, retention decreased in the wetland after modification for all constituents except ammonium nitrogen.

Transport ratios and retention efficiencies (by association) for individual storms were shown to be strongly related to both stormwater volume and relative constituent concentrations in stormwater and antecedent pond water for many constituents. A simple analytical model of pond-water and stormwater mixing showed that changes observed in retention efficiency can be generally explained by increases in the effective or "flushable" volume of pond and wetland storage, (by as much as a factor of 2 in the pond) and by increases in constituent capture rates during storms for suspended constituents. Increased flushing of the pond and wetland after modification (plug flow) caused retention efficiencies to decrease for constituents that increase in concentration between storms, and to increase for constituents that increase in concentration between storms (suspended solids, lead, zinc). Flushing of accumulated sediments from the wetland caused significant decreases in retention efficiency for suspended metals and organic nutrients.

A comparison of observed transport ratios to an expected outcome based on the analytical mixing model also suggests that some of the increase in retention efficiencies for lead and zinc in the pond was a result of a general decrease in antecedent pond-water constituent concentrations. Lead concentrations in stormwater inflow decreased from a mean of 62 micrograms down to 19 micrograms per liter over the period of the study (1982 to 1992)—most likely the effect of controlling lead in automobile fuels. This large decrease in lead concentrations in stormwater inflow had a transient effect on in-pond concentrations by reducing post-storm suspended metals concentrations, which generally reduced antecedent concentrations for the next storm. This effect was relatively less for zinc which can provide a somewhat better indication of true treatment effect on suspended metals.

Because constituent retention efficiencies are dependent on stormwater and antecedent pond-water constituent concentrations, and stormwater volume and flow characteristics, the distribution of individual storm efficiencies can not be assumed to be either random or normal. This presents a significant problem in the accurate evaluation of treatment effectiveness in these systems. The correlation of transport ratios to storm volume in lead, for example, shows that the average retention efficiency for lead is strongly dependent on the range and distribution of storms sampled. The addition of several larger storms to the data set would likely have the effect of increasing the average transport ratio and would therefore decrease the apparent retention efficiency for lead. Consequently, the range in storm volumes, inter-event times, inflow rates, and seasonal effects on pond-water temperature and chemical evolution, must all be sampled in proper proportion to their long-term distributions to determine average retention efficiencies with minimal bias.

SELECTED REFERENCES

Aitchison, J., and Brown, J.A.C., 1969, The lognormal distribution: Cambridge University Press, Cambridge.

Driscoll, E.D., 1983, Performance of detention basins for control of urban runoff quality: Lexington, University of Kentucky, 1983 International symposium on Urban hydrology, Hydraulics and sediment control, 46 p.

Driscoll, E.D., Shelley, P.E., and Streeker, E.W., 1990, Pollutant loadings and impacts from highway stormwater runoff, Volume III-Analytical investigation and research report:
U.S. Department of Transportation, Federal Highway Administration Publication FHWA-RD-88-008, 160 p.

Ferrara, R.A., and Witkowski, Patrick, 1983, Stormwater quality characteristics in detention basins *in* Proceedings of the American Society of Civil Engineers: Journal of the Environmental Engineering, v. 109, no. 2, Paper no. 17846, p. 428-447.

Finnemore, E.J., 1982, Stormwater pollution control *in* Proceedings of the American Society of Civil Engineers: Journal of the Environmental Engineering Division, v. 108, no.EE5, p. 835-851.

Fisher, H.B., List, E.J., Koh, R.C.Y., Imberger, J., and Brooks, N.H., 1979, Mixing in inland and costal waters, Academic Press, New York, p. 211-212 and p 483.

Fisher, G.T., and Katz, B.G., 1988, Urban stormwater runoff--Selected background information and techniques for problem assessment, with a Baltimore, Maryland, Case Study: U.S. Geological Survey Water-Supply Paper 2347, 30 p.

Fishman, M.J., and Friedman, L.C., eds., 1989, Methods for determination of inorganic substances in water and fluvial sediments (3rd ed.): U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. A1, 545 p.

Gietz, R.J., 1983, Urban runoff treatment in the Kennedy-Burnett settling pond, Rideau River stormwater management study: Ontario, Regional Municipality of Ottawa-Carleton, 12 p.

Gilbert, R.O., 1987, Statistical methods for environmental pollution monitoring: New York, Van Nostrand Reinhold Co., 320 p.

Hampson, P.S., 1986, Effects of detention on water quality of two stormwater detention ponds receiving highway surface runoff in Jacksonville, Florida: U.S. Geological Survey Water-Resources Investigations 86-4151, 69 p.

———1989, Dissolved-oxygen concentrations in a central Florida wetlands stream, *in* Fisk, D.W., ed., Wetlands: concerns and successes, Proceedings of the American Water Resources Association: American Water Resources Association Technical Publication TBS-89-3, p. 149-160.

Luskow, S.M., Scherger, D.A., and Davis, Jr., J.A., 1981, Effectiveness of two in-line urban storm water best management practices (BMP's) *in* 1981 international symposium on urban hydrology, hydraulics, and sediment control: Lexington, University of Kentucky, p. 193-206.

Martin, E.H., 1988, Effectiveness of an urban runoff detention pond-wetlands system: Journal of Environmental Engineering, v. 114, no. 4, August 1988, p. 810-827.

Martin, E.H., and Smoot, J.L., 1986, Constituent-load changes in urban stormwater runoff routed through a detention pond-wetlands system in central Florida: U.S. Geological Survey Water-Resources Investigations Report 85-4310, 74 p.

McCuen, R.H., 1980, Water quality trap efficiency of storm water management basins: American Water Resources Association, Water Resources Bulletin, v. 16, no. 1, p. 15-21.

Neter, John, and Wasserman, William, 1974, Applied linear statistical models, Homewood, Ill., Richard D. Irwin, Inc., 842 p.

Oliver, L.J., and Grigoropoulos, S.G., 1981, Control of storm-generated pollution using a small urban lake: Journal of the Water Pollution Control, v. 53, no. 5, p. 594-603.

Pope, L.M., and Hess, L.G., 1989, Load-detention efficiencies in a dry-pond basin *in* Design of Urban Runoff Quality Controls: Proceedings of an Engineering Foundation Conference on Current Practice and Design Criteria for Urban Quality Control, July 10-15, 1988, Potosi, Missouri: New York, American Society of Civil Engineers, p. 258-267.

Randall, C.W., 1982a, Stormwater detention ponds for water quality control, *in* Proceedings of the Conference on Stormwater Detention Facilities, August 2-6, 1982, Henniker, New Hampshire: New York, American Society of Civil Engineers, p. 200-204.

———1982b, Urban runoff pollutant removal by sedimentation, *in* Proceedings of the Conference on Stormwater Detention Facilities, August 2-6, 1982, Henniker, New Hampshire: New York, American Society of Civil Engineers, p. 205-219.

Roesner, L.A., Urbonas, Ben, and Sonnen, M.B., eds., 1989, Design of urban runoff quality controls: Potosi, Miss., Proceedings of an engineering foundation conference on current practice and design criteria for urban quality control, 490 p.

Scherger, D.A., Davis, Jr., J.A., 1982, Control of stormwater runoff pollutant loads by a wetland and retention basin: Lexington, University of Kentucky, 1982 International Symposium on Urban Hydrology, Hydraulics and Sediment Control (July 27-29, 1982), p. 109-123.

Schiffer, D.M., 1989a, Effects of highway runoff on the quality of water and bed sediments of two wetlands in central Florida: U.S. Geological Survey Water-Resources Investigations, Report 88-4200, 63 p.

———1989b, Effects of three highway-runoff detention methods on water quality of the surficial aquifer system in central Florida: U.S. Geological Survey Water-Resources Investigations Report 88-4170, 79 p.

SELECTED REFERENCES --CONTINUED

Schueler, T.R., and Helfrich, Mike, 1989, Design of extended detention wet pond systems *in* Design of Urban Runoff Quality Controls: Proceedings of an Engineering Foundation Conference on Current Practice and Design Criteria for Urban Quality Control, July 10-15, 1988, Potosi, Missouri: New York, American Society of Civil Engineers, p. 180-202.

Sloat, J.V., 1990, Sediment accumulation in wet detention/retention ponds receiving highway runoff: Orlando, University of Central Florida, Thesis, 153 p.

Small, M.J., and DiToro, D.M., 1979, Stormwater treatment systems: Journal of the Environmental Engineering Division, ASCE 105, no. EE3, p. 557-569.

Striegl, R.G., 1987, Suspended sediment and metals removal from urban runoff by a small lake: Water Resources Bulletin, v. 23, no. 6, p. 985-996.

U.S. Environmental Protection Agency, 1983, Results of the nationwide urban runoff program, Volume 1 - Final report: U.S. Environmental Protection Agency, Water Planning Division Report WH-554, chap. 8, p. 8-1–8-14.

———1986, Quality criteria for water: U.S. Environmental Protection Agency Report EPA/440/5-86/001.

Veenhuis, J.E., Parrish, J.H., and Jennings, M.E., 1989, Monitoring and design of stormwater control basins *in* Design of Urban Runoff Quality Controls: Proceedings of an Engineering Foundation Conference on Current Practice and Design Criteria for Urban Quality Control, July 10-15, 1988, Potosi, Missouri: New York, American Society of Civil Engineers, p. 224-238.

Wanielista, M.P., Yousef, Y.A., and Cameron, A.B, 1988, Alternatives for the treatment of groundwater contaminants, a detention pond with groundwater inflow: Florida Department of Transportation, Bureau of Environment Environmental Research, FL-ER-88-40, 105 p.

Weber, Jr., W.J., 1972, Physicochemical processes for water quality control: New York, John Wiley & Sons, 639 p.

Wu, J.S., Holman, Bob, and Dorney, John, 1989, Water quality study on urban wet detention ponds *in* Design of Urban Runoff Quality Controls: Proceedings of an Engineering Foundation Conference on Current Practice and Design Criteria for Urban Quality Control, July 10-15, 1988, Potosi, Missouri: New York, American Society of Civil Engineers, p. 280-289.

Yousef, Y.A., Wanielista, M.P., Dietz, J.D., Lin, L.Y., and Brabhim. M., 1990, Efficiency optimization of wet detention ponds for urban stormwater management, Final report submitted to Florida Department of Environmental Regulation, DER Contract WM159 (A1 and A2):University of Central Florida, College of Engineering, 86 p.