Factors Affecting Phosphorus Transport at a Conventionally-Farmed Site in Lancaster County, Pennsylvania, 1992-95

by Daniel G. Galeone

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CONVERSION FACTORS, ABBREVIATED WATER-QUALITY UNITS, AND VERTICAL DATUM

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
acre	0.4047	hectare
	Volume	
gallon (gal)	3.785	liter
	Mass	
pound (lb)	0.4536	kilogram
	Temperature	
degree Fahrenheit (°F)	°C = (5/9) × (°F-32)	degree Celsius (°C)

Other Abbreviations

Abbreviated water-quality units used in report:

- grams (g)
- grams per cubic centimeter (g/cm^3)
- inches per hour (in/hr)
- kilograms (kg)
- kilograms per acre (kg/acre)
- liters (L)
- liters per acre (L/acre)
- micrometers (mm)
- microsiemens per centimeter at 25 degrees Celsius (mS/cm)
- milligrams (mg)
- milligrams per liter (mg/L)
- milliliters (ml)
- millimeters (mm)
- parts per million (ppm)

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."

FACTORS AFFECTING PHOSPHORUS TRANSPORT AT A CONVENTIONALLY-FARMED SITE IN LANCASTER COUNTY, PENNSYLVANIA, 1992-95

By Daniel G. Galeone

ABSTRACT

The U.S. Geological Survey and the Bureau of Land and Water Conservation of the Pennsylvania Department of Environmental Protection conducted a cooperative study to determine the effects of manure application and antecedent soil-phosphorus concentrations on the transport of phosphorus from the soil of a typical farm site in Lancaster County, Pa., from September 1992 to March 1995. The relation between concentrations of soil phosphorus and phosphorus transport needs to be identified because excessive phosphorus concentrations in surface-water bodies promote eutrophication.

The objective of the study was to quantify and determine the significance of chemical, physical, and hydrologic factors that affected phosphorus transport. Three study plots less than 1 acre in size were tilled and planted in silage corn. Phosphorus in the form of liquid swine and dairy manure was injected to a depth of 6-8 inches on two of the three study plots in May 1993 and May 1994. Plot 1 received no inputs of phosphorus from manure while plots 2 and 3 received an average of 56 and 126 kilograms of phosphorus per acre, respectively, from the two manure applications. No other fertilizer was applied to any of the study plots.

From March 30, 1993, through December 31, 1993, and March 10, 1994, through August 31, 1994 (the study period), phosphorus and selected cations were measured in precipitation, manure, soil, surface runoff, subsurface flow (at 18 inches below land surface), and corn plants before harvest. All storm events that yielded surface runoff and subsurface flow were sampled. Surface runoff was analyzed for dissolved (filtered through a 0.45-micron filter) and total concentrations. Subsurface flow was only analyzed for dissolved constituents. Laboratory soil-flask experiments and geochemical modeling were conducted to determine the maximum phosphate retention capacity of sampled soils after manure applications and primary mineralogic controls in the soils that affect phosphate equilibrium processes.

Physical characteristics, such as particle-size distributions in soil, the suspended sediment and particle-size distribution in surface runoff, and surface topography, were quantified. Hydrologic characteristics, such as precipitation intensity and duration, volumes of surface runoff, and infiltration rates of soil, were also monitored during the study period.

Volumes of surface runoff differed by plot. Volumes of surface runoff measured during the study period from plots 1 (0.43 acres), 2 (0.23 acres), and 3 (0.28 acres) were 350,000, 350,000, and 750,000 liters per acre, respectively. About 90 percent of the volume of surface runoff occurred after October 1993 because of the lack of intense precipitation from March 30, 1993, through November 30, 1993. For any one precipitation amount, volumes of surface runoff increased with an increase in the maximum intensity of precipitation and decreased with an increase in storm duration. The significantly higher volume of surface runoff for plot 3 relative to plots 1 and 2 was probably caused by lower infiltration rates on plot 3.

Soil concentrations of plant-available phosphorus (PAP) for each study plot were high (31-60 parts per million) to excessive (greater than 60 parts per million) for each depth interval (0-6, 6-12, and 12-24 inches) and sampling period except for some samples collected at depths of 12-24 inches. The high levels of PAP before manure applications made it difficult to detect any changes in the concentration of soil PAP caused by manure applications. Manure applications to the study area prior to this study resulted in relatively high concentrations of soil PAP; however, the manure applications to plot 3 during the study period did cause an increase in the soil concentration of PAP after the second manure application. The percentages of total phosphorus in plant-available and inorganic forms were about 5 and 80 percent, respectively, in the 0-24-inch depth interval of soil on the study plots. Concentrations of total phosphorus on sand, silt, and clay particles from soil were 700, 1,000, and 3,400 parts per million, respectively. About 70 percent of the total mass of phosphorus in soil to a depth of 24 inches was associated with silt and clay particles.

Soil-flask experiments indicated that soils from the study plots were not saturated with respect to phosphorus. Soils had the capacity to retain 694 to 1,160 milligrams of phosphorus per kilogram of soil. The measured retention capacity probably exceeded the actual retention capacity of soil because laboratory conditions optimized the contact time between soil and test solutions.

Geochemical modeling indicated that the primary mineralogical controls on the concentration of dissolved phosphorus in surface runoff and subsurface flow were aluminum and iron oxides and strengite (if it exists). Aluminum and iron oxides bind phosphate in solution and strengite is an iron-phosphate mineral. The mineralization of organic phosphorus into dissolved inorganic forms could also supply phosphorus to surface runoff and subsurface flow.

Phosphorus inputs to the plots during the study period were from precipitation and manure. Phosphorus inputs from precipitation were negligible. The loads of phosphorus to the plots from manure applications in May 1993 and May 1994 were 112 and 251 kilograms per acre for plots 2 and 3, respectively; about 60 percent of the load occurred in 1994.

Phosphorus outputs in surface runoff differed between study plots. The cumulative yields of total phosphorus during the study period for plots 1, 2, and 3 were 1.12, 1.24, and 1.69 kilograms per acre, respectively. Differences between plots were primarily evident for dissolved yields of phosphorus. The percentage of the total phosphorus output in surface runoff that was in the dissolved phase varied from 6 percent for plot 1 to 26 percent for plot 3.

The cumulative yields of dissolved phosphorus from plots 2 and 3 were 135 and 500 percent greater, respectively, than the dissolved yield from plot 1. Even though volumes of surface runoff were different on the plots, the primary cause of the difference between plots in the yield of dissolved phosphorus in surface runoff was differences in the concentration of dissolved phosphorus. After the second manure application, concentrations of dissolved phosphorus in surface runoff on plots 2 and 3 were significantly higher than the concentration for plot 1.

An increase in the concentration of dissolved phosphorus in subsurface flow from plots 2 and 3 was measured after manure applications. The mean concentrations of dissolved phosphorus in subsurface flow after the first manure application were 0.29, 0.57, and 1.45 milligrams per liter of phosphorus for plots 1, 2, and 3, respectively.

The loss of dissolved phosphorus in surface runoff was related to the soil concentration of PAP. The model relating dissolved phosphorus in surface runoff to soil PAP indicated that concentrations of dissolved phosphorus in surface runoff would exceed 0.1 milligram per liter if soil concentrations of PAP exceeded 9 parts per million; this PAP concentration was exceeded by each study plot. Over 50 percent of the variation of dissolved phosphorus in surface runoff was explained by soil concentrations of PAP in the 0-6-inch depth interval.

The loss of suspended phosphorus in surface runoff was primarily affected by the particle-size distribution of suspended sediment in surface runoff. Surface runoff was enriched with fines relative to the soil matrix. Generally, over 90 percent of sediment in runoff was comprised of silt and clay particles; only 50-60 percent of particle sizes from the intact soil matrix were in the silt- to clay-size range. Concentrations of suspended phosphorus in surface runoff were not significantly related to soil concentrations of total phosphorus in the 0-6-inch depth interval.

Concentrations of dissolved phosphorus in subsurface flow were also related to soil concentrations of PAP. The relation indicated that dissolved concentrations of phosphorus in subsurface flow would exceed 0.1 milligram per liter if soil concentrations of PAP in the 0-6-inch depth interval of soil were greater than 49 parts per million; this PAP concentration was exceeded by each study plot.

The significant relation of high concentrations of dissolved phosphorus in water to soil concentrations of PAP indicated that soils with comparable concentrations of soil PAP would be potential sources of dissolved phosphorus to surface water and subsurface water tables. The percentage of the total phosphorus lost from a system in the dissolved form increased as soil concentrations of PAP increased. This indicates that best-management practices to reduce phosphorus losses from this system not only need to target suspended forms of phosphorus but also dissolved forms. Practices aimed at reducing the loss of dissolved phosphorus from the system increase in importance with an increase in soil concentrations of PAP.

INTRODUCTION

The processes that control phosphorus transport from agricultural soils to surface water are of particular concern to water-quality agencies. Information on processes that affect phosphorus transport from soil to water is especially critical because of the elevated concentrations of soil phosphorus measured in areas where phosphorus has been applied in organic or inorganic forms over several years (Sharpley and others, 1994). Increased concentrations of total phosphorus in soil can cause increased concentrations of soluble and sediment-associated phosphorus in surface runoff (Romkens and Nelson, 1974). The transfer of soil phosphorus to surface-water bodies is dependent on chemical (Holford and Mattingly, 1976), physical (Sharpley, 1985), and hydrologic (Nagpal, 1986) characteristics of the system. Chemical characteristics include soil mineralogy, the concentration of ions in soil solution, and the quantity of ions adsorbed to soil particles. Physical characteristics include particle size, bulk density, and surface topography. Hydrologic characteristics include soil moisture, soil-infiltration rates, water-residence time in the soil matrix, and the duration and intensity of precipitation.

Excessive concentrations of soil phosphorus and its subsequent transport to surface-water bodies cause nutrient imbalances that promote eutrophication (Bachmann, 1980; Lee, 1973). Because of a nutrient imbalance in the Chesapeake Bay, the 1987 Chesapeake Bay Agreement set a goal to reduce the controllable load of phosphorus to the Chesapeake Bay by 40 percent by the year 2000. Data for the late 1980's show that the estimated phosphorus load (90 percent of which is considered controllable) to the Chesapeake Bay is 27 million pounds per year; 50 percent of this load is estimated to originate from agricultural sources (Chesapeake Bay Program, 1992). To assist in reaching the goal set by the 1987 Bay Agreement, an understanding of processes involved in transport of soil phosphorus to surface water is necessary so that management strategies can be developed to reduce phosphorus losses from agricultural areas. From 1992 through 1995, a study to evaluate the effects of manure application and soil conditions on the transport of phosphorus within the soil-water system of a conventionally-managed farm site in Lancaster County, Pa., was conducted by the U.S. Geological Survey (USGS). The field and laboratory study was done in cooperation with the Bureau of Land and Water Conservation within the Pennsylvania Department of Environmental Protection (PaDEP).

Purpose and Scope

This report quantifies and determines the significance of chemical, physical, and hydrologic factors that affected transport of soil phosphorus to surface runoff and subsurface flow. A field and laboratory study structured to identify specific factors affecting transport of soil phosphorus was conducted from September 1992 to March 1995 at three plots less than 1 acre in size on a minimum-till farm site in Lancaster County, Pa. Before and after various quantities of phosphorus in manure were applied to soil, characteristics that affect phosphorus transport were identified. Because of climatic factors, the study period for collection of field data encompassed the time intervals from March 30, 1993, through December 31, 1993, and March 10, 1994, through August 31, 1994. Phosphorus and selected cation inputs to soil from precipitation and manure were measured, as were phosphorus and selected cation outputs from soil in surface runoff, subsurface flow, and plant harvest. Laboratory soil-flask experiments and geochemical modeling analysis were conducted to determine maximum phosphate (PO_4) retention capacity of soil and primary chemical controls that affect PO_4 equilibrium processes in soil.

Site Description

The study site is located within the Mill Creek Basin in central Lancaster County, Pa., approximately 2 mi south-southwest of the city of Lancaster (fig. 1). The site is within the Lancaster County Central Park and is leased for agricultural purposes. From the study site, Mill Creek flows about 2.5 mi and discharges into the Conestoga River, which flows into the Susquehanna River near Safe Harbor, Pa.

The growing season at the site is from early May until mid-October. The annual average precipitation and temperature are about 41 in. and 51.7 °F, respectively, on the basis of climatological data collected by the National Oceanic and Atmospheric Administration (NOAA) (1993) at Lancaster for the past 108 years.

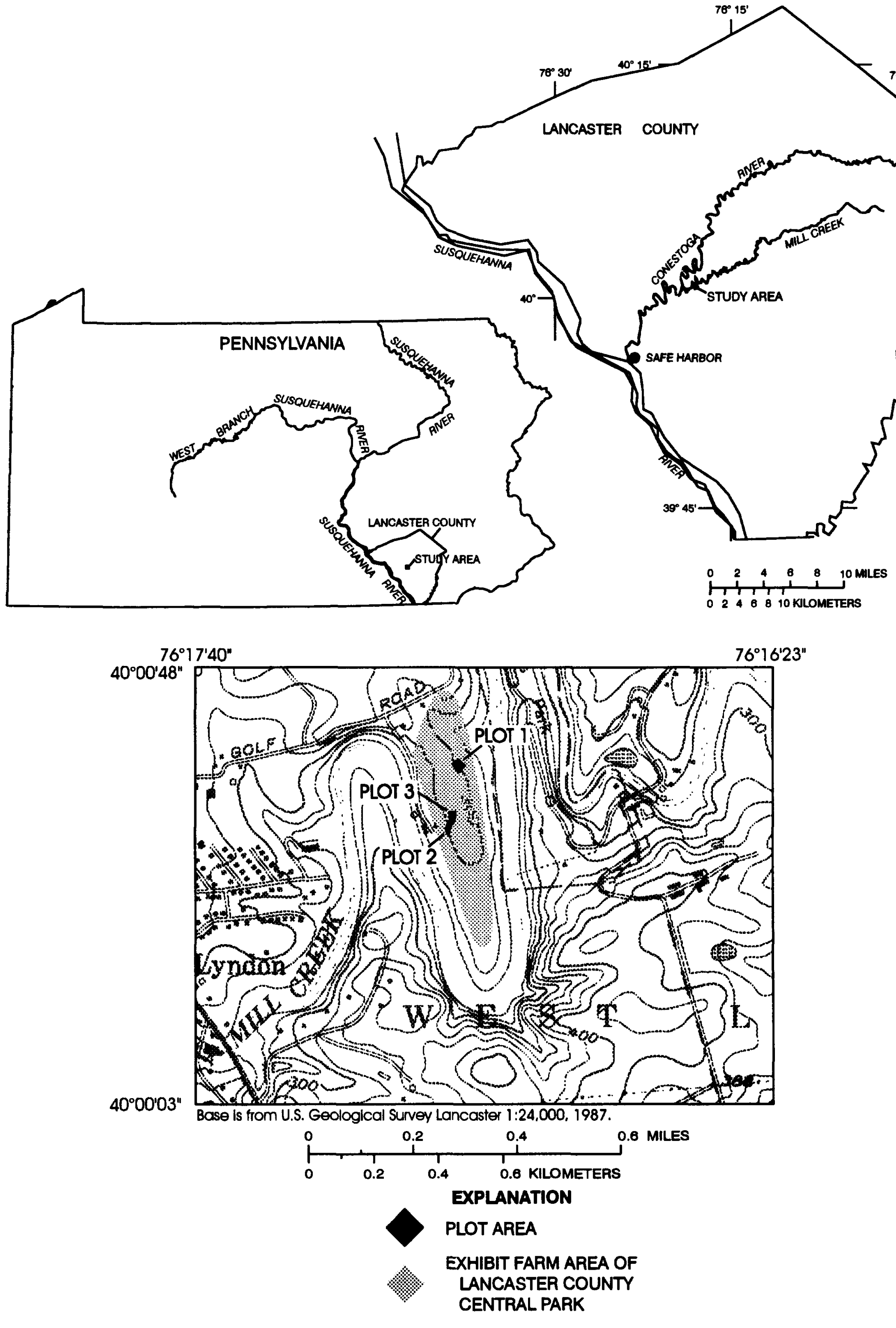

Figure 1. Location of study area and study plots.

Soil at the site is of the Hollinger series, which is a fine-loamy, mixed, mesic Typic Hapludalf (Custer, 1985). Hollinger soil is well drained and derived from micaceous limestone and calcareous schist. Five to 15 ft below the regolith is bedrock of the Conestoga Formation, an Ordovician-aged rock that consists primarily of crystalline limestone with interbedded layers of thin graphite and mica (Poth, 1977).

Acknowledgments

The cooperation of John Mikowychok, the executive director of the Lancaster County Central Park, made the study possible, as did the assistance and flexibility of J. Harold Fritz, the farmer who leases the land from the park. Larry Nygren of PaDEP, Bureau of Land and Water Conservation, spent numerous hours discussing technical details with project personnel and his help was greatly appreciated. The author would also like to acknowledge the help of numerous USGS employees for providing technical, field, and laboratory assistance during the study.

DATA COLLECTION AND ANALYSIS METHODS

Before data collection, a site suitable for the study was located. Officials of Lancaster County Central Park and J. Harold Fritz were amenable to cooperating with the USGS to conduct the study.

Experimental Design

The study was designed to vary the concentration of soil phosphorus so that factors that affect phosphorus transport could be identified. After a 2-month period of initial site characterization, two of the three study plots were fertilized with manure phosphorus at different rates. The first and second manure applications to the plots were during May 1993 and May 1994. The effects of phosphorus applications on concentrations of soil phosphorus and phosphorus transport were monitored until August 31, 1994. Data on soil characteristics, precipitation, manure, surface runoff, subsurface flow, and plant tissue were collected. Surface-runoff and subsurface-flow samples were not collected from January 1, 1994, through March 9, 1994, because of the presence of a significant snowpack. Data collected were used to determine effects of increased phosphorus inputs and antecedent phosphorus concentrations in the soil on phosphorus concentrations in output compartments. Soil-chemical characteristics, as determined by analysis of soil samples collected throughout the study period, soil-flask experiments, and geochemical models, were used to identify factors that affect the adsorption, precipitation, and solubility of PO_4 within the soil-water system.

Sampling Network

The three study plots are located within a 40-acre section of Lancaster County Central Park designated as the Exhibit Farm (fig. 1). The study plots range in size from 0.23 to 0.43 acres and are spatially located within 800 ft of each other (fig. 2).

Study plots were selected on the basis of pre-application concentrations of soil phosphorus and topography. Two plots with above optimum levels of plant-available phosphorus (PAP) for silage-corn production and one plot with near optimum levels of PAP (Pennsylvania State University, 1991) within the upper soil horizons were necessary to meet the experimental design. Areas to meet the first criterion were identified by collecting soil samples from the 0-6-in. depth interval across the study site. Results showed distinct areas of the site where PAP was above optimum and other areas where PAP was near optimum for silage-corn production. The second criterion for plot selection was to identify three study plots with slopes steep enough to allow surface runoff. An areal survey of the study site was used to determine areas suitable for study. Over the past 10-15 years, agricultural practices were somewhat different on plot 1 relative to plots 2 and 3 (table 1). No till was practiced on plot 1 for 4-5 years while minimum till was practiced on plots 2 and 3 during years when silage corn was planted. When no till was practiced, less manure was applied to plot 1 relative to plots 2 and 3 because surface application of liquid manure increases the likelihood of manure being lost by overland runoff.

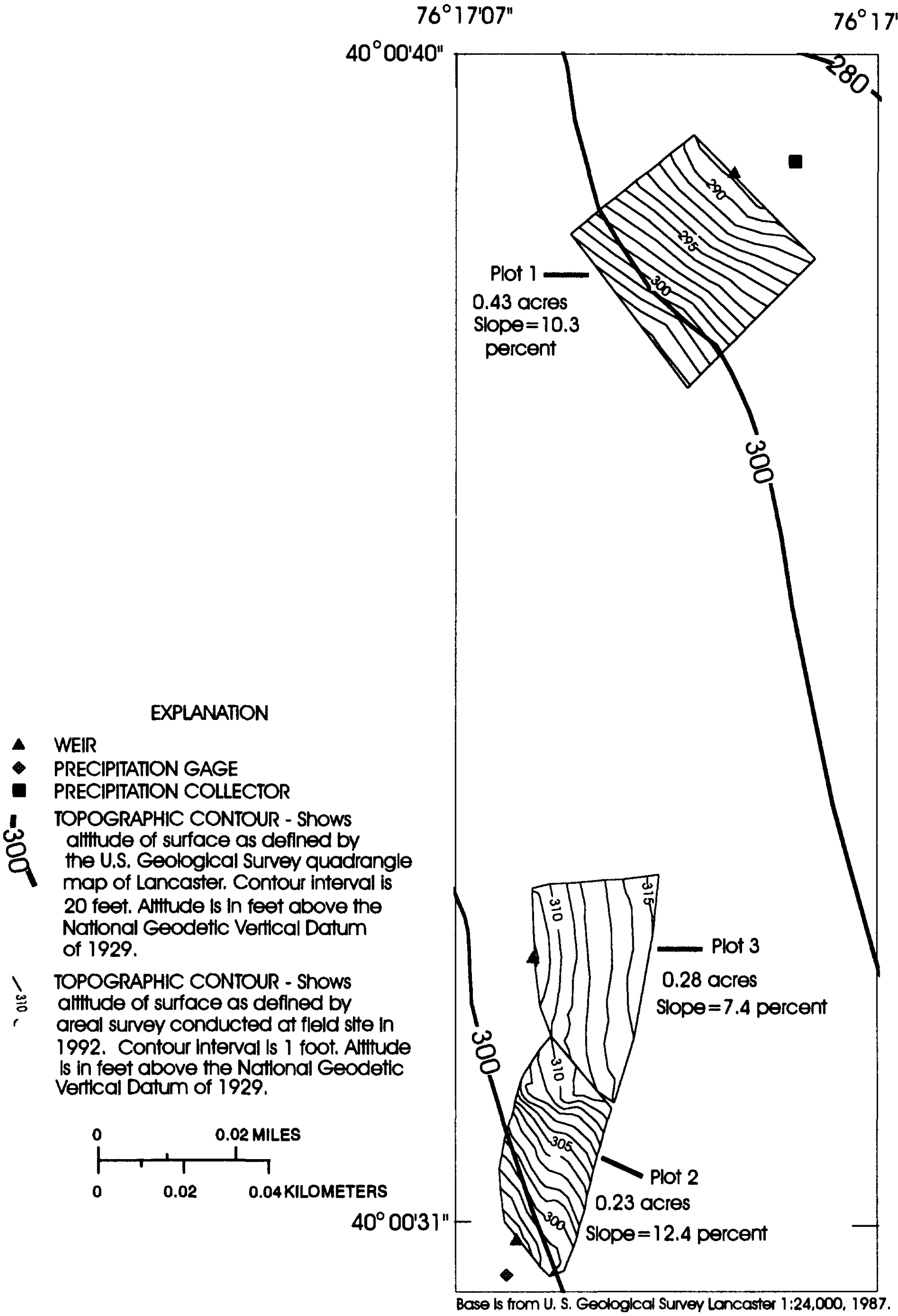

Figure 2. Location and area of study plots at field scale, topographic contours of study plots with mean slopes, and location of instrumentation.

Table 1. Agricultural practices on three study plots during the 10-15 years prior to study

Study plot	Agricultural practices over past 10-15 years prior to beginning of this study
Plot 1	Every 4-5 years, crop was rotated from silage corn to alfalfa. No manure was applied to alfalfa. Phosphorus applied as commercial fertilizer to alfalfa was based on soil-test results and recommendations from Pennsylvania State University soil-testing laboratory. Applied less than 20,000-40,000 liters per acre per year of liquid swine/dairy manure by surface application to fields planted in silage corn during period of no till. No till was practiced for 4-5 years. Applied 20,000-40,000 liters per acre per year of liquid swine/dairy manure by injection to a depth of 6-8 inches when plot was planted in silage corn and minimum till was practiced. Plot was rotated back to silage corn 3 years prior to study.
Plots 2 and 3	Every 4-5 years, crop was rotated from silage corn to alfalfa. No manure was applied to alfalfa. Phosphorus applied as commercial fertilizer to alfalfa was based on soil-test results and recommendations from Pennsylvania State University soil-testing laboratory. Applied 20,000-40,000 liters per acre per year of liquid swine/dairy manure by injection to a depth of 6-8 inches to fields planted in silage corn. Minimum till was practiced. Plots were rotated back to silage corn 3 years prior to study.

Manure Application and Crop Planting

Different phosphorus amounts in manure were applied to study plots to further vary concentrations of soil phosphorus. Significant factors affecting phosphorus transport through hydrologic pathways would be difficult to identify without varying concentrations of soil phosphorus.

Manure phosphorus was applied to the two study plots (plots 2 and 3) with above optimum levels of PAP before crop planting in spring 1993 and spring 1994; whereas on the plot (plot 1) with near optimum levels of PAP, no manure was applied in either year. Liquid swine manure was initially applied on May 17, 1993. Liquid swine and dairy manure was also applied to plots 2 and 3 on May 14, 1994. Manure was applied at rates of 49,600 to 110,700 L/acre.

During both years, manure was injected to a depth of 6 to 8 in. The plots were chisel-plowed to the same depth as injection during the manure application. Plot 1 was chisel-plowed to the same depth as the other plots. Light disking of the study plots 1 week after manure applications helped to distribute applied manure throughout the first 8 in. of soil. Silage corn was sowed on each plot on May 25 of both years.

Data Collection and Laboratory Analysis

Samples collected from the study plots were chemically and physically analyzed. These data were subsequently used to determine the primary factors that affected phosphorus transport from the study plots.

Soil

Soil samples to determine chemical, physical, and hydrologic characteristics were collected five times from each study plot. The first set of samples was collected in April 1993 before the first manure application. Subsequent samples were collected during July 1993, October 1993, April 1994, and July 1994.

Before collection of soil samples for chemical and particle-size analyses, systematic soil sampling across one plot was conducted to determine the number of soil samples per plot that would adequately characterize soil chemistry. Sixteen soil cores were collected over one plot at a depth of 0-6 in. The mean and variance of PAP for these samples and an equation given by Petersen and Calvin (1986) were used to determine the number of samples needed to adequately represent the sample population for each study plot. The 0-6-in. depth interval was used knowing that as depth increases, variability in soil chemistry generally decreases (Petersen and Calvin, 1986), and as variability decreases, the number of samples required decreases. Results showed that 25 samples were the minimum number of samples per plot that would adequately represent the soil chemistry.

Composite soil samples were collected for chemical and particle-size analyses. Sample grids were placed over each plot and sample locations were systematically selected. At each sample location, soil was extracted to a depth of 24 in. Separate soil cores were extracted for the 0-6-in., 6-12-in., and 12-24-in. depth intervals. A hammer auger with a 1-in.-diameter steel corer and sampler body was used to extract soil cores. Approximately 40 soil cores per site for each depth interval were composited before analyses. Before chemical and particle-size analyses, soil samples were air dried and all soil particles larger than sand size (greater than 2.0 mm in diameter) (Guy, 1969) were removed by dry sieving. Subsamples for particle-size analysis were then split from some samples in order to determine the fractions of sand-, silt-, and clay-size particles. Subsamples for chemical analysis were split from every composite sample and sent to two soil-testing laboratories for analysis (table 2).

After the removal of gravel particles by dry sieving, some of the composite soil samples were further processed to separate particle-size fractions before chemical analysis. Sand was removed from the silt and clay fraction (fines) by wet sieving the soil through a series of successively smaller sieves with the smallest sieve having a pore size of 62 μm (Guy, 1969). Soil retained on the sieves was dried and weighed before chemical analysis. The fines that passed through the sieves were initially dried in an oven at 60°C to evaporate water used during the wet-sieving procedure. Some of the dried fines were further separated into silt- and clay-size fractions by use of Stokes' Law and settling cylinders (Krumbein and Pettijohn, 1938). Aggregates in the fines were dispersed by use of an ultrasound bath (Edwards and Bremner, 1967; Saly, 1967) with a frequency of 47 kilohertz. After dispersion, 50 g of fines were placed in a 2-L graduated cylinder filled with distilled water. The fines-water solution was mixed thoroughly and allowed to sit 6-8 hours at room temperatures of about 23°C. The settling velocity of the smallest silt particles was estimated by use of Stokes' Law and multiplied by the time that the fines were allowed to settle. This provided the distance that the smallest silt particle settled from the top of the water column. Liquid above this distance was decanted and liquid below this distance was resuspended in the column. The procedure was repeated and the resuspended solution was decanted after 6-8 hours. The decanted solutions from both suspensions contained the clay fraction of the fines sample. The solutions below the distance contained the silt fraction. Both fractions were dried in evaporating dishes at 60°C in an oven, weighed, and submitted for chemical analysis.

Soil mineralogy for each study plot was characterized by an x-ray diffraction technique, specifically automated powdered diffraction (Whittig and Allardice, 1986). Samples from each plot and from different soil depths were initially separated into sand and fines fractions. Samples were then pulverized before slide preparation and thinly spread over glass petrographic slides by use of a petroleum jelly mounting agent. An x-ray diffractometer was used as the x-ray source and the resultant pattern of diffraction spacing and intensity was input to a matching program to qualitatively determine the most likely minerals present in the sample.

Other soil characteristics studied were soil moisture, bulk density, and infiltration rate. For soil moisture and bulk density, samples were collected from depths of 0-6 in., 6-12 in., and 12-24 in. with a hammer auger and tared butyrate liners in the 1-in.-diameter sampler body. Samples were capped after extraction and the wet weight of the soil was measured. The sample volume was determined from the length and diameter of the soil core. Soil samples were extracted from the liners and dried. Gravel-size particles were removed and weighed after drying. Dry weight without the gravel was used to determine soil moisture (Gardner, 1986). The dry weight including the gravel and the sample volume were used to determine bulk density (Blake and Hartge, 1986). For each plot and depth, two samples were collected during each sampling event for soil moisture and bulk density. The infiltration rate of soil was estimated by use of a single-ring infiltrometer (Bouwer, 1986). A sheet-metal cylinder with a 13-in. diameter and 24-in. height was pressed 2-3 in. into the soil surface. Water with a specific conductance of rainwater (approximately 20 μS/cm) was poured into the infiltrometer. Infiltration-rate data were recorded after the rate of decrease in the head of the water in the infiltrometer stabilized. After stabilization, 1 hour of infiltration-rate data were collected. One infiltration test was conducted per plot for each sampling event.

Table 2. List of chemical and physical constituents for which soil samples were analyzed, number of samples submitted, and detection limits

[Unless otherwise noted, all analyses were performed according to procedures by Page and others (1982) at the soil-testing laboratory of the Colorado State University in Fort Collins, Colo.; mg/kg, milligrams per kilogram; meq/100g, milliequivalents per 100 grams; mmhos/cm, millimhos per centimeter at 25 degrees Celsius; lb/acre, pounds per acre]

Characteristic or constituent	Number of samples submitted		Detection limit
	Before particle-size separation	After particle-size separation	
Phosphorus, total (mg/kg)	45	78	0.1
Phosphorus, inorganic (mg/kg)	45	78	.1
Phosphorus, organic (mg/kg)	45	78	.1
Calcium, total (mg/kg)	27	18	.5
Magnesium, total (mg/kg)	27	18	.05
Aluminum, total (mg/kg)	27	18	.5
Iron, total (mg/kg)	27	18	.05
Sodium, total (mg/kg)	27	18	.05
Potassium, total (mg/kg)	27	18	.5
Exchangeable aluminum (mg/kg)	27	18	.1
Free iron oxide (mg/kg)	27	18	.1
Exchangeable sodium (meq/100g)	27	18	.01
Carbon, organic (in percentage mass)	45	18	.01
Electrical conductivity (mmhos/cm)	45	18	.1
Plant-available phosphorus (lb/acre of P_2O_5)[1]	45	34	5
pH[1]	27	18	.02
Exchangeable potassium[1] (meq/100g)	45	34	.01
Exchangeable calcium[1] (meq/100g)	45	34	.01
Exchangeable magnesium[1] (meq/100g)	45	34	.01
Cation exchange capacity[1] (meq/100g)	45	34	.01
Percentage of sand, silt, clay (in percentage mass)[2]	27		.01

[1] Analysis performed according to procedures by Baker and Amacher (1981) by the Agricultural Analytical Services Laboratory at the Pennsylvania State University in University Park, Pa.

[2] Analysis performed according to procedures by Guy (1969) by the U.S. Geological Survey Sediment Laboratory in Lemoyne, Pa.

Soil-flask experiments were conducted on soil samples from each plot to determine the maximum phosphate retention capacity of the soil as predicted by the Langmuir isotherm equation (Olsen and Watanabe, 1957; Woodruff and Kamprath, 1965; Syers and others, 1973). Soil (that was previously dry sieved to remove gravel) from the 0-6-in. depth interval collected during April and July 1994 was used for the experiments. Five concentrations of phosphorus solutions with a range of 125 to 225 mg/L of phosphorus were developed using distilled water and potassium phosphate (KH_2PO_4). Each phosphorus solution developed was adjusted to pH 7 with sodium hydroxide solution. Each phosphorus solution was applied to soil samples from each 1994 sample date and study plot, with one replicate per sample. Twenty grams of dry soil were added to 200 ml of solution for each flask. Samples were continuously agitated on an orbital shaker for 2 days at a temperature of about 25°C. Chloroform was added to reduce microbial activity. After shaking, samples were filtered through a 0.1-µm filter and shipped to the USGS National Water Quality Laboratory for dissolved orthophosphate (PO_4^{3-}) analysis. Samples had to be filtered through a pore size less than 0.24 µm because the finest clay particle is 0.24 µm in diameter.

Precipitation

Precipitation quantity and intensity data were collected at the study site (fig. 2) using a weighing-bucket precipitation gage with a strip-chart recorder. From March 1993 through August 1994, only one storm was not recorded. Intensity and duration for this storm was estimated using data from a USGS precipitation gage 1.3 mi to the east-southeast.

The precipitation-quality sampler consisted of a 13-in.-diameter plastic funnel attached to tygon tubing. The precipitation sample passed through the tubing to a plastic collection bottle stored in a bucket buried at ground level. The funnel was supported by a wooden frame 7 ft above ground surface and was sufficiently isolated from vegetation to reduce the potential for collecting precipitation that interacted with plant material. Samples were collected and processed 1-2 days after a storm. Upon sample collection, the sample was removed and the funnel and tubing were cleaned with distilled water. The sampler collected wet and dry deposition because the sampler was not covered or removed from the site during the study. Only selected precipitation samples were analyzed for the characteristics and constituents listed in table 3. No precipitation that fell in frozen form was chemically analyzed.

Manure

Manure samples were collected during application. In May 1993, 11,400 and 31,000 L of manure were applied to plots 2 and 3, respectively. In May 1994, 11,400 and 29,500 L of manure were applied to plots 2 and 3, respectively. Manure samples were collected directly from an outflow pipe on the manure-spreading truck. In 1993, samples were collected before, during, and after manure application on the study plots. In 1994, samples were collected before and after application. Samples were immediately delivered to Agri Analysis Laboratory[1] for chemical analysis (table 4).

Surface Runoff

Surface-runoff volumes were collected and quantified for each study plot from March 30, 1993, through December 31, 1993, and March 10, 1994, through August 31, 1994. Plastic sheeting was used to cover mounded soil on the downslope edge of each plot to intercept surface runoff and channel it to a weir located at the lowest point of each plot. The remaining perimeter was trenched and mounded to keep runoff from migrating into the plots from other parts of the Exhibit Farm (fig. 2). A stilling well instrumented with a Stevens[1] graphic stage recorder at the upslope side of each weir was used to measure runoff volumes from each plot. Runoff passed through the weir into polyvinylchloride (PVC) pipe that discharged runoff into below-ground collection boxes lined with plastic tarpaulins. The collection boxes were 7 ft by 7 ft by 4 ft and had the capacity to hold approximately 5,700 L.

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[1] The use of trade, product, industry, or firm names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

Table 3. List of water-quality characteristics and constituents for which surface-runoff, subsurface-flow, and precipitation samples were analyzed, number of samples submitted, and detection limits

[Unless otherwise noted, all analyses were performed according to procedures by Fishman and Friedman (1989) at the U.S. Geological Survey National Water Quality Laboratory in Arvada, Colo.; total, unfiltered; dissolved, filtered through a 0.45-µm filter; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; °C, degrees Celsius; µg/L, micrograms per liter]

Characteristic or constituent	Number of samples submitted			Detection limits
	Surface runoff	Subsurface flow	Precipitation	
Phosphorus, total (mg/L)	91	0	16	0.01
Phosphorus, dissolved (mg/L)	91	70	0	.01
Phosphorus, ortho, dissolved (mg/L)	73	62	0	.01
Phosphorus, hydrolyzable and ortho, dissolved (mg/L)	18	8	0	.01
Phosphorus, hydrolyzable and ortho, total (mg/L)	17	0	3	.01
Specific conductance[1] (µS/cm)	91	65	16	1
pH [1]	91	64	16	.02
Temperature [1] (°C)	91	63	16	.1
Carbon, organic total (mg/L)	67	0	7	.1
Carbon, organic dissolved (mg/L)	5	45	0	.1
Calcium, total (mg/L)	58	0	7	1
Calcium, dissolved (mg/L)	57	40	0	.1
Magnesium, total (mg/L)	58	0	7	.1
Magnesium, dissolved (mg/L)	57	40	0	.1
Sodium, total (mg/L)	58	0	7	.1
Sodium, dissolved (mg/L)	57	40	0	.1
Potassium, total (mg/L)	58	0	6	.1
Potassium, dissolved (mg/L)	57	38	0	.1
Iron, total (µg/L)	58	0	7	10
Iron, dissolved (µg/L)	57	40	0	10
Aluminum, total (µg/L)	58	0	7	10
Aluminum, dissolved (µg/L)	57	40	0	10
Sediment, suspended (mg/L)	92	0	0	1
Sediment, suspended, fall diameter percentage finer than 0.004 mm [2]	78	0	0	.01
Sediment, suspended, fall diameter percentage finer than 0.062 mm [2]	92	0	0	.01

[1] Analysis performed during sample collection.

[2] Analysis performed according to procedures by Guy (1969) at the U.S. Geological Survey Sediment Laboratory in Lemoyne, Pa.

Table 4. List of chemical constituents for which manure samples were analyzed, number of samples submitted, and detection limits

[Analyses were performed at Agri-Analysis Laboratory, in Leola, Pa., by use of a inductively coupled plasma method with a spectrometer; ppm, parts per million]

Constituent	Number of samples	Detection limit (ppm)
Phosphorus	8	1
Potassium	8	2
Calcium	8	2
Magnesium	8	2
Iron	8	.1
Aluminum	8	.1
Sodium	8	.1
Copper	8	.1
Manganese	8	.1
Zinc	8	.1
Nitrogen	8	1

Surface-runoff samples for water-quality analyses were collected from the retention boxes. Before sample retrieval, water within the boxes was mixed vigorously with an oar covered with plastic sheeting. A plastic bucket attached to a rope was immersed in the runoff water approximately 10 times in order to fill two 5-gal plastic buckets with sample. The 10 gallons were poured into a cooler and subsamples were collected from the cooler during continuous mixing for chemical and sediment analyses (table 3).

After samples were collected, water was pumped from the retention boxes and the volume discharged was measured. After each runoff event, the plastic liner was removed from the box and a clean liner was installed. The runoff volume collected in the box was used to calibrate the strip-chart records from the stilling wells. Calibration of the strip charts to the actual volume collected within the boxes was necessary in order to determine runoff volumes for storm events that generated runoff volumes exceeding the capacity of the collection boxes.

Subsurface Flow

Water moving below the soil surface was collected for chemical analyses from each study plot from late March 30, 1993, through December 31, 1993, and March 10, 1994, through August 31, 1994. A pit near the weir location was excavated outside the plot boundaries to install the subsurface-flow collection devices. Approximately 18 in. below the soil surface on the vertical face of the pit, a bucket auger was used to drill a hole 12 ft into the soil matrix of each study plot. The hole was drilled at an angle that followed the topography of the soil surface. Semi-perforated (perforations on top side of pipe and no perforations on bottom side) PVC pipe wrapped with spun-bonded polypropylene was placed into the excavated hole and the soil removed from the hole was packed around the outside of the PVC pipe to maximize contact between the pipe and the surrounding soil matrix. Subsurface flow entering the pipe was collected in a 5-gal bucket attached to the pipe outflow.

Subsurface-flow samples were retrieved for chemical analyses after each storm that generated subsurface flow to the collection buckets. It was assumed that any suspended particles in samples of subsurface flow were caused by the pipe-installation process; therefore, samples were filtered through a 0.45-µm filter prior to chemical analyses (table 3).

Plant Tissue

Corn-plant material for chemical analysis was collected immediately before harvest during 1993 and 1994. Four plants were randomly selected from each study plot and the entire plant was removed. Plants from each study plot were composited into two samples before drying and subsampling for chemical analysis. Plants were washed thoroughly and the stem, husk, root, leaf, and vegetable material were separated before drying. Once dry, plant matter was ground with a sample mill to pass through a 1-mm screen. Ground plant material was bagged and shipped to the Agricultural Analytical Laboratory at the Pennsylvania State University where material was chemically analyzed for phosphorus, potassium, calcium, magnesium, manganese, iron, copper, boron, aluminum, zinc, and sodium. Analyses were performed by use of the inductively coupled plasma method with a spectrometer.

Quality Assurance

Approximately 10 percent of samples submitted for laboratory analyses were quality-assurance samples. Only duplicate samples were submitted for soil and plant analyses. Duplicate samples and deionized-water blanks were submitted for water analysis. Blank samples submitted were at or below detection limits for the constituents analyzed. Duplicate samples were submitted in order to check the quality of sampling and analytical procedures. Most duplicate samples did not exceed a relative percentage difference (RPD) of 5 percent. The RPD (Witt and others, 1992) is equal to

$$\frac{2(\text{difference between duplicate samples})}{\text{sum of duplicate samples}} \times 100. \qquad (1)$$

Documented quality-assurance and control plans were followed by each laboratory that conducted analyses for this study. The plans are available on request to the appropriate laboratory.

Data Analysis

The sample type and the characteristic evaluated dictated the method of data analysis. Qualitative analysis was a graphical display of data. Quantitative analysis involved statistical procedures to determine relations or significant differences in data. The significance level for each statistical procedure was set at alpha equal to 0.05. Therefore, decisions on the basis of test results had a 95-percent probability of not being erroneous.

The hydrologic characteristics of the study plots were summarized by developing a water budget (Thornthwaite and Mather, 1957). Precipitation inputs and surface-runoff outputs were measured; soil-water storage and evapotranspiration were estimated. Input not accounted for by measured and estimated variables was considered subsurface-water movement through the soil system.

Physical and chemical characteristics of soil from each study plot were qualitatively and quantitatively compared. Physical characteristics of the soil, such as slope and infiltration rate, were compared qualitatively. Trends in concentrations of soil phosphorus were graphically compared among plots at different depth intervals of soil. For quantitative analysis, concentrations of total and PAP in soil were initially tested for normality. If data were normally distributed, Pearson correlation coefficients were generated between soil phosphorus and other chemical characteristics of the soil. If data were not normally distributed, Spearman correlation coefficients were generated. Correlation coefficients measure the strength of association between two variables but do not imply a causal relation. Correlation coefficients, which are dimensionless, range from -1 to +1. Variables with no correlation have a coefficient of zero (Helsel and Hirsch, 1992). Regression models between concentrations of soil phosphorus and other chemical characteristics were generated in a stepwise manner by use of Mallow's C(p) statistics. Mallow's C(p) statistic is used in stepwise regression processes to identify the best possible model in a multivariate analysis. Mallow's C(p) is designed to explain as much variation in the regressed (y) variable without incorporating an excessive number of predictor (x) variables. In general, the lower the C(p) value, the better the model (Helsel and Hirsch, 1992). The chemical characteristics of the soil that affected PO_4 equilibrium reactions in soil were determined by use of the WATEQ4F geochemical modeling program (Ball and Nordstrom, 1991).

Maximum phosphate retention capacities for soil from each plot were estimated by use of the soil-flask experimental results and the Langmuir isotherm equation. The form of the equation (Olsen and Watanabe, 1957) is

$$\frac{C}{x/m} = \frac{1}{kb} + \frac{C}{b}, \qquad (2)$$

where C is the equilibrium phosphorus concentration (the concentration of phosphorus after filtration at the end of 48-hour shaking period), in moles per liter;

x/m is milligrams of phosphorus retained per 100 g of soil;

k is the constant related to bonding energy of phosphate to the soil; and

b is the retention maximum.

To determine b, C/x/m (ordinate axis) and C (abscissa axis) are plotted, with the slope of the line equal to 1/b. The constant k is equal to the slope divided by the intercept of the ordinate axis.

Phosphorus outputs, expressed as concentration (in units of mg/L) or yield (in units of kg/acre), were quantitatively compared within and among plots for five time periods determined according to timing of manure application and growing season. The Kruskal-Wallis test was used to conduct within-plot comparisons to determine if dissolved phosphorus (in surface runoff and subsurface flow) and suspended phosphorus (in surface runoff) were significantly different between time periods. The Kruskal-Wallis test is a nonparametric procedure with a null hypothesis that all of the groups have identical distributions. Upon rejection of the null hypothesis, a multiple-comparison test can be conducted to determine which groups are significantly different from one another (Helsel and Hirsch, 1992). The Tukey multiple-comparison test was used if the null hypothesis was rejected. The signed-rank test was used to conduct between-plot comparisons to determine if dissolved phosphorus (in surface runoff and subsurface flow) and suspended phosphorus (in surface runoff) were significantly different for each time period. The null hypothesis for this nonparametric test is that the median difference between two sets of observations is zero (Helsel and Hirsch, 1992). The Tukey multiple-comparison test was used if the null hypothesis was rejected.

Regression models were developed to determine the relation between phosphorus outputs in water and soil phosphorus. Concentrations of dissolved phosphorus in surface runoff and subsurface flow were regressed against concentrations of soil PAP. Concentrations of suspended phosphorus in surface runoff were regressed against the concentration of total phosphorus in the soil. Median concentrations of phosphorus in surface runoff and subsurface flow for each of the five periods were used for the models. The concentrations of phosphorus in soil for the different time intervals were used as predictor variables.

Other variables that could affect phosphorus output in water, such as the contact time of the water with the soil, which is related to precipitation energy and intensity variables, the concentration of cations and organic carbon in solid and liquid phases, and physical soil characteristics, were used in correlation and regression analysis. Phosphorus concentrations in surface runoff and subsurface flow were initially tested for normality to determine distributions and the appropriate correlation analysis. As with soil-phosphorus data, regression models for phosphorus in water were generated by use of Mallow's C(p) statistic.

PHYSICAL AND HYDROLOGIC CHARACTERISTICS

The physical and hydrologic characteristics of a system affect phosphorus transport. The Universal Soil Loss Equation (USLE) uses physical and hydrologic properties of a system to predict erosional losses (Wischmeier and Smith, 1978). Erosional loss of soil through hydrologic pathways transports phosphorus in suspended form. Phosphorus in dissolved form is transported from soil by surface runoff and subsurface flow.

Topography

Mean slopes for the three study plots were 10.3, 12.4 and 7.4 percent for plots 1, 2, and 3, respectively (fig. 2). The change in elevation from highest to lowest points on plots 1 and 2 was about 15 ft; on plot 3, the change in elevation was about 7 ft. Mean slopes were calculated by drawing five transects perpendicular to the contoured elevation data for each study plot. The change in elevation over distance was averaged for the five transects to calculate the mean slope.

Soil

Particle-size distributions of soil to a depth of 2 ft showed that plot 3 had a higher percentage (60.5 percent) of silt and clay than plots 1 (47.6 percent) and 2 (46.2 percent) (fig. 3). Only minor differences existed in the particle-size distributions between plots 1 and 2. Soils on the study plots are considered loam on the basis of particle-size distributions (Brady, 1974), which is consistent with the description of the Hollinger soil series given by Custer (1985). Particle-size data for plots 1 and 2 indicated an increase in the percentage of coarse (gravel and sand) material with an increase in depth.

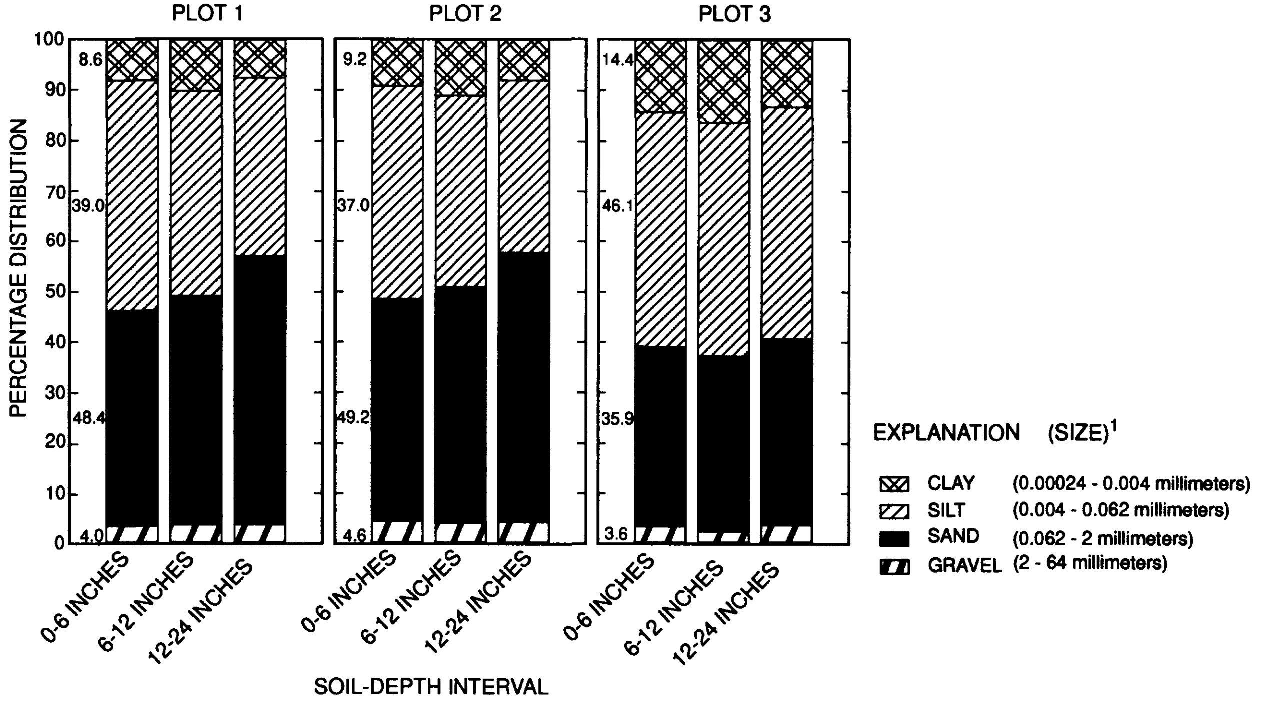


Figure 3. Particle-size distribution on a per-weight basis for 0-6-inch, 6-12-inch, and 12-24-inch soil-depth intervals for three study plots. (Particle-size distributions were determined for soil samples collected during April, July, and October 1993; mean values for 0-24-inch depth of soil are given at left of bar for the 0-6-inch depth interval of soil.)

[1] Particle-size ranges are from Guy (1969).

Bulk densities (pd), which are a measure of dry weight mass per unit volume, measured for each plot (table 5) were typical for loam soils (Brady, 1974). Differences between the study plots were small; plot 3 had the highest mean pd (1.39 g/cm^3).

Table 5. Mean bulk density, in grams per cubic centimeter, of soil by depth interval and number of samples for three study plots

[pd, bulk density; n, number of samples]

Depth	Plot 1		Plot 2		Plot 3	
	pd	n	pd	n	pd	n
0-6 inches	1.33	12	1.34	12	1.30	12
6-12 inches	1.40	11	1.39	12	1.43	12
12-24 inches	1.33	10	1.30	10	1.42	10

Infiltration rates of soil, which are a measure of the maximum rate at which precipitation can enter the soil (Kohnke and Bertrand, 1959), were lowest for plot 3 (median = 0.91 in/hr). Plots 1 and 2 had similar median infiltration rates (1.62 and 1.80 in/hr, respectively) (fig. 4). Data are typical for a Hollinger soil type (Custer, 1985). The low infiltration rate for plot 3 is reflective of a soil with relatively high clay content and pd (Kohnke and Bertrand, 1959).

Soil-moisture data showed no major differences between plots or within plots at different depth intervals (fig. 5). Data did indicate a decrease in soil moisture during the growing season.

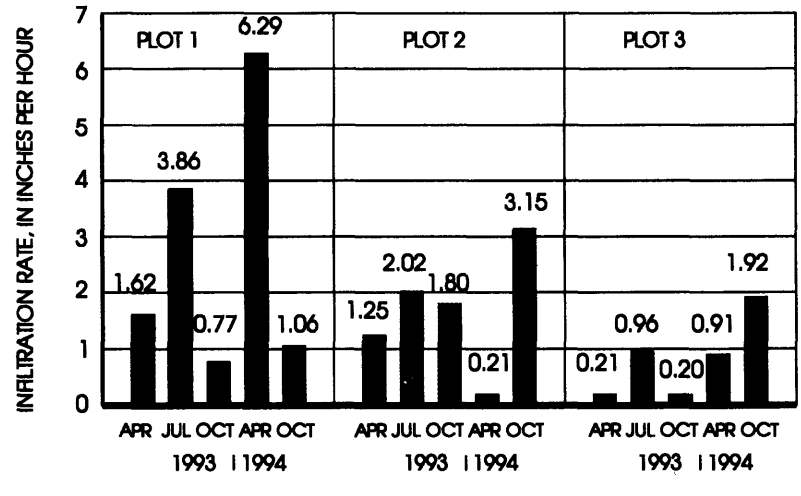


Figure 4. Infiltration rates of soil for three study plots.

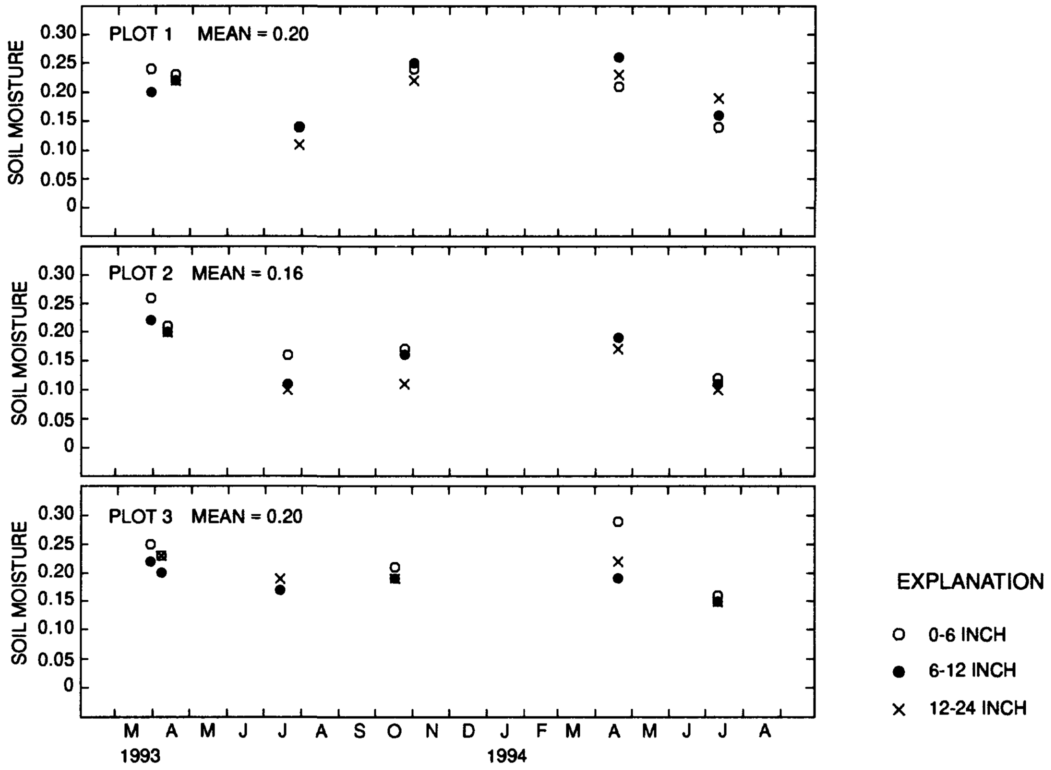


Figure 5. Soil moisture for three study plots for different depth intervals. (Soil moisture is equal to the weight of wet soil divided by the weight of dry soil with the quotient subtracted by 1; the mean for each plot is the average of all soil-moisture data collected for that study plot.)

Precipitation

Precipitation from March 1993 through August 1994 showed considerable variation (fig. 6). From May through August 1993, the total precipitation was 10.9 in.; during the same period in 1994, 20.9 in. of rain fell. From March 15, 1993, through August 31, 1994, five storms exceeded a 2 in.-per-day intensity—one in late November 1993, one in early December 1993, and three during summer 1994.

Most precipitation from January through mid-March 1994 was frozen. A snowpack of 1-2 ft on the study plots was common during this period.

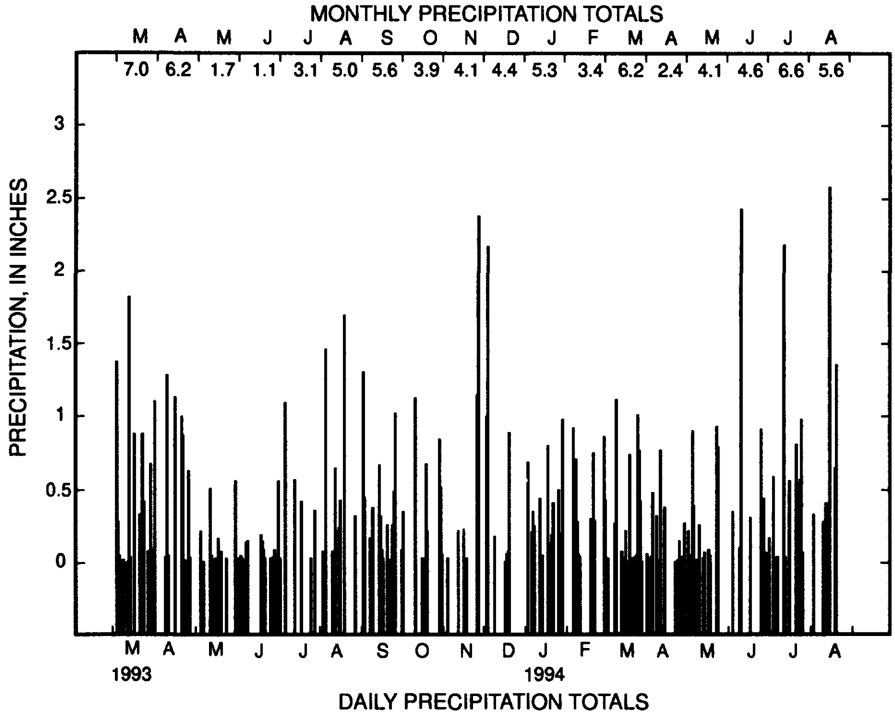


Figure 6. Daily and monthly precipitation totals at the study site. (The precipitation axis extends below zero to clarify the occurrence of precipitation events at or below 0.1 inches.)

Surface Runoff

Surface-runoff volumes showed substantial variation over the study period. Only about 10 percent of the total runoff volume measured from the three study plots for the entire study occurred from April through October 1993 (fig. 7). The major precipitation events in late November 1993 and early December 1993 accounted for about 35 percent of the total runoff volume measured with the remaining runoff volume primarily occurring during summer 1994. Surface runoff from the study plots could not be measured during January 1, 1994, through March 9, 1994, because of climatic factors.

Volumes of surface runoff measured from the study plots during the study period were significantly different on the basis of the signed-rank test. The cumulative runoff volume from plot 3 exceeded the cumulative volume from plots 1 and 2 by 39 and 163 percent, respectively. The cumulative yield of surface runoff from plot 3 exceeded the cumulative yield from plots 1 and 2 by 113 and 116 percent, respectively. Because plot 3 has the lowest mean slope (fig. 2) and cover-crop conditions were similar between plots, the probable cause for the significant difference in surface-runoff volumes between plot 3 and the other study plots were differences in infiltration rates of soil (fig. 4).

The volume of surface runoff from the study plots was dependent on the interaction of the physical characteristics of the study plots and precipitation events. The USLE (Wischmeier and Smith, 1978) is an empirical model that estimates erosion losses on the basis of the physical characteristics of a site, such as slope, slope length, and crop cover, and the physical characteristics of a precipitation event, such as kinetic energy of raindrops impacting the soil and maximum intensity during the event. Parts of USLE were extracted and modified to develop multiple-variable regressions (table 6) that relate volumes of surface

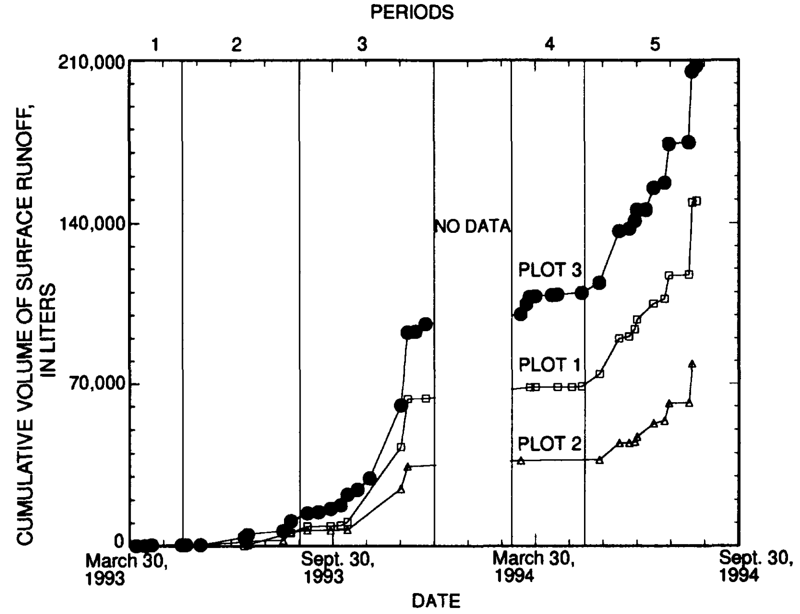


Figure 7. Cumulative volume of surface runoff for three study plots. (See table 15 for PERIOD definitions.)

runoff for each study plot to variables listed in table 6 (see appendix 1 for actual data). Kinetic energy (E) of a storm, expressed in foot-tons per acre per inch of rain, is based on the summation of E for the entire storm, where

$$E = 916 + (331 \times \mathrm{LOG10}(\mathrm{intensity})), \qquad (3)$$

and intensity is equal to inches per hour. Intensities were calculated for each hour of a storm. Any hourly estimate of E that was less than zero was set to zero for summation purposes.

The models in table 6 indicated that runoff volumes increase with an increase in E and maximum intensity (MAXINT) of the storm. The model also indicated that for any one precipitation amount, as the duration increased, volume of surface runoff decreased. Coefficient estimates for different study plots indicated that the effects of E and MAXINT were accentuated on plot 3. This is most evident from differences in volumes of surface runoff from the study plots (fig. 7). The differences in volumes of surface runoff between plots was probably related to differences in the soil infiltration rates (fig. 4).

For the majority of storms for all study plots, the measured soil-infiltration rates exceeded the maximum intensities that produced surface runoff. The reasons for this are beyond the scope of this study, but potential factors are (1) infiltration rates were measured by applying 1-2 ft of water into a ringed cylinder. This applied pressure to the soil helped to force water downward. This situation does not occur during a storm event; (2) infiltration rates were measured in a cylinder; therefore, surface slope did not affect the measured infiltration rate; and (3) subsurface stormflow can contribute to the volume of surface runoff during the latter stages of a storm event (Sherman and Musgrave, 1942).

The effect of the maximum intensity of a storm on volumes of surface runoff from study plots was dependent on season (table 7). Over 70 percent of the surface runoff from each study plot during the period when silage corn covered the soil (mid-June until harvest) occurred when maximum storm intensities exceeded 1 in/hr. Less than 30 percent of the surface runoff from each study plot during the period when silage corn did not cover the soil occurred when maximum storm intensities exceeded 1 in/hr.

Table 6. Regression models for surface-runoff volumes for each study plot with independent variables generated from energy-based precipitation data

[VOLUME, surface-runoff volume, in liters; E, kinetic energy of storm in (foot-tons per acre per inch of rain)/100; C, soil-loss ratio on the basis of crop cover and tilling method; C increases with an increase in crop cover; MAXINT, maximum intensity of storm, in inches per hour (on the basis of 1-hour increments); EIC = E × MAXINT × C; DURATION, duration of storm in hours; EDUR = E × DURATION; EICDUR = EIC × DURATION; Adj. R^2, coefficient of determination; n, number of observations; see Wischmeier and Smith (1978) for detailed discussion of energy and precipitation variables.]

	n	Adj. R^2
Plot 1		
VOLUME = -144 + 563 (EIC) - 3.09 (EDUR) + 18.6 (EICDUR)	113	0.65
Plot 2		
VOLUME = -134 + 333 (EIC) - 1.48 (EDUR) + 7.59 (EICDUR)	113	.64
Plot 3		
VOLUME = -123 + 716 (EIC) - 3.42 (EDUR) + 20.8 (EICDUR)	113	.76
All parameters and models are significant at alpha=0.05		

Table 7. Percentage of total surface runoff for each study plot for different maximum intensities of storms yielding surface runoff and for different seasons

Maximum intensity (inches per hour)	Percentage of total surface runoff					
	Time periods = Mar. 30, 1993 - June 15, 1993; Oct. 2, 1993 - Dec. 31, 1993; and Mar. 10, 1994 - June 15, 1994			Time periods = June 16, 1993 - Oct. 1, 1993; and June 16, 1994 - Aug. 31, 1994		
	Plot 1	Plot 2	Plot 3	Plot 1	Plot 2	Plot 3
0-0.10	[1]--	--	[2]0	--	--	--
0.11-0.20	0.2	--	4.3	--	--	--
0.21-0.30	1.6	0.8	5.8	2.2	0.7	1.7
0.31-0.40	--	--	--	.5	--	1.3
0.41-0.50	14.2	13.2	16.4	--	--	--
0.51-0.60	--	0	0	.3	.6	1.6
0.61-0.70	--	--	--	.6	0	.5
0.71-0.80	22.3	23.1	15.8	0	1.6	1.6
0.81-0.90	--	--	--	1.4	1.4	1.1
0.91-1.00	--	--	--	5.1	3.6	4.8
1.01-1.50	3.8	.3	2.2	21.8	22.8	16.0
1.51-2.00	--	--	--	--	--	--
> 2.0	10.8	9.4	11.4	15.2	22.3	15.2
Total	52.9	46.8	55.9	47.1	53.0	43.8

[1] Indicates no storm produced surface runoff for that plot, season, and maximum-intensity interval.

[2] Indicates that surface runoff occurred, but percentage of total surface runoff was less than 0.1 percent.

Water Budget

Evapotranspiration (ET) for the study plots was estimated using methodology developed by Thornthwaite and Mather (1957). The method uses monthly precipitation and temperature data, soil type, cover crop, and other variables related to geographic location. Estimated ET for the study plots was about 70 percent of measured precipitation during the study period (fig. 8). The percentage of precipitation estimated as ET for the study plots was greater than estimates reported by Poth (1977) (58 percent) and U.S. Department of Agriculture (1992) (about 50 percent) for Lancaster County. The differences were caused by the lack of data for January 1 through March 9, 1994. ET is low during the winter (Thornthwaite and Mather, 1957).

Estimated ET and measured surface runoff were used to estimate subsurface flow from the study plots by use of the equation

$$\text{Precipitation} = \text{ET} + \text{surface runoff} + \text{subsurface flow} \qquad (4)$$

where all variables are in inches. Because it was assumed that ET losses for each study plot were equal and changes in soil moisture were zero, differences in estimated subsurface flows between study plots were caused by differences in measured volumes of surface runoff.

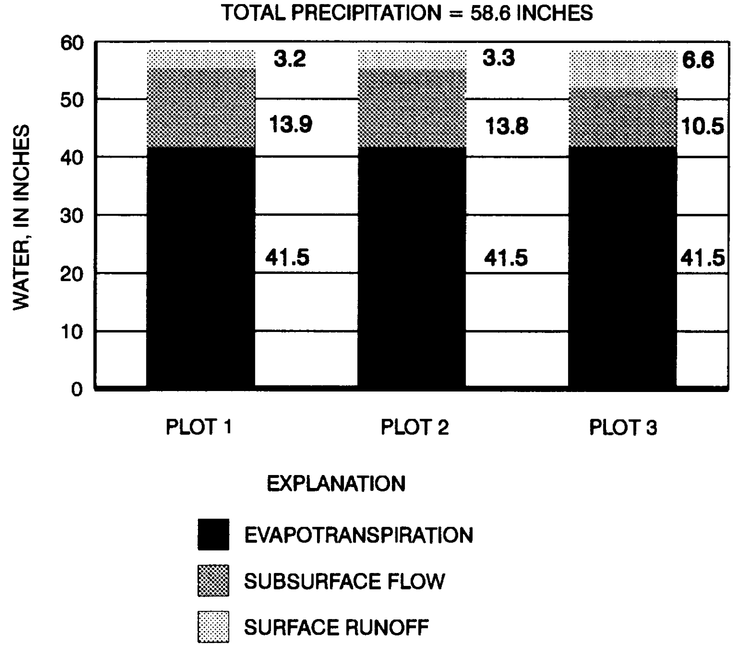


Figure 8. Water-budget outputs for three study plots for the periods April 1, 1993, through December 31, 1993, and April 1, 1994, through August 31, 1994. (Values to right of bars are estimated outputs, in inches, for the output compartment.)

The percentage of precipitation that left the study plots during the study period as surface runoff, which was defined as the volume of water that moved through the weir at the lowest point of each plot, ranged from 5 to 6 percent for plots 1 and 2 to 11 to 12 percent for plot 3. These surface runoff to precipitation percentages were similar to the measured percentages at Field Sites 1 and 2 of the Conestoga Headwaters project conducted in Lancaster County (U.S. Department of Agriculture, 1992). These field sites were also located in carbonate-rock areas. Typically, about one-sixth of the precipitation in Pennsylvania is discharged as surface runoff (U.S. Geological Survey, 1990). For this study, the percentage of precipitation that discharged as surface runoff would have been greater if snowmelt runoff was measured. The development of an ice layer below the snowpack during winter 1993-94 reduced infiltration of melting snow during March 1994.

SOIL PHOSPHORUS

The concentration and speciation of phosphorus in soil partially controls the loss of phosphorus from the soil through hydrologic pathways (Sharpley, 1980). The capacity of the soil to retain phosphorus added in the form of manure is determined by the phosphate retention capacity of the soil particles, the geochemical status of the system, and mineralization of organic phosphorus in soil.

Chemical Characteristics

Concentrations of soil phosphorus were more variable over the different depth intervals sampled on the treated plots (2 and 3) than on the untreated plot (1) (tables 8 and 9). The concentrations of total phosphorus and PAP on plot 1 were fairly consistent over the study period. The maximum differences between concentrations of phosphorus for different depths (0-6 in., 6-12 in., and 12-24 in.) on plot 1 for any sampling period were 110 and 23 ppm for total phosphorus and PAP, respectively. For plot 2, the maximum differences in the concentration of total phosphorus and PAP between different depths were 310 and 96 ppm, respectively, before manure application, and 280 and 111 ppm, respectively, after the second manure application. For plot 3, the maximum differences in the concentrations of total phosphorus and PAP between different depths were 400 and 114 ppm, respectively, before manure application, and 520 and 193 ppm, respectively, after the second manure application. Thus, higher variability in soil phosphorus between depth intervals on plots 2 and 3 relative to plot 1 was evident before and after manure applications during this study. Differences in agricultural practices between study plots (table 1) prior to the study caused differences between study plots in the distribution of phosphorus in the soil matrix. However, manure applied during the study appeared to increase differences in the concentration of soil phosphorus for different depth intervals on plot 3.

Differences in soil phosphorus between plots increased over the study period. The weighted mean (mean for the 0-24-in. depth interval) phosphorus concentrations from the first set of samples collected in April 1993 to the last set collected in July 1994 indicated that concentrations of total phosphorus and PAP increased on plot 3 by 70 and 35 ppm, respectively. For plots 1 and 2 over the same period, there was virtually no change in the weighted mean concentrations of PAP and a 40 ppm decrease in the concentration of total phosphorus for plot 1.

PAP concentrations for all plots exceeded or were within range of the recommended amount of phosphorus required for production of silage corn. The optimum concentration range for this crop is 140 to 230 lb/acre of P_2O_5 (Pennsylvania State University, 1991), which is equal to 30-50 ppm of phosphorus. According to criteria published by Gartley and Sims (1994), concentrations of PAP for each study plot were high (31-60 ppm) to excessive (greater then 60 ppm) for each depth interval and sampling period except for three samples for the 12-24-in. depth on plot 3.

Overall, the percentages of total phosphorus in plant-available and inorganic forms were about 5 and 80 percent, respectively; however, the percentage of total phosphorus available to plants and the percentage of the total in inorganic and organic forms varied among plots (table 10). Four percent of the total phosphorus was available to plants, and inorganic and organic forms comprised 86 and 14 percent, respectively, of the total phosphorus for plot 1. These results were fairly consistent over the study period and soil depth for plot 1. For plot 2, the percentage of total phosphorus available to plants (about 6 percent) was fairly stable over time, but the relative percentage of total phosphorus in inorganic form increased by 10 percent over the study period. Decreases in percentages of total phosphorus in plant-available and organic forms were evident for plot 2 with increase in depth. For plot 3, the percentage of total phosphorus in plant-available form also decreased with depth but increased from 11 to 16 percent for the 0-6-in. depth interval over the study period. The percentage of total phosphorus in inorganic form for plot 3 increased by approximately 20 percent over the study period. Increases in the percentage of total phosphorus in plant-available and inorganic forms on plots 2 and 3 were probably caused by manure applications because manure supplies PAP and about 80 percent of the total phosphorus in swine manure is inorganic (Peperzak and others, 1959). The increase in the percentage of total phosphorus in inorganic form after application of swine manure was also found by Sharpley and others (1991). Another factor that could cause a decrease in the percentage of total phosphorus in organic forms on plots 2 and 3 is the increased mineralization of organic phosphorus with the addition of inorganic phosphorus (Dalal, 1977).

Table 8. Concentrations of total phosphorus in soil for three study plots for different depth intervals

[The value for the 0-24-inch depth interval was calculated by multiplying 0-6-inch data by 0.25, 6-12-inch data by 0.25, and 12-24-inch data by 0.5. These values were summed to generate the value for the 0-24-inch depth interval.]

Depth interval	Total phosphorus, in parts per million					
	Time periods					
	Apr.1- May 17, 1993	May 18 - Aug. 31, 1993	Sept. 1 - Dec. 31, 1993	Mar. 10 - May 14, 1994	May 15 - Aug. 31, 1994	Mean
			Plot 1			
0-6 inch	1,030	1,140	1,060	1,130	1,020	1,080
6-12 inch	1,140	1,040	1,080	1,090	1,030	1,080
12-24 inch	1,090	1,110	1,150	1,140	1,080	1,110
0-24 inch	1,090	1,100	1,110	1,120	1,050	1,090
			Plot 2			
0-6 inch	1,320	1,270	1,230	1,220	1,250	1,260
6-12 inch	1,010	1,130	1,050	1,080	970	1,050
12-24 inch	1,130	1,260	1,070	1,070	1,200	1,150
0-24 inch	1,150	1,230	1,100	1,110	1,160	1,150
			Plot 3			
0-6 inch	1,270	1,320	1,290	1,420	1,400	1,340
6-12 inch	910	1,060	860	950	1,030	960
12-24 inch	870	960	830	910	880	890
0-24 inch	980	1,080	950	1,050	1,050	1,020

Table 9. Concentrations of plant-available phosphorus in soil for three study plots for different depth intervals

[The value for the 0-24-inch depth interval was calculated by multiplying 0-6-inch data by 0.25, 6-12-inch data by 0.25, and 12-24-inch data by 0.5. These values were summed to generate the value for the 0-24-inch depth interval.]

Depth interval	Plant-available phosphorus, in parts per million					
	Time periods					
	Apr. 1- May17, 1993	May 18 - Aug. 31, 1993	Sept. 1 - Dec. 31, 1993	Mar. 10 - May 14, 1994	May 15 - Aug. 31, 1994	Mean
			Plot 1			
0-6 inch	62	59	56	59	54	58
6-12 inch	42	42	42	48	42	43
12-24 inch	39	42	42	40	44	41
0-24 inch	46	46	46	47	46	46
			Plot 2			
0-6 inch	132	141	141	141	146	140
6-12 inch	52	66	44	52	64	56
12-24 inch	36	52	39	42	35	41
0-24 inch	64	78	66	69	70	69
			Plot 3			
0-6 inch	136	150	155	160	226	165
6-12 inch	36	54	40	42	62	47
12-24 inch	22	32	22	29	33	28
0-24 inch	54	67	60	65	88	67

Table 10. Weighted means for the percentages of total phosphorus in plant-available, inorganic, and organic forms in soil over the study period and means for the percentages of total phosphorus in plant-available, inorganic, and organic forms in soil for three depth intervals for each study plot (The weighted mean was calculated by multiplying 0-6-inch data by 0.25, 6-12-inch data by 0.25, and 12-24-inch data by 0.5. These values were summed to generate the weighted mean.)

[PAP, percentage of total phosphorus in plant-available form; IP, percentage of total phosphorus in inorganic form; OP, percentage of total phosphorus in organic form; in., inches]

Date	Plot 1			Plot 2			Plot 3		
	PAP	IP	OP	PAP	IP	OP	PAP	IP	OP
April 1993	4.2	86	14	5.4	75	25	4.9	68	32
July 1993	4.2	84	16	6.3	81	19	5.8	70	30
October 1993	4.1	86	14	5.7	74	26	5.5	70	30
April 1994	4.2	90	10	6.1	83	17	5.5	76	24
July 1994	4.4	84	16	6.0	86	14	7.4	87	13
Depth									
0-6 in.	5.4	85	15	11	76	24	12	78	22
6-12 in.	4.0	84	16	5.3	74	26	4.9	72	28
12-24 in.	3.7	88	12	3.6	85	15	3.1	73	27

The concentration of PAP for this study was determined by the Mehlich-III procedure (Mehlich, 1984). This is a weak-acid digestion procedure that solubilizes phosphorus associated with calcium, iron, and aluminum in the soil. If manure phosphorus is applied to a site over a number of years, the concentration of PAP in upper soil horizons generally increases. When manure phosphorus is applied to a site where minimum to no till is practiced, stratification of PAP concentrations usually occurs with concentrations decreasing from surface to deeper soil horizons (Sharpley and others, 1994).

Chemical analysis of different particle-size classes indicated that clay particles, on a per weight basis, retained three to five times more phosphorus than either sands or silts (table 11). The overall concentrations of phosphorus associated with sand, silt, and clay particles were 700, 1,000, and 3,400 ppm, respectively, for the 0-24-in. depth interval. Overall, the largest mass of phosphorus in the soil was attached to silt particles because each plot was comprised of 3 to 4.5 times more silt than clay (fig. 3). Overall, about 70 percent of the total mass of phosphorus in the soil to a depth of 24 in. was associated with silt and clay particles. The major difference between plots was the greater percentage of phosphorus mass associated with clay particles on plot 3; this difference was primarily because of the higher clay content on plot 3 relative to the other two plots.

X-ray diffraction analysis of soil samples collected from each of the plots did not verify the existence of any phosphate minerals. The qualitative nature of the procedure and the overlap of wavelengths from minerals most prevalent in the samples made it difficult to identify phosphate minerals, which are typically not very abundant relative to other minerals in the soil matrix (Larsen, 1967). Besides quartz, the only minerals qualitatively identified were clay minerals, including illite, montmorillonite, nontronite (a derivative of montmorillonite), and muscovite.

Correlation and regression analysis for concentrations of total phosphorus and PAP indicated that variations in concentrations of soil phosphorus were explained to a significant degree by only a few chemical variables (table 12). Concentrations of total phosphorus and PAP were significantly correlated to the concentration of total organic carbon (TOC) and cation exchange capacity (CEC). The significant relation of phosphorus concentrations to TOC may be caused by manure application because manure tends to increase soil organic carbon (Khaleel and others, 1981). CEC is a measure of the net negative charge in the soil. Soils with high clay content and organic matter typically have relatively high CEC (Brady, 1974). Thus, the significant relation of soil phosphorus to CEC could be related to some extent by the higher percentage of clay and higher concentration of soil phosphorus on plot 3. An increase in organic matter potentially caused by manure application could also affect the CEC-(soil phosphorus) relation.

Table 11. Concentrations of total phosphorus for selected particle sizes in soil and the percentage of total phosphorus in soil for each particle-size class for three depth intervals for each study plot

[mg/kg, milligrams per kilogram; percentage of total mass, percentage of total-phosphorus mass for that particle-size class which represents the total-phosphorus mass for an unseparated soil sample]

	Depth interval					
	0-6 inches		6-12 inches		12-24 inches	
Particle size	Total-phosphorus concentration (mg/kg)	Percentage of total mass[1]	Total-phosphorus concentration (mg/kg)	Percentage of total mass [1]	Total-phosphorus concentration (mg/kg)	Percentage of total mass [1]
Plot 1						
Sand	790	31	630	26	770	37
Silt	1,150	49	960	36	1,160	36
Clay	[2] 3,245	25	[2] 3,830	36	[2] 3,600	25
Plot 2						
Sand	790	27	610	26	820	38
Silt	1,130	37	950	33	1,150	34
Clay	[2] 3,520	26	[2] 3,550	37	[2] 3,260	23
Plot 3						
Sand	880	24	560	20	530	22
Silt	1,100	39	750	37	760	39
Clay	[2] 3,340	37	[2] 2,910	51	[2] 3,440	52

[1] Because of rounding, analytical and sampling errors, and estimates of concentrations of total phosphorus for clay, the percentage of total mass did not sum to 100. The percentage of total mass was estimated using the mean concentration of total phosphorus for samples collected during 1993.

[2] Concentrations of total phosphorus for clay were estimated using the difference between total phosphorus for silt and for silts and clays (fines) combined. Particle-size distribution data were used to determine percentages of silt and clay in a fines sample.

Table 12. Relation of soil concentrations of total phosphorus and plant-available phosphorus to other chemical parameters measured in soil at three study plots

[Unless otherwise noted, units are in parts per million; meq/100g, milliequivalents per 100 grams; mmhos/cm, millimhos per centimeter; n, number of observations; Adj. R^2, coefficient of determination]

REGRESSIONS

Total phosphorus = -276 + 0.0391 (total organic carbon) + 1.37 (total sodium) + 0.0568 (total magnesium)

n = 27 Adj. $R^2 = 0.61$

Plant-available phosphorus = -6.41 + 0.00425 (total organic carbon) + 0.901 (exchangeable potassium)

n = 45 Adj. $R^2 = 0.79$

CORRELATIONS

Total phosphorus			Plant-available phosphorus		
Parameter	n	Spearman coefficient	Parameter	n	Spearman coefficient
Total calcium	27	0.49	Total organic carbon	45	0.79
Total organic carbon	45	.40	Exchangeable magnesium	45	.74
Cation exchange capacity (meq/100g)	45	.60	Exchangeable potassium	45	.78
			Electrical conductivity (mmhos/cm)	45	.36
			Cation exchange capacity (meq/100g)	45	.43

All parameters and models are significant at alpha = 0.05.

Maximum Phosphate Retention Capacity

Results from the soil-flask experiments indicated that soil collected from the 0-6-in. depth interval on each study plot was not saturated with respect to phosphorus (fig. 9). The maximum retention capacity (b) of the soils ranged from 694 to 1,160 mg of phosphorus per kg of soil. The maximum retention capacity would be near zero if soil was saturated with respect to phosphorus; therefore, the soils from the study plots have the capacity to retain more phosphorus. The methods used to conduct the soil-flask experiments required that the test solution contact the soil for 48 hours and that phosphate be the only major anion competing for adsorption sites. Because these two conditions are unlikely to take place in nature, the ability of the plot soils to retain phosphorus under field conditions was probably less than the experimental results would suggest. By definition, results generated from the Langmuir isotherm equation yield an adsorption maximum (Olsen and Watanabe, 1957). A more appropriate term for this study is retention maximum because phosphorus was taken out of solution during the experiment, with the phosphorus either adsorbing to a charged surface or precipitating out of solution because of the high phosphate concentrations applied in the flask experiments.

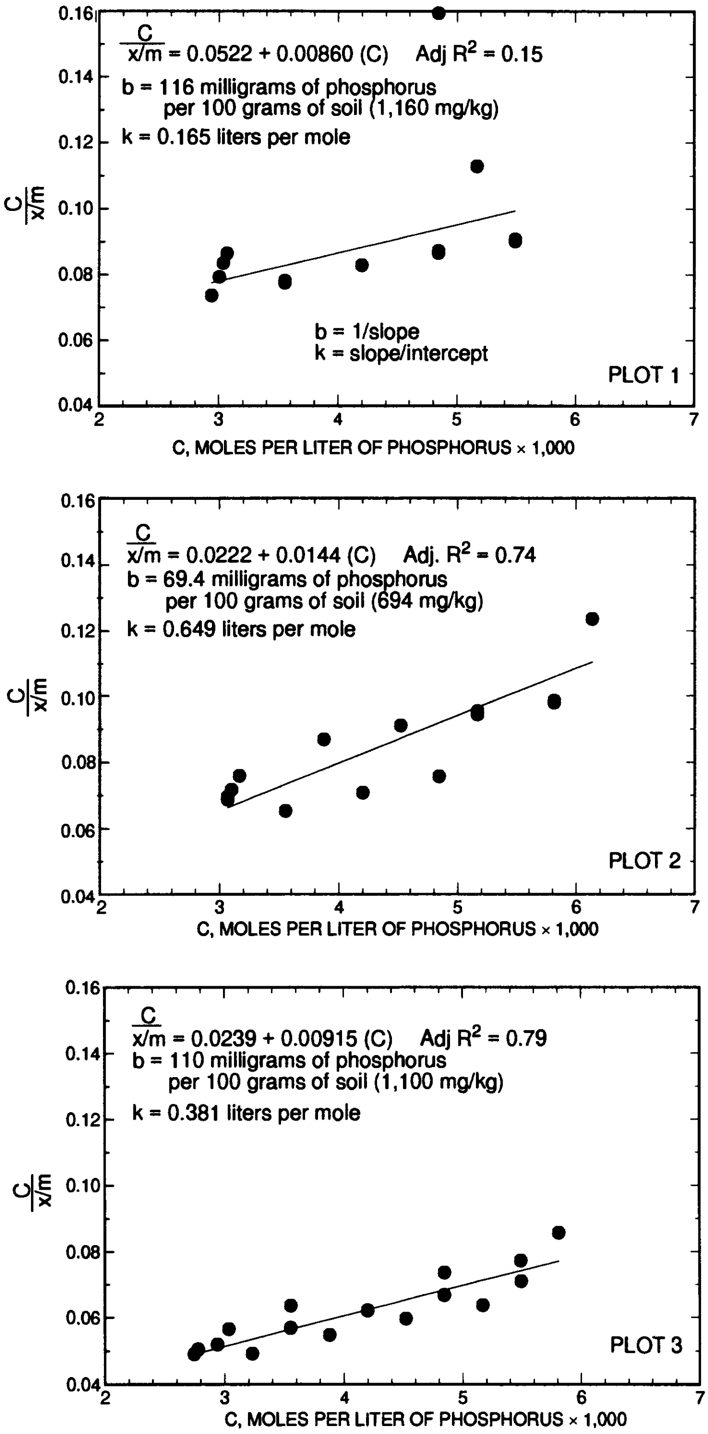
Results from the soil-flask experiments identified differences between plots in the maximum amount of phosphorus that could be retained in the soil. Retention maxima (b) calculated for plots 1 and 3 were similar, whereas b for plot 2 was 400-500 mg of phosphorus per kg lower than plots 1 and 3. Also, the phosphate bonding energies of the soils were different. Bonding energy (k) was inversely related to maximum retention capacity (b), so that the plots with higher retention maxima had lower bonding energies.

Differences in b between plots cannot be attributed to differences in concentrations of soil phosphorus because data were corrected for surface-phosphate concentrations (see Olsen and Watanabe (1957) for methodology). Other soil factors, such as clay content and soil chemistry, specifically exchangeable aluminum, organic carbon, and free iron oxides, can cause differences in b (Syers and others, 1973), but these data for plots 1 and 2 were similar. One factor that can cause differences in b and k is the degree of weathering (Syers and others, 1973; Olsen and Watanabe, 1957). This factor was not specifically measured for this study, but the facts that the gravel content in the soils of plot 2 was higher than for the soil of plots 1 and 3 (fig. 3) and plot 2 was the only plot with rock outcrops suggest differences in rock weathering between plots.

Chemical Factors Affecting Phosphate Equilibrium Reactions

Median concentrations of dissolved constituents in surface runoff and subsurface flow measured over the entire study period from the three study plots were input to the WATEQ4F geochemical modeling program (Ball and Nordstrom, 1991) to determine the mineralogical controls on phosphate solubility. Solid-phase phosphorus in the soil is either adsorbed to surfaces, bound in mineral form, or associated with organic matter. Phosphorus bound in mineral form is considered non-labile; phosphorus adsorbed to surfaces is considered labile; organic phosphorus in soil is typically in labile and non-labile forms (Larsen, 1967). Phosphorus transfer from the non-labile to labile phase in the soil is slow compared to the transfer from the labile phase to a soluble form (Larsen, 1967). As with any chemical reaction, the movement of phosphorus to different phases is driven by equilibrium processes. For example, if soluble inorganic phosphorus is added to an equilibrated system, some of that phosphorus is taken out of solution by adsorbing to surfaces and/or precipitating in a mineral form. Even though adsorbed phosphorus significantly affects the concentration of soluble phosphorus in the soil, the upper and lower limits of phosphorus in soil solution are primarily determined by phosphate minerals (Larsen, 1967). Therefore, geochemical modeling was used only to characterize the mineralogical controls on phosphate solubility.

Mineral saturation indices were computed by use of the WATEQ4F program and concentrations of dissolved constituents in surface runoff and subsurface flow. The saturation index (SI) provides a basis for evaluating mineralogical controls on the concentration of ions in solution. If SI for a mineral is negative, the system is undersaturated with respect to that mineral, and the mineral would tend to dissolve. If SI for a mineral is positive, then that mineral will not dissolve and possibly could precipitate from solution. If SI is near zero, the system is at equilibrium with respect to that mineral (Drever, 1982).



EXPLANATION

C = EQUILIBRIUM PHOSPHORUS CONCENTRATION IN MOLES PER LITER (1 mole of phosphorus equals 30.97 milligrams)

x/m = MILLIGRAMS OF PHOSPHORUS ADSORBED PER 100 GRAMS OF SOIL

b = MAXIMUM RETENTION CAPACITY

k = CONSTANT RELATED TO BONDING ENERGY OF PHOSPHATE TO THE SOIL

Figure 9. Langmuir-isotherm parameters calculated from soil-flask experiments conducted on soil collected from the 0-6-inch depth interval for each study plot. [mg/kg, milligrams per kilogram; Adj. R^2, coefficient of determination]

The system is defined to include all three study plots from the surface to a depth of 18 in. below land surface. Chemical and x-ray diffraction analyses of soil from the study plots indicated the presence of Fe oxides (Appendix 2), quartz, and some specific clay minerals. However, because x-ray diffraction analysis is not sensitive to amorphous forms or crystalline minerals in trace amounts, the lack of detection of specific solids does not indicate their absence. On the basis of water chemistry, the system was undersaturated with respect to Ca minerals (table 13). This indicated that Ca minerals, if present, would dissolve. Because dissolution of calcium phosphates (if present), such as hydroxyapatite, would increase the concentration of phosphorus in solution, calcium phosphates could be a source for phosphorus in solution, but Ca minerals would not limit phosphate solubility. The system was supersaturated with respect to clay minerals such as muscovite and montmorillonite; hence, these minerals would not tend to dissolve. The system was near equilibrium with amorphous forms of quartz (chalcedony), gibbsite ($Al(OH)_3(a)$), and Fe oxides (ferrihydrite). Al and Fe oxides bind phosphate in soil (Sample and others, 1980). Although not detected in soil samples, strengite was the only phosphate mineral near equilibrium according to calculated SI values. Data from the study plots showed that median concentrations of dissolved phosphorus in water samples and the SI for strengite increased from untreated to treated plots. As the SI for strengite increases from a negative to positive value, the probability of strengite precipitating and phosphorus being removed from solution increases. Thus, if soluble phosphorus is applied to this system, there is a potential for it to be removed from solution by either precipitating in the form of strengite or binding to Al and Fe oxides. Conversely, without any further application of phosphorus to the system, phosphorus may be mobilized from Fe and Al oxides or from dissolution of strengite (if strengite exists). Thus, it appears that the primary mineralogical controls on the concentration of phosphorus in solution for this system were Al and Fe oxides and possibly strengite.

The organic pool of phosphorus, which was evident from chemical analysis of the soil, could affect the concentration of phosphorus in solution. The mineralization of organic phosphorus would increase the concentration of dissolved phosphorus in this system. With all other factors held constant, concentrations of dissolved phosphorus elevated by organic phosphorus mineralization would increase the SI for all phosphate minerals. However, if strengite or another phosphate mineral is an effective solubility control in an equilibrated system where organic phosphorus is being mineralized, then inorganic phosphate concentrations would not increase above concentrations necessary to achieve a saturation index of zero.

Table 13. Saturation indices of selected minerals for surface and subsurface (18 inches below land surface) systems for each study plot
[Unless otherwise noted, saturation indices were calculated by the use of WATEQ4F (Ball and Nordstrom, 1991).
Dissolved concentrations input to the program were median values collected for each plot over the study period; (a), amorphous]

Mineral	Chemical composition	Saturation indices					
		Plot 1		Plot 2		Plot 3	
		Surface	Subsurface	Surface	Subsurface	Surface	Subsurface
Calcite	$CaCO_3$	-2.66	-2.96	-2.53	-1.94	-2.70	-1.01
Dolomite	$CaMg(CO_3)_2$	-5.57	-6.10	-5.16	-4.40	-5.48	-2.22
Hydroxyapatite	$Ca_5(PO_4)_3OH$	-8.33	-9.16	-6.08	-4.21	-7.03	-.779
Octacalcium phosphate [1]	$Ca_4H(PO_4)_3 \bullet 3H_2O$	-10.6	-11.1	-8.70	-7.17	-9.28	-4.23
Dicalcium phosphate dihydrate [1]	$CaHPO_4 \bullet 2H_2O$	-3.28	-3.36	-2.74	-2.41	-2.83	-1.59
Ferrihydrite	$Fe(OH)_3$	.050	-.336	.370	.247	-.111	-.156
Goethite	$FeOOH$	5.94	5.56	6.26	6.14	5.78	5.74
Siderite	$FeCO_3$	-1.84	-2.33	-1.66	-1.73	-2.01	-1.74
Strengite	$FePO_4 \bullet 2H_2O$	-.278	-.631	.419	-.102	.068	-.198
Vivianite	$Fe_3(PO_4)_2 \bullet 8H_2O$	-4.00	-4.89	-2.49	-3.21	-3.49	-3.89
$Al(OH)_3$ (a)		.203	-.392	.303	-.071	.264	-.384
Gibbsite	$Al(OH)_3$	2.98	2.41	3.06	2.73	3.03	2.42
Variscite [1]	$Al(OH)_2PO_4$	1.57	.414	1.49	.976	2.13	1.31
Chalcedony	SiO_2	-.120	-.082	-.147	-.089	-.126	-.085
SiO_2 (a)		-.991	-.964	-1.01	-.969	-.995	-.966
Quartz	SiO_2	.338	.386	.303	.377	.330	.382
Albite	$NaAlSi_3O_8$	-2.94	-3.46	-2.70	-2.76	-2.54	-1.74
Chlorite	$Mg_5Al_2Si_3O_{10}(OH)_8$	-14.8	-16.8	-12.4	-12.7	-13.9	-9.27
Illite	$K_{0.6}Mg_{0.25}Al_{2.3}Si_{3.5}O_{10}(OH)_2$	4.30	3.06	4.76	4.46	4.72	3.95
Kaolinite	$Al_2Si_2O_5(OH)_4$	7.42	6.37	7.51	6.99	7.52	6.37
Muscovite	$KAl_3Si_3O_{10}(OH)_2$	11.8	10.1	12.4	11.9	12.4	11.0
Montmorillonite	$(H,NA,K)_{0.42}Mg_{0.45}Fe^{3+}_{0.34}Al_{1.47}Si_{3.82}O_{10}(OH)_2$	1.93	.729	2.74	2.23	2.41	2.37

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[1] The equilibrium constant to generate the saturation index was taken from Lindsay and Moreno (1960). The activities for individual constituents for these three minerals were taken from WATEQ4F output.

PHOSPHORUS INPUTS

Inputs of phosphorus to the study plots from manure applications and precipitation were quantified during the period of field-data collection. Deposition of phosphorus from wind was assumed to be negligible.

Precipitation

The mean concentration of total phosphorus in precipitation at the study site was 0.07 mg/L (Appendix 3). This concentration was similar to data presented by Langland (1992) for another agricultural site in the Lower Susquehanna River Basin. The phosphorus input to the study plots from precipitation for the study period (April 1, 1993, through December 31, 1993, and March 10, 1994, through August 31, 1994) was 0.42 kg/acre. Because all precipitation events were not sampled for water-quality concentrations, the input estimate of phosphorus was based on the mean concentration (0.07 mg/L) multiplied by the total precipitation (fig. 8) over the study period. Compared to the manure input of phosphorus, phosphorus input from precipitation was negligible on plots 2 and 3.

Manure

Manure was applied to plots 2 and 3 in May 1993 and 1994 (table 14). The volumes applied to each plot were similar for both years, but the concentration of phosphorus applied during 1994 was greater (Appendix 4). The phosphorus inputs to plots 2 and 3 averaged 56 and 126 kg/acre, respectively. The phosphorus inputs to the treated plots exceeded the amounts recommended by the Pennsylvania State University (1991) for silage corn; however, the volume of manure applied to the study plots may not be uncommon given the high density of farm animals in some areas and the lack of viable transport of farm-animal manure to areas that are less populated with farm animals.

Table 14. Total volume of manure applied and phosphorus and nitrogen loads from manure applied per acre to study plots during 1993 and 1994

[kg/acre, kilograms per acre]

Date applied	Plot	Manure volume applied (liters)	Phosphorus (kg/acre)	Nitrogen (kg/acre)
May 17, 1993	2	11,400	44	118
May 17, 1993	3	31,000	107	318
May 14, 1994	2	11,400	68	167
May 14, 1994	3	29,500	144	358

PHOSPHORUS OUTPUTS

Outputs of phosphorus from the study plots via surface runoff, subsurface flow, and plant harvest were quantified during the study period. Other potential outputs of phosphorus, such as wind erosion of soil particles, were assumed to be negligible.

Surface Runoff

The concentration of total phosphorus in surface runoff is equal to the concentration of dissolved and suspended forms of phosphorus. Total and dissolved concentrations of phosphorus were measured in surface runoff.

Total

The concentrations of total phosphorus in surface runoff for any one storm-runoff event from the three study plots varied from 0.23 mg/L for plot 1 to 150 mg/L for plot 3 (Appendix 3); the median concentration from the three sites was 1.5 mg/L. The cumulative yield of total phosphorus over the study period from the study plots showed that plot 3 had the highest yield (1.69 kg/acre), followed by plot 2 (1.24 kg/acre) and plot 1 (1.12 kg/acre) (fig. 10). The majority of the yield of total phosphorus for the study plots occurred during spring-summer 1994 because of the high intensity and frequency of storms during this period relative to earlier periods of the study.

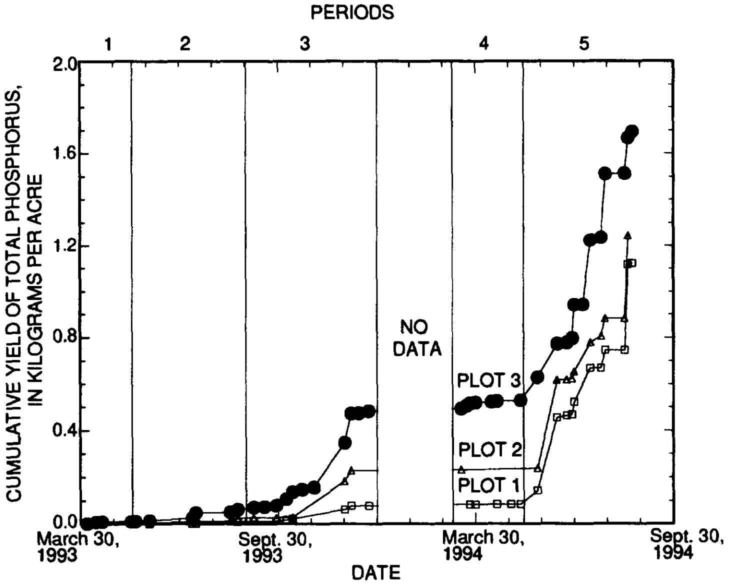


Figure 10. Cumulative yield of total phosphorus in surface runoff for three study plots. (See table 15 for PERIOD definitions.)

Data were divided into five time intervals (PERIOD 1 through PERIOD 5) in order to determine if there were significant differences in outputs of total phosphorus from surface runoff (table 15). The intervals chosen were primarily based on time of manure application and growing season. The only significant difference among plots in the concentrations or yields of total phosphorus in surface runoff was for PERIOD 3 for the yield of total phosphorus between plots 1 and 3 (figs. 11 and 12). This difference was primarily caused by differences in the concentration of total phosphorus for runoff events that occurred in late November and early December 1993. The concentrations of total phosphorus for plots 1, 2, and 3 for the November 29, 1993, runoff event were 0.52, 2.0, and 1.7 mg/L, respectively. The concentrations of total phosphorus for plots 1, 2, and 3 for the December 6, 1993, runoff event were 0.33, 1.1, and 1.1 mg/L, respectively. The total runoff volumes for plots 1, 2, and 3 for both runoff events were 52,780, 27,340, and 63,320 L, respectively.

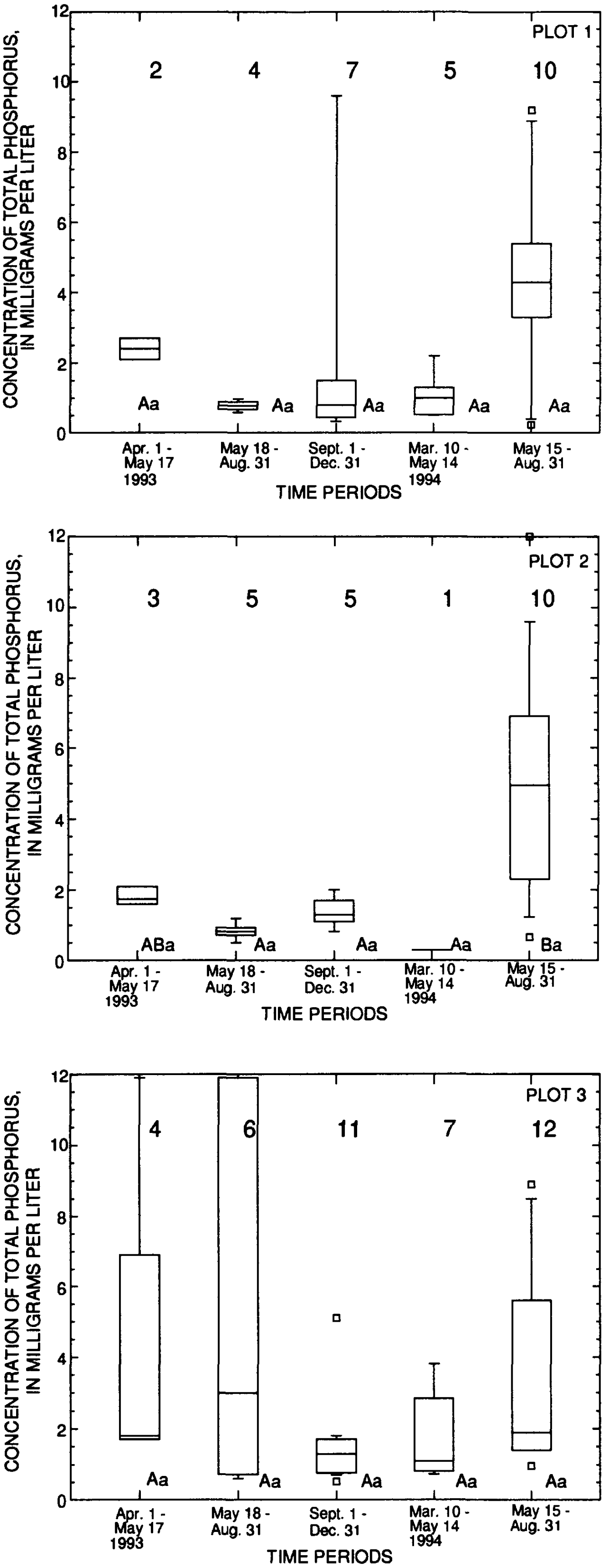
Table 15. Time intervals used to separate water-quality data for statistical analyses

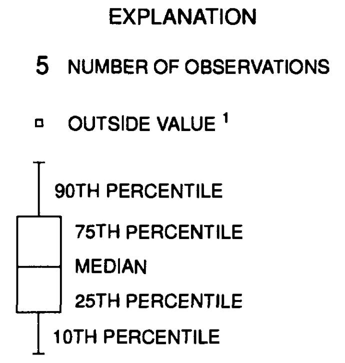
Time interval	Description	Designation
April 1, 1993 - May 17, 1993	Period before first manure application	PERIOD 1
May 18, 1993 - Aug. 31, 1993	Period from first manure application to one month before corn harvest	PERIOD 2
Sept. 1, 1993 - Dec. 31, 1993	One month before corn harvest to end of 1993	PERIOD 3
Jan. 1, 1994 - Mar. 9, 1994	No data collected because of snowpack	
Mar. 10, 1994 - May 14, 1994	Period after significant snowpack melting to date of second manure application	PERIOD 4
May 15, 1994 - Aug. 31, 1994	Period from second manure application to end of data collection	PERIOD 5

Significant differences in total phosphorus for surface runoff within plots for different time intervals were evident for concentrations of total phosphorus for plot 2 and yields of total phosphorus for plots 1 and 3. These differences were evident for PERIOD 5 (the time interval from immediately after the second manure application through August 31, 1994) relative to earlier time periods. The difference in the concentration of total phosphorus for plot 2 was caused by increased concentrations of suspended phosphorus for PERIOD 5 and differences for plots 1 and 3 were partially caused by increased yields of dissolved phosphorus for PERIOD 5. These differences are discussed in the following sections.

Dissolved

The concentration of dissolved phosphorus in surface runoff was affected by manure applications to the study plots. From fall 1993 through the end of the study, there was a marked increase in concentrations of dissolved phosphorus from the treated plots relative to plot 1 (fig. 13). Mean concentrations of dissolved phosphorus in surface runoff after the first manure application for plots 1, 2, and 3 were 0.30, 0.60, and 1.28 mg/L, respectively. The cumulative yields of dissolved phosphorus during the study period (fig. 14) from plots 2 and 3 were about 135 and 500 percent greater, respectively, than plot 1. The cumulative yield of dissolved phosphorus for plots 1, 2, and 3 were 0.074, 0.174, and 0.443 kg/acre, respectively. Runoff yields during the study period from plots 1, 2, and 3 were 347,200, 342,800, and 741,200 L/acre, respectively.





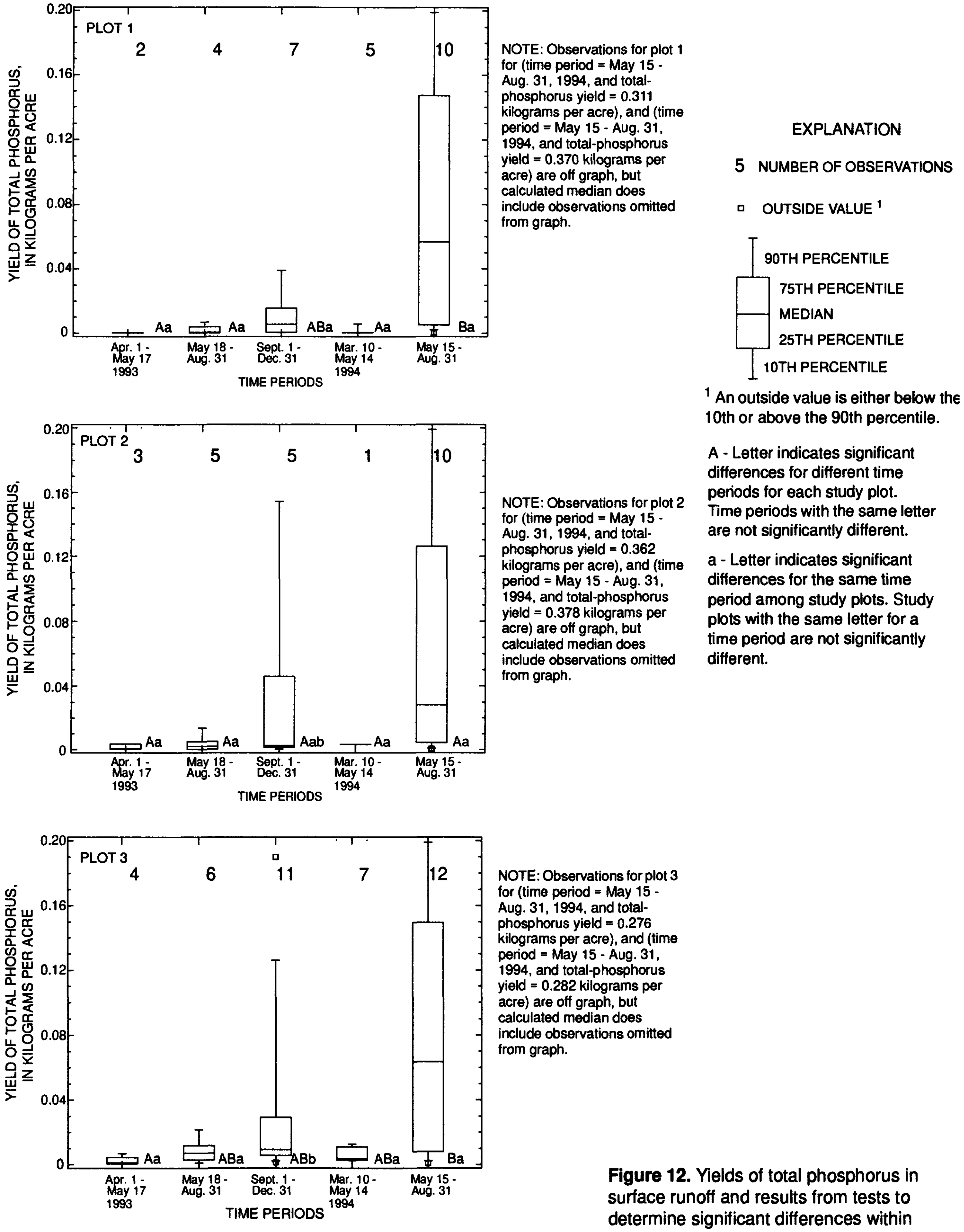
[1] An outside value is either below the 10th or above the 90th percentile.

A - Letter indicates significant differences for different time periods for each study plot. Time periods with the same letter are not significantly different.

a - Letter indicates significant differences for the same time period among study plots. Study plots with the same letter for a time period are not significantly different.

NOTE: Observations for plot 3 (time period = Apr. 1 - May 17, 1993, and total phosphorus = 150 milligrams per liter), (time period = May 18 - Aug. 31, 1993, and total phosphorus = 38 milligrams per liter), and (time period = May 18 - Aug. 31, 1993, and total phosphorus = 140 milligrams per liter) are off graph, but calculated median includes observations omitted from graph.

Figure 11. Concentrations of total phosphorus in surface runoff and results from tests to determine significant differences within and among three study plots.



NOTE: Observations for plot 1 for (time period = May 15 - Aug. 31, 1994, and total-phosphorus yield = 0.311 kilograms per acre), and (time period = May 15 - Aug. 31, 1994, and total-phosphorus yield = 0.370 kilograms per acre) are off graph, but calculated median does include observations omitted from graph.

NOTE: Observations for plot 2 for (time period = May 15 - Aug. 31, 1994, and total-phosphorus yield = 0.362 kilograms per acre), and (time period = May 15 - Aug. 31, 1994, and total-phosphorus yield = 0.378 kilograms per acre) are off graph, but calculated median does include observations omitted from graph.

NOTE: Observations for plot 3 for (time period = May 15 - Aug. 31, 1994, and total-phosphorus yield = 0.276 kilograms per acre), and (time period = May 15 - Aug. 31, 1994, and total-phosphorus yield = 0.282 kilograms per acre) are off graph, but calculated median does include observations omitted from graph.

EXPLANATION

5 NUMBER OF OBSERVATIONS

□ OUTSIDE VALUE[1]

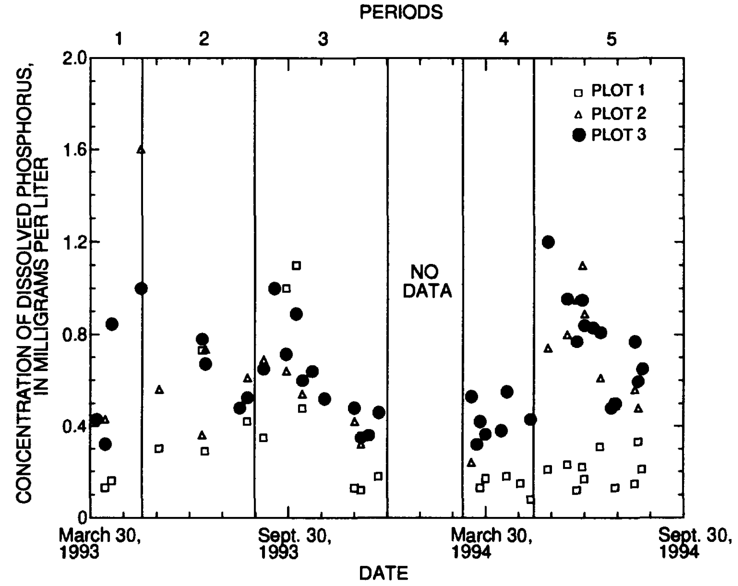
90TH PERCENTILE
75TH PERCENTILE
MEDIAN
25TH PERCENTILE
10TH PERCENTILE

[1] An outside value is either below the 10th or above the 90th percentile.

A - Letter indicates significant differences for different time periods for each study plot. Time periods with the same letter are not significantly different.

a - Letter indicates significant differences for the same time period among study plots. Study plots with the same letter for a time period are not significantly different.

Figure 12. Yields of total phosphorus in surface runoff and results from tests to determine significant differences within and among three study plots.



NOTE: Observations for plot 3 for (date = May 19, 1993, and dissolved phosphorus = 20 milligrams per liter) and for (date = June 1, 1993, and dissolved phosphorus = 4.7 milligrams per liter) are not plotted.

Figure 13. Concentrations of dissolved phosphorus in surface runoff for three study plots.

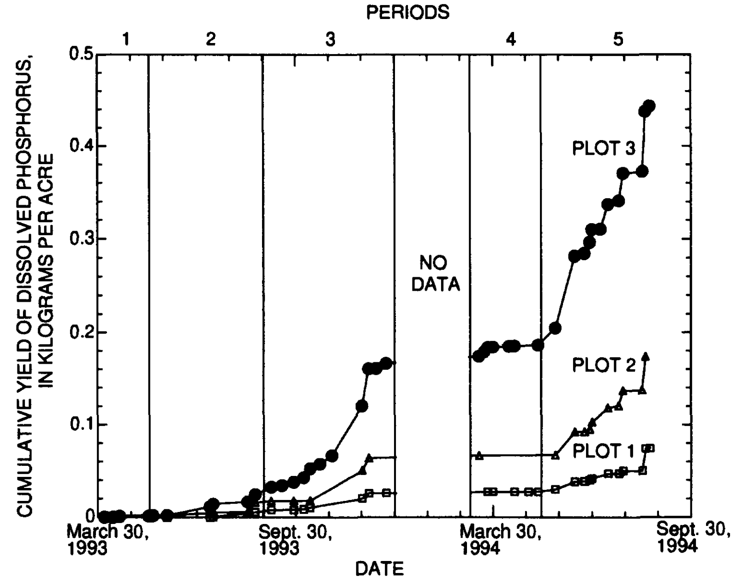


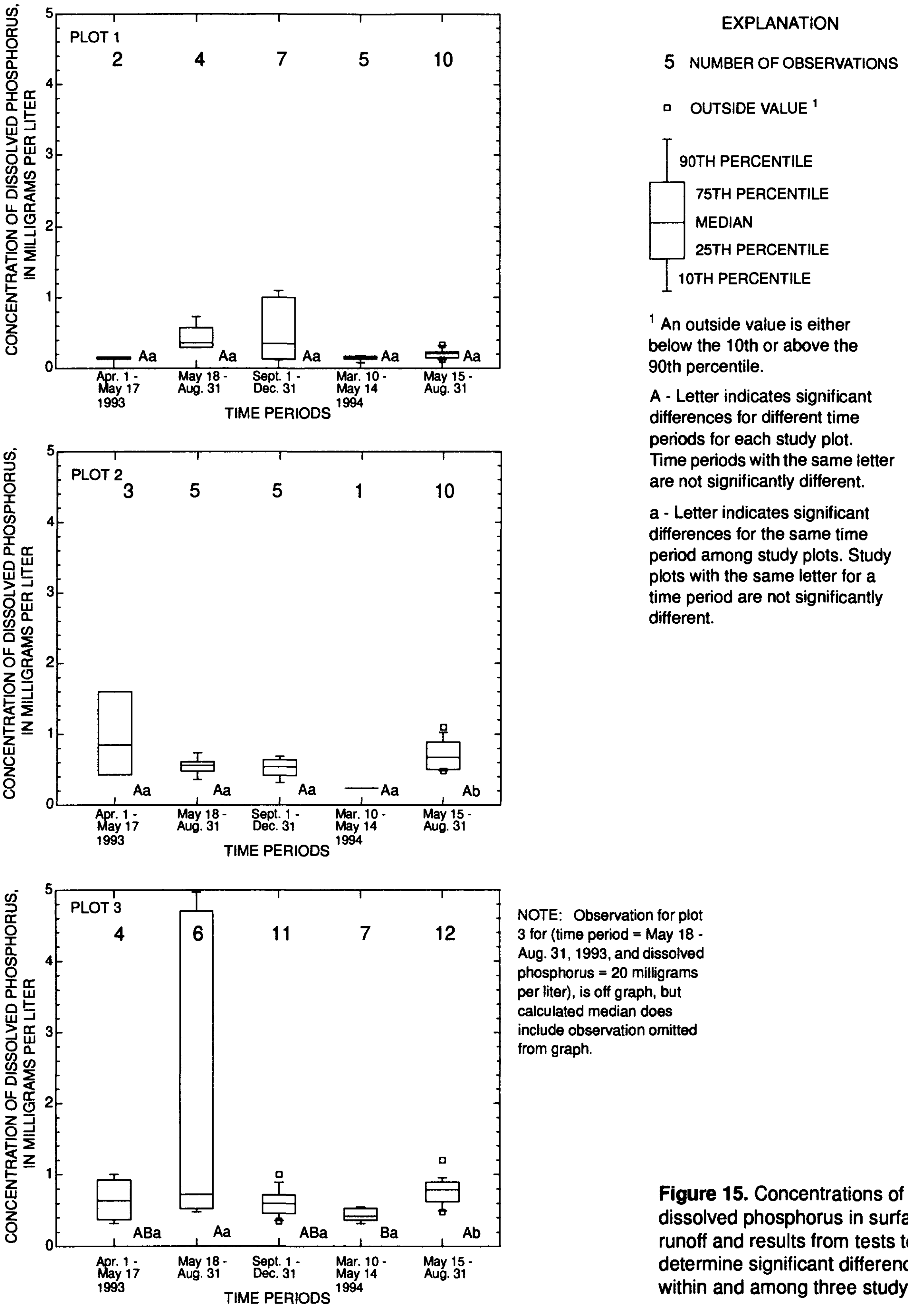
Figure 14. Cumulative yield of dissolved phosphorus in surface runoff for three study plots.

Tests to determine differences within and among plots showed that the second manure application had a significant effect on the concentration of dissolved phosphorus in surface runoff. For the time interval after the second manure application (PERIOD 5), the mean concentration of dissolved phosphorus was significantly higher in runoff from plots 2 and 3 (0.71 and 0.78 mg/L, respectively) than in runoff from plot 1 (0.21 mg/L) (fig. 15). There were no conclusive temporal trends in concentrations of dissolved phosphorus within plots.

Significant differences in yields of dissolved phosphorus in surface runoff were evident among and within plots (fig. 16). Yields of dissolved phosphorus were significantly different between plots 1 and 3 for PERIOD 3 and yields were significantly different among all plots for PERIOD 5. For PERIOD 3, the yields of surface runoff from plots 1 and 3 were 134,800 and 305,200 L/acre, respectively; the mean concentrations of dissolved phosphorus for plots 1 and 3 were 0.48 and 0.61 mg/L, respectively. Thus, the significant difference in yields of dissolved phosphorus between plots 1 and 3 for PERIOD 3 appeared to be primarily caused by differences in runoff volumes. For PERIOD 5, the yields of surface runoff from plots 1, 2, and 3 were 187,400, 182,800, and 349,500 L/acre, respectively. Because concentrations of dissolved phosphorus in surface runoff were significantly higher for plots 2 and 3 relative to plot 1 for PERIOD 5, the significant difference between treated and untreated plots in yields of dissolved phosphorus in surface runoff was primarily caused by differences in concentration. The significant difference in yields of dissolved phosphorus between plots 2 and 3 for PERIOD 5 was probably because of the large difference in the yield of surface runoff. Plots 1 and 3 showed significant within-plot variations in the yield of dissolved phosphorus in surface runoff. PERIODS 3 and 5 had the highest median yields of dissolved phosphorus for each plot; however, these PERIODS were only significantly higher than other PERIODS for plots 1 and 3. The significant differences were primarily caused by higher volumes of surface runoff for PERIODS 3 and 5; however, the concentration of dissolved phosphorus in surface runoff for plot 3 for PERIOD 5 was also significantly higher than some earlier time periods.

Suspended

The concentration and yield of suspended phosphorus in surface runoff were similar for the three study plots over the study period and did not appear to be affected by manure applications (figs. 17 and 18). Approximately 80 percent of the yield of suspended phosphorus from the three study plots occurred after mid-May 1994. Cumulative yields of suspended phosphorus during the study period for plots 1, 2, and 3 were 1.05, 1.07, and 1.25 kg/acre, respectively. The cumulative yield of suspended sediment during the study period for plots 1, 2, and 3 were 1,520, 1,420, and 2,180 kg/acre, respectively (fig. 19). If the yield of suspended phosphorus is divided by the yield of suspended sediment, the ratio is lowest for plot 3, which indicates the sediment from plot 3 was less concentrated with phosphorus relative to plots 1 and 2. This phenomenon may be analogous to the loss of phosphorus from water to sediment identified by Taylor and Kunishi (1971). Taylor and Kunishi found that dissolved phosphate was adsorbed to streambed sediments in an equilibration process. For this study, the equilibration process may have caused movement of readily-available phosphorus from soil to surface-runoff water. As stated earlier, concentrations of dissolved phosphorus were elevated on plot 3 relative to plots 1 and 2.



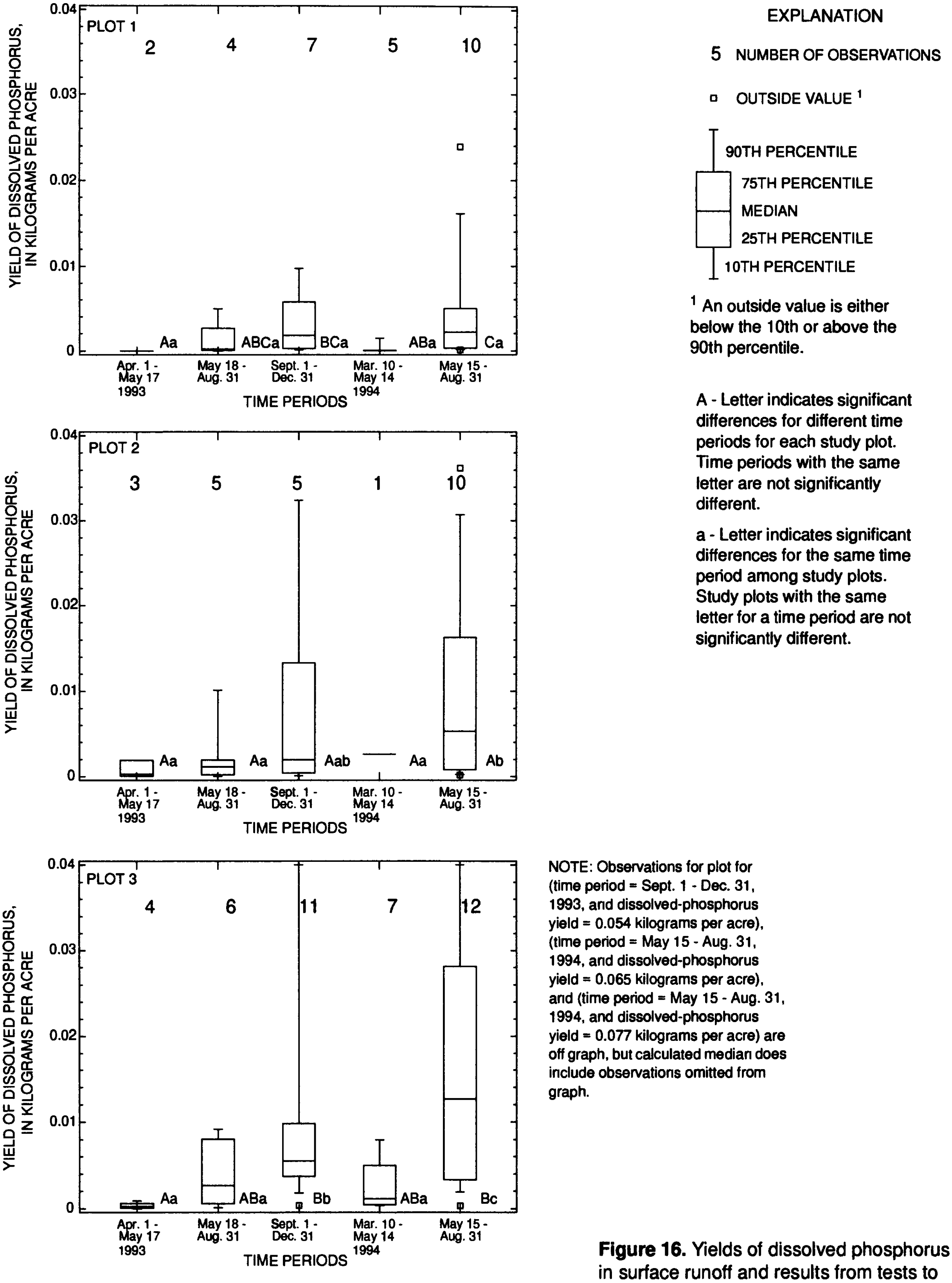
[1] An outside value is either below the 10th or above the 90th percentile.

A - Letter indicates significant differences for different time periods for each study plot. Time periods with the same letter are not significantly different.

a - Letter indicates significant differences for the same time period among study plots. Study plots with the same letter for a time period are not significantly different.

NOTE: Observation for plot 3 for (time period = May 18 - Aug. 31, 1993, and dissolved phosphorus = 20 milligrams per liter), is off graph, but calculated median does include observation omitted from graph.

Figure 15. Concentrations of dissolved phosphorus in surface runoff and results from tests to determine significant differences within and among three study plots.



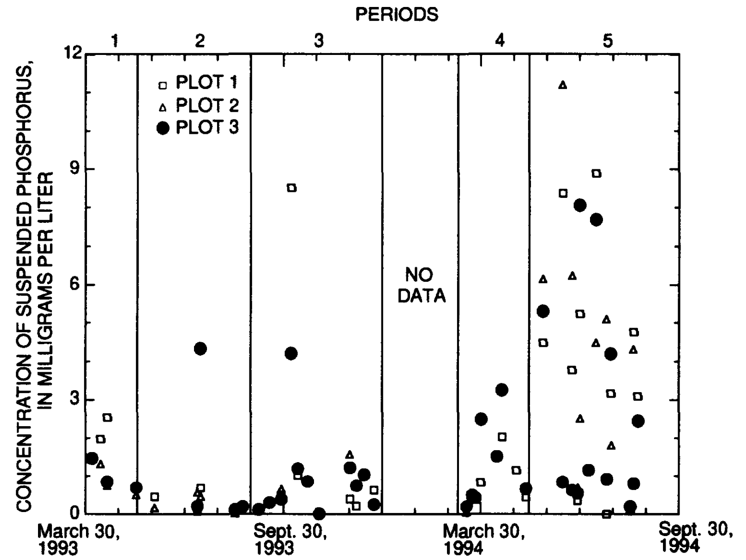
[1] An outside value is either below the 10th or above the 90th percentile.

A - Letter indicates significant differences for different time periods for each study plot. Time periods with the same letter are not significantly different.

a - Letter indicates significant differences for the same time period among study plots. Study plots with the same letter for a time period are not significantly different.

NOTE: Observations for plot for (time period = Sept. 1 - Dec. 31, 1993, and dissolved-phosphorus yield = 0.054 kilograms per acre), (time period = May 15 - Aug. 31, 1994, and dissolved-phosphorus yield = 0.065 kilograms per acre), and (time period = May 15 - Aug. 31, 1994, and dissolved-phosphorus yield = 0.077 kilograms per acre) are off graph, but calculated median does include observations omitted from graph.

Figure 16. Yields of dissolved phosphorus in surface runoff and results from tests to determine significant differences within and among three study plots.



NOTE: Observations for plot 3 for (date = April 11, 1993, and suspended phosphorus = 150 milligrams per liter), (date = May 19, 1993, and suspended phosphorus = 18 milligrams per liter), and (date = June 1, 1993, and suspended phosphorus = 135 milligrams per liter) are not plotted.

Figure 17. Concentrations of suspended phosphorus in surface runoff for three study plots.

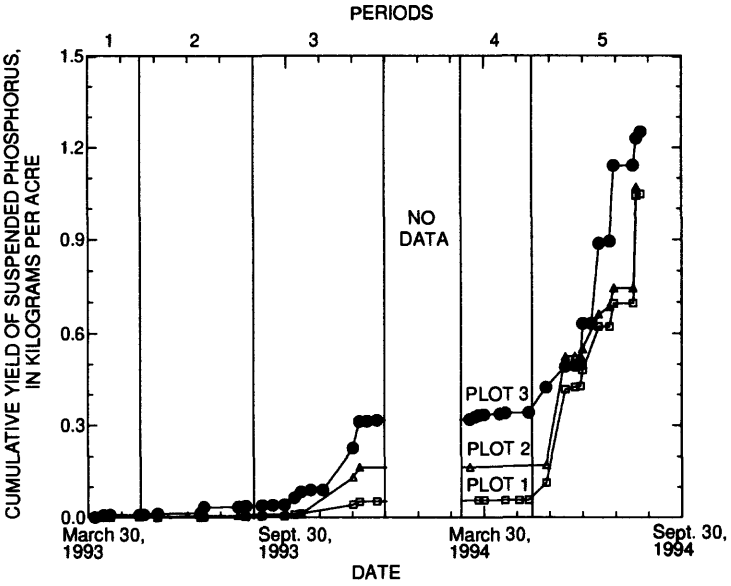


Figure 18. Cumulative yield of suspended phosphorus in surface runoff for three study plots.

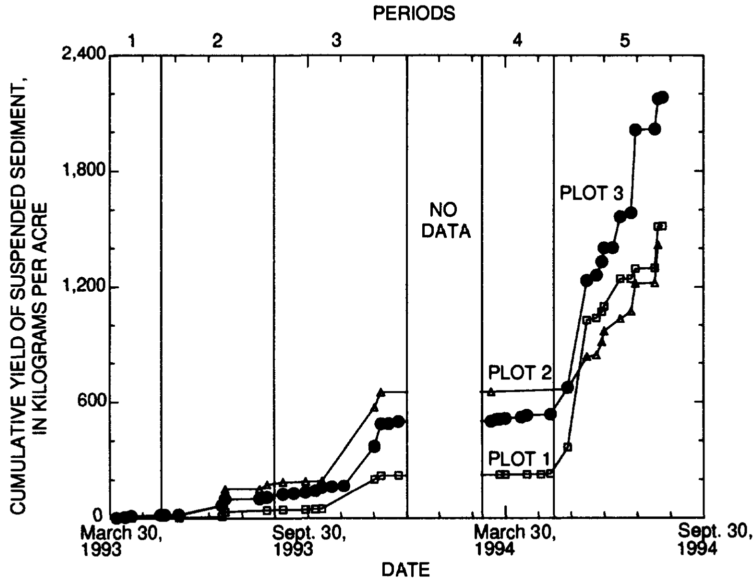
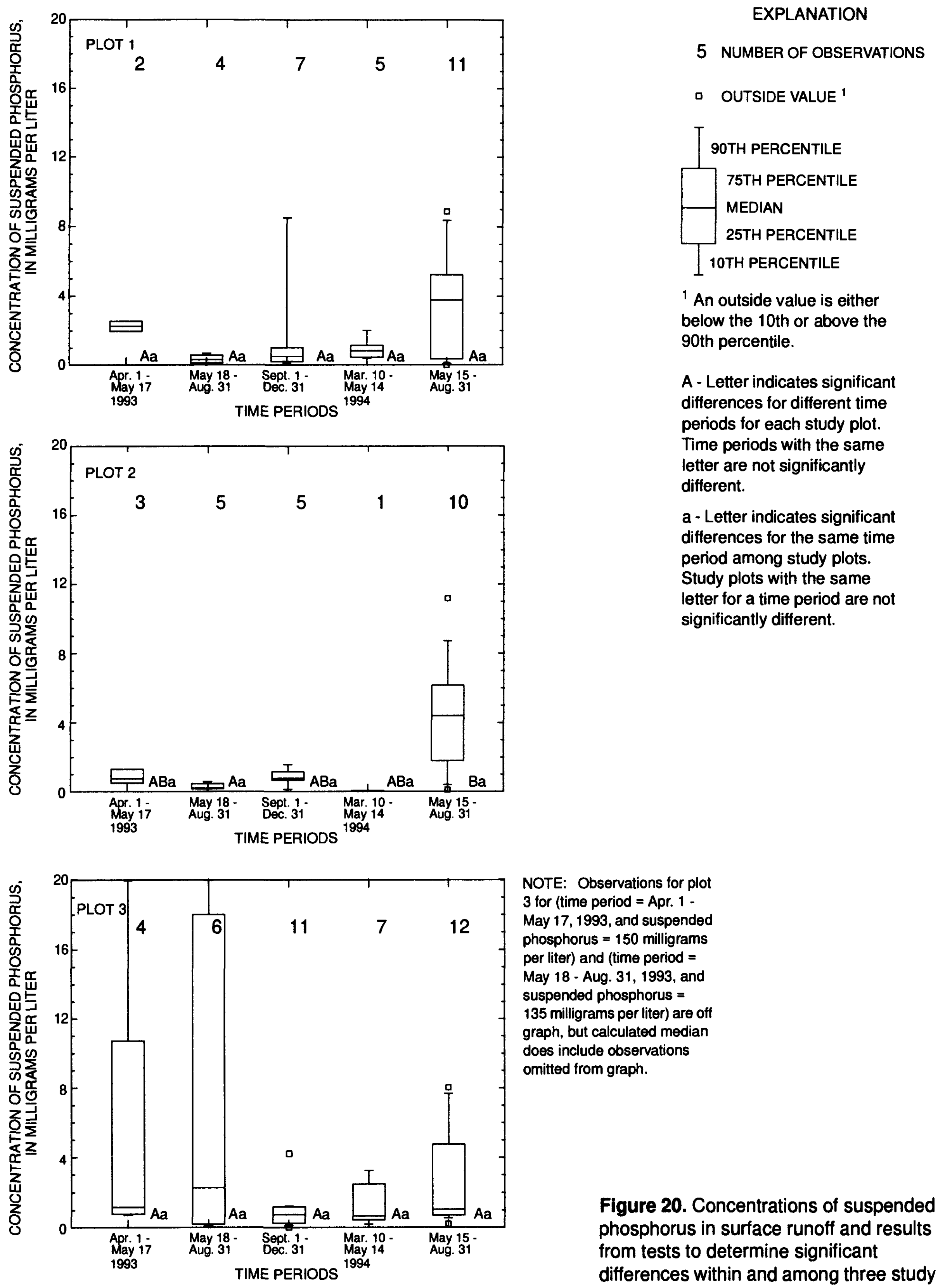


Figure 19. Cumulative yield of suspended sediment in surface runoff for three study plots.

Statistical tests for concentrations and yields of suspended phosphorus for surface runoff indicated some differences within and among plots for the time intervals tested (figs. 20 and 21). Large variability in concentrations of suspended phosphorus made it difficult to document significant changes among and within plots over time. For plots 1 and 2, median concentrations of suspended phosphorus were highest during PERIOD 5. The elevated concentrations of suspended phosphorus appear to be related to high storm intensities that occurred during PERIOD 5. The median yields of suspended phosphorus were highest during PERIOD 5 for all three plots, yet no significant differences from earlier periods were evident.

Subsurface Flow

The manure applications affected the concentration of dissolved phosphorus in subsurface flow (fig. 22). Temporal trends for plots 2 and 3 indicated that applications caused an increase in the concentration of dissolved phosphorus for subsurface samples collected 18 in. below land surface. Mean concentrations of phosphorus for subsurface flow for plots 1, 2, and 3 after the first application (PERIOD 2 through PERIOD 5) were 0.29, 0.57, and 1.45 mg/L, respectively. Mean concentrations of dissolved phosphorus for surface runoff during the same period were 0.30, 0.60, and 1.28 mg/L for plots 1, 2, and 3, respectively. Similarities in concentrations of dissolved phosphorus between surface runoff and subsurface flow could indicate that mineralogic controls on phosphorus solubility at the surface and 18 in. below land surface were similar. Other processes that could contribute to similarities between surface and subsurface samples are the mineralization of organic phosphorus into dissolved forms of phosphorus above the 18-in. depth in the soil and the potential for macropore flow from surface to a depth of 18 in. below land surface.



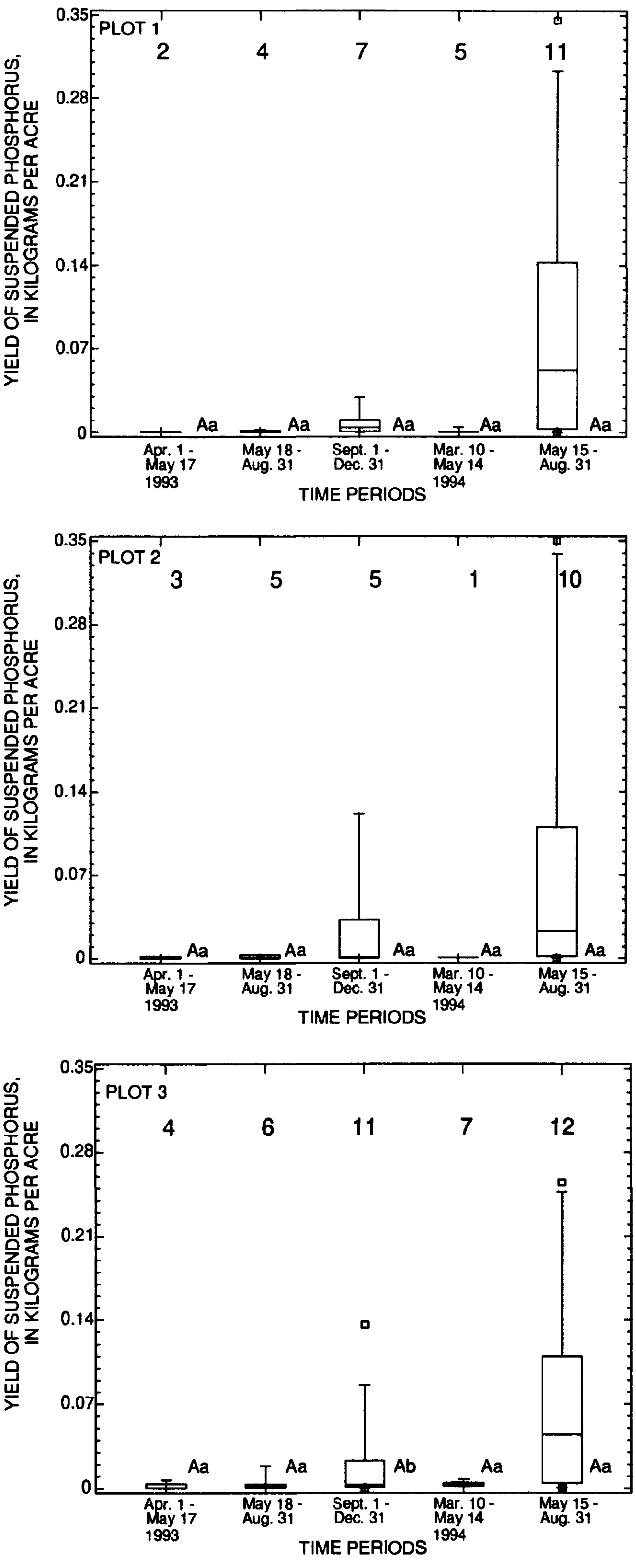
[1] An outside value is either below the 10th or above the 90th percentile.

A - Letter indicates significant differences for different time periods for each study plot. Time periods with the same letter are not significantly different.

a - Letter indicates significant differences for the same time period among study plots. Study plots with the same letter for a time period are not significantly different.

NOTE: Observations for plot 3 for (time period = Apr. 1 - May 17, 1993, and suspended phosphorus = 150 milligrams per liter) and (time period = May 18 - Aug. 31, 1993, and suspended phosphorus = 135 milligrams per liter) are off graph, but calculated median does include observations omitted from graph.

Figure 20. Concentrations of suspended phosphorus in surface runoff and results from tests to determine significant differences within and among three study plots.



EXPLANATION

5 NUMBER OF OBSERVATIONS

□ OUTSIDE VALUE [1]

90TH PERCENTILE
75TH PERCENTILE
MEDIAN
25TH PERCENTILE
10TH PERCENTILE

[1] An outside value is either below the 10th or above the 90th percentile.

A - Letter indicates significant differences for different time periods for each study plot. Time periods with the same letter are not significantly different.

a - Letter indicates significant differences for the same time period among study plots. Study plots with the same letter for a time period are not significantly different.

Figure 21. Yields of suspended phosphorus in surface runoff and results from tests to determine significant differences within and among three study plots.

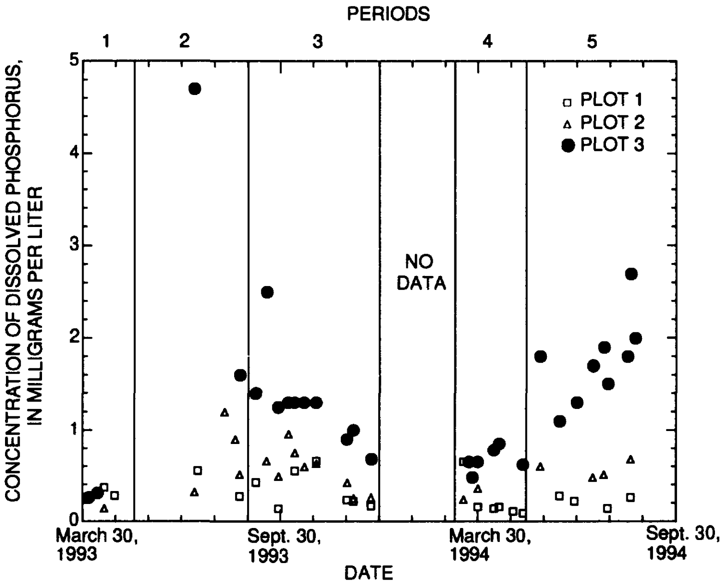
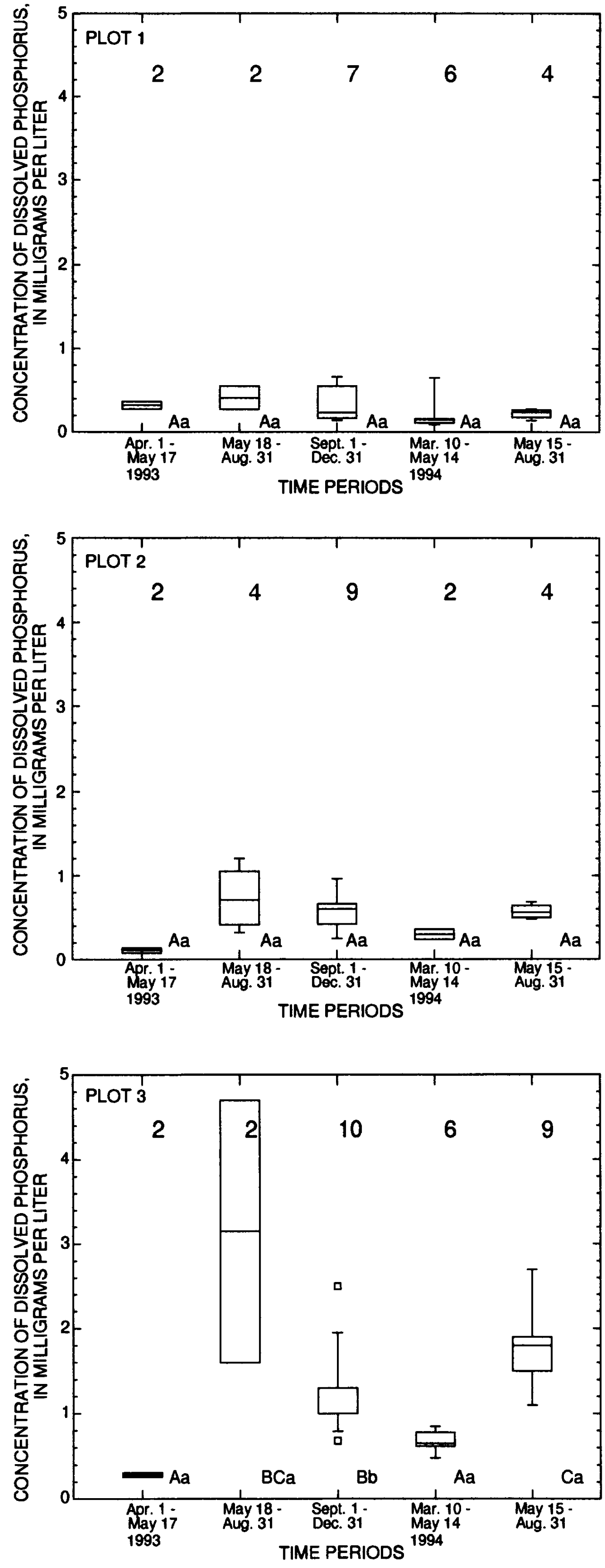
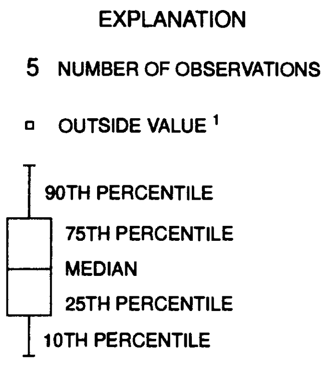


Figure 22. Concentrations of dissolved phosphorus in subsurface flow for three study plots.

Statistical tests did not identify many significant differences within and among plots in the concentrations of dissolved phosphorus in subsurface flow for the different time periods (fig. 23). Significant differences within plots were not found for plots 1 and 2. For plot 3, most of the periods starting at the first manure application in May 1993 and ending at the end of field-data collection in August 1994 (PERIODS 2, 3, and 5) had significantly higher concentrations of dissolved phosphorus than PERIOD 1. Only one significant difference in the concentration of dissolved phosphorus in subsurface flow among plots was identified for the five time periods even though the temporal trends in the concentration of dissolved phosphorus indicated differences among plots. When all data for dissolved phosphorus were grouped for the period from after the first manure application through the end of the study period, the concentration of dissolved phosphorus for subsurface flow was significantly higher for plot 3 relative to plots 1 and 2.





[1] An outside value is either below the 10th or above the 90th percentile.

A - Letter indicates significant differences for different time periods for each study plot. Time periods with the same letter are not significantly different.

a - Letter indicates significant differences for the same time period among study plots. Study plots with the same letter for a time period are not significantly different.

Figure 23. Concentrations of dissolved phosphorus in subsurface flow and results from tests to determine significant differences within and among three study plots.

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Plant Harvest

The largest phosphorus output measured from plots during the study period was a result of plant harvests in early October 1993 and 1994; the mean removal rates of phosphorus from plots 1, 2, and 3 were 16, 16, and 22 kg/acre per year, respectively. The cumulative yield of total phosphorus in surface runoff for each study plot during the study period was less than 2 kg/acre (fig. 10). Phosphorus removed during harvest increased from 1993 to 1994 on the treated plots (2 and 3); whereas for the untreated plot (1), data indicated virtually no change from 1993 to 1994 (table 16). The increased phosphorus output from 1993 to 1994 from plots 2 and 3 during plant harvest was because of increased growth of individual plants and higher concentrations of phosphorus in the corn plants harvested. The increased growth on plots 2 and 3 was at least partially caused by the increased precipitation during the growing season of 1994 relative to 1993. From May through August 1993 and 1994, 10.9 and 20.9 in. of precipitation were measured, respectively (fig. 6). The decreased phosphorus output from 1993 to 1994 for plot 1 relative to plots 2 and 3 was probably because of a nutrient deficiency (phosphorus was not deficient according to soil-sample results) caused by 2 years of corn growth without any fertilizer application. Neither nitrogen nor phosphorus was applied to plot 1 during the study period. Yellowing of leaves of corn plants on plot 1 during 1994 was probably caused by a nitrogen deficiency (Salisbury and Ross, 1985).

Table 16. Mean mass of phosphorus per corn plant, mean dry weights for individual corn plants, phosphorus removed during harvest of silage corn, and kilograms of silage corn removed from each study plot during 1993 and 1994

[kg/acre, kilograms per acre]

Plot	Phosphorus mass per corn plant [1] (grams)		Corn-plant dry weight [1] (kilograms)		Phosphorus removed [1] (kg/acre)		Kilograms of silage corn removed [1, 2] (kg/acre)	
	1993	1994	1993	1994	1993	1994	1993	1994
1	0.74	0.68	0.31	0.28	17	16	7,360	6,650
2	.56	1.0	.31	.44	11	20	6,180	8,780
3	.70	1.1	.34	.51	15	28	7,320	10,970

[1] Root mass was not used for calculations because roots were not removed from the study plots during harvest.

[2] Multiply kilograms per acre of corn removed by 0.0011 to calculate tons of silage corn removed. Mass of silage corn removed was based on dry weights.

SUMMARY OF PHOSPHORUS INPUTS, OUTPUTS, AND SOIL CONCENTRATIONS

Phosphorus inputs from precipitation were negligible compared to phosphorus inputs from manure on the treated plots (table 17). Liquid swine/dairy manure was applied twice (May 1993 and May 1994) to the treated plots by injection to a depth of 6-8 in. This method of application reduced surface runoff of the liquid manure so that the amount applied was held by the study plots.

Table 17. Area of study plots, volume of manure applied, phosphorus inputs, phosphorus outputs, phosphorus concentrations in output compartments, and concentrations of plant-available phosphorus in the 0-6-inch and 0-24-inch depth intervals of soil for each study plot during the study period

[Unless otherwise noted, data are for entire study period; concentration data are means for that specific time period. kg/acre, kilograms per acre; mg/L, milligrams per liter; ppm, parts per million]

	Plots		
	1	2	3
Plot size (acres)	0.43	0.23	0.28
Volume of manure applied (liters)			
May 17, 1993	0	11,400	31,000
May 14, 1994	0	11,400	29,500
Phosphorus inputs			
Manure (kg/acre)			
May 17, 1993	0	44	107
May 14, 1994	0	68	144
Precipitation (kg/acre)	.42	.42	.42
Phosphorus outputs			
Surface runoff			
Dissolved yield (kg/acre)	.074	.174	.443
Dissolved concentration (mg/L)			
April 1, 1993-May 17, 1993	.14	.96	.65
May 18, 1993-Aug. 31, 1994	.30	.60	1.28
Suspended yield (kg/acre)	1.05	1.07	1.25
Suspended concentration (mg/L)			
April 1, 1993-May 17, 1993	2.26	.86	38.18
May 18, 1993-Aug. 31, 1994	2.21	2.30	5.84
Subsurface flow			
Dissolved concentration (mg/L)			
April 1, 1993-May 17, 1993	.32	.11	.28
May 18, 1993-Aug. 31, 1994	.29	.57	1.45
Plant harvest (kg/acre)	33	31	43
Soil			
Plant-available phosphorus (ppm) for the 0-6-inch depth interval			
April 1, 1993-May 17, 1993	62	132	136
May 15, 1994-Aug. 31, 1994	54	146	226
Plant-available phosphorus (ppm) for the 0-24-inch depth interval			
April 1, 1993-May 17, 1993	46	64	54
May 15, 1994-Aug. 31, 1994	46	70	88

The primary phosphorus output from the study plots was phosphorus removed during plant harvest (table 17). Plant harvest during 1993 and 1994 removed 33, 31, and 43 kg/acre from plots 1, 2, and 3, respectively. The total yield of phosphorus in surface runoff was 1.12, 1.24, and 1.69 kg/acre for plots 1, 2, and 3, respectively. Thus, the loss of phosphorus from the study plots in surface runoff was only 3-4 percent of the loss of phosphorus from plant harvest.

Phosphorus outputs in surface runoff from the study plots were primarily in the suspended form. The percentage of total phosphorus lost in suspended forms was 94, 86, and 74 percent for plots 1, 2, and 3, respectively. Thus, the control of erosion would help to reduce the loss of suspended forms of phosphorus from these study plots. Yields of suspended phosphorus in surface runoff were similar among study plots. The mean concentration of suspended phosphorus for plot 3 was affected by very high concentrations (150 and 135 mg/L) for two samples collected in April and June 1993.

The loss of phosphorus in subsurface flow can be estimated using the water budget from figure 8 and the mean concentration of dissolved phosphorus in subsurface flow. Assuming that the water-budget estimate of subsurface flow is correct and the concentration of dissolved phosphorus in the water can be applied to all subsurface flow, the dissolved yield of phosphorus in subsurface flow over the study period was 0.41, 0.75, and 1.48 kg/acre from plots 1, 2, and 3, respectively.

Concentrations of PAP in soil changed over the study period on the plots that received manure. The most dramatic increase occurred on plot 3. Concentrations of PAP on plot 3 in the 0-6-in. depth interval of soil increased from 136 ppm prior to the first manure application to 226 ppm after the second application. When data for all three soil depths sampled are averaged, the concentration of PAP in soil over the study period increased by 6 and 34 ppm on plots 2 and 3, respectively.

FACTORS AFFECTING CONCENTRATIONS OF PHOSPHORUS IN HYDROLOGIC PATHWAYS

Phosphorus transported from soil by water was affected by different factors. The significance of factors on phosphorus transport was dependent on the form of phosphorus (dissolved or suspended) and the water pathway (surface runoff or subsurface flow).

Surface Runoff

The yield of dissolved phosphorus as a percentage of total phosphorus in surface runoff from the study plots over the entire study was 6, 14, and 26 percent for plots 1, 2, and 3, respectively. The increased dissolved- to total-phosphorus ratio from plot 1 to plot 3 primarily reflected differences in soil chemistry among plots. Soil chemistry was affected by manure applications prior to and during this study.

Dissolved Outputs

Dissolved concentrations of phosphorus in surface runoff were significantly correlated to specific conductance and all dissolved concentrations of cations (except H and Al) in surface runoff for which analyses were conducted (table 3). The regression model indicated that dissolved forms of Na, K, and Fe account for nearly all of the variation in dissolved phosphorus (adjusted $R^2 = 0.99$) (fig. 24). In any water system, the equivalence per liter of anions must equal the equivalence per liter of cations to keep the solution electrically neutral (Hem, 1985). The relation of dissolved phosphorus to dissolved cations in surface runoff suggests a mechanism that was similar to the relation between soil PAP and exchangeable cations in the soil (table 12). A significant predictor of soil PAP was exchangeable K, and soil PAP was significantly correlated to exchangeable forms of K and Mg. The relation of phosphorus to cations in soil and surface runoff could be partially caused by manure application. Manure supplied phosphorus and cations (Appendix 4).

Concentrations of dissolved phosphorus in surface runoff showed no significant relation to the total volume of surface runoff or energy and intensity variables related to precipitation (table 6). Input of precipitation energy and intensity variables to regression models explained virtually no variation in dissolved phosphorus.

Regression analysis indicated a significant relation between the concentrations of dissolved phosphorus in surface runoff and concentrations of soil PAP (alpha = 0.0014) (fig. 24). Soil concentrations of PAP in the 0-6-in. depth interval explained over 50 percent of the variation in the median concentrations of dissolved phosphorus in surface runoff for the five time periods defined earlier (table 15). The model predicted that concentrations of soil PAP equal to 9 ppm (18 lb/acre of phosphorus or 44 lb/acre of P_2O_5) would result in a concentration of dissolved phosphorus in runoff of 0.1 mg/L. All study plots exceeded concentrations of soil PAP of 9 ppm (table 9). For plot 3, the concentration of PAP in the 0-6-in. depth interval of soil was 136 ppm in April 1993 and 226 ppm after the second manure application in May 1994. According to the regression equation, the change in soil PAP for plot 3 during the study period would result in a 0.31 mg/L increase in the concentration of dissolved phosphorus in surface runoff.

The relation between dissolved phosphorus in surface runoff and soil PAP explained the difference in the ratio of yields of dissolved to total phosphorus from the three study plots. Concentrations of soil PAP and dissolved phosphorus in surface runoff were the least from plot 1 and greatest from plot 3. The relation of concentrations of dissolved phosphorus to soil concentrations of phosphorus has been identified in other studies (Sharpley and others, 1994; Romkens and Nelson, 1974).

The 0.1-mg/L goal for phosphorus is suggested for flowing waters that do not directly discharge to lakes or reservoirs (U.S. Environmental Protection Agency, 1986). Surface runoff for this study was collected at the edge of the field and concentrations of dissolved phosphorus in surface runoff do not necessarily reflect conditions in Mill Creek (the stream that drains the study area).

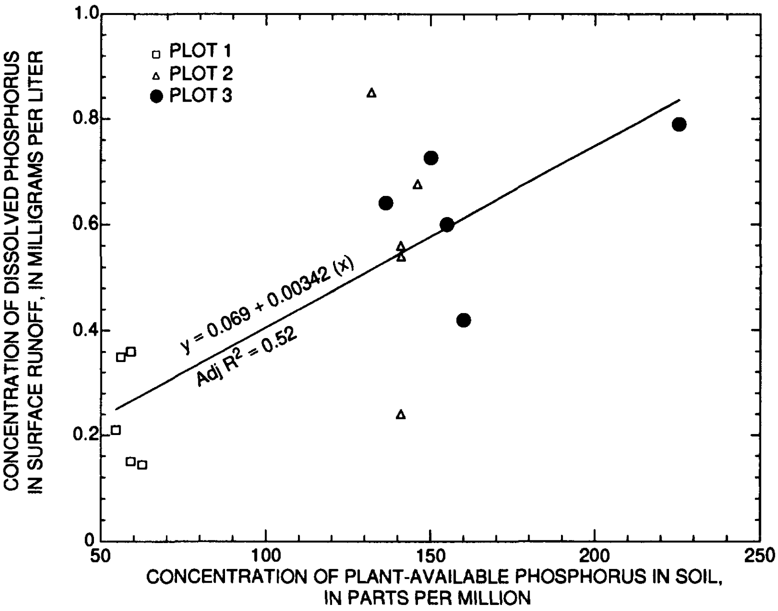
REGRESSIONS

A) Regression of dissolved phosphorus in surface runoff against dissolved concentrations of other constituents in surface runoff

Dissolved phosphorus = 0.102 + 0.271 (dissolved sodium) + 0.00799 (dissolved potassium) + 0.736 (dissolved iron)

Number of observations = 57 Adj R^2 = 0.99

B) Regression of the concentration of dissolved phosphorus in surface runoff against the concentration of plant-available phosphorus (PAP) in the 0-6-inch depth interval of soil. Median values for the concentration of dissolved phosphorus in surface runoff for each time interval (see table 15) were regressed against the concentration of PAP in soil for that time interval. The graph below includes the regression equation and the values used to generate the regression equation.



CORRELATIONS		
Surface-runoff parameter	Number of observations	Spearman coefficient
Specific conductance (microsiemens per centimeter)	92	0.55
Dissolved calcium	57	.50
Dissolved magnesium	57	.60
Dissolved sodium	57	.43
Dissolved potassium	57	.53
Dissolved iron	57	.26

All parameters and models are significant at alpha = 0.05.

Figure 24. Relation of the concentrations of dissolved phosphorus in surface runoff to other chemical parameters measured in surface runoff and soil at three study plots. [Unless otherwise noted, all units are in milligrams per liter; Adj R^2, coefficient of determination]

Suspended Outputs

The concentration of suspended phosphorus in surface runoff was significantly correlated to the concentrations of TOC in surface runoff, suspended sediment, and each of the different size fractions (sand, silt, and clay) (table 18). Concentrations of total phosphorus in soil also were correlated with the concentration of TOC in soil (table 12). The regression model indicated that the suspended concentration of Ca and the concentrations of different size fractions in surface runoff accounted for 45 percent of the variability in the concentration of suspended phosphorus in surface runoff (table 18). The relation of suspended concentrations of phosphorus and Ca in surface runoff may be related to pH conditions of the soil. Soil pH ranged from a mean (for the entire study for the 0-6-in. depth interval of soil) of 6.7 for plot 3 to 7.2 for plot 2 (Appendix 2). At these pH values, phosphorus can be bound to Ca in relatively unavailable forms (Brady, 1974). The significance of silt and clay in the model and the positive coefficient relating silt and clay to suspended phosphorus reflected the fact that the majority of phosphorus in soil was associated with silt- and clay-size particles (table 11).

Over 90 percent of the mass of suspended sediment in surface runoff consisted of fines. The percentage distribution of particle-size classes in the 0-6-in. depth interval of soil and in surface runoff indicated an enrichment in fines (silts and clays) in the runoff sediment relative to the soil (fig. 25). The percentage mass of fines in the 0-6-in. depth interval of soil was 54, 51, and 60 percent for plots 1, 2, and 3, respectively, and in runoff was 93, 92, and 96 percent for plots, 1, 2, and 3, respectively. A review of concentrations of suspended phosphorus relative to percentages of fines in runoff indicated that most of the highest concentrations of suspended phosphorus in surface runoff were associated with samples that had a percentage of fines near or greater than 90 percent of the total mass of suspended sediment (fig. 26).

Table 18. Relation of the concentrations of suspended phosphorus in surface runoff to other parameters measured in surface runoff at three study plots

[Unless otherwise noted, all units are in milligrams per liter; n, number of observations; Adj. R^2, coefficient of determination]

REGRESSION

Regression of concentration of suspended phosphorus in surface runoff against concentrations of other constituents in surface runoff.

Suspended phosphorus = -3.62 + 0.00142 (silt and clay) - 0.00643 (sand) + 0.304 (suspended calcium)

n = 67 Adj. $R^2 = 0.45$

CORRELATIONS

Parameter	n	Spearman coefficient
Total organic carbon	67	0.42
Suspended sediment	92	.40
Sand	92	.39
Silt	77	.24
Clay	77	.32

All parameters and models are significant at alpha = 0.05.

The relation of concentrations of suspended phosphorus in surface runoff to soil concentrations of total phosphorus for the 0-6-in. depth interval of soil was not significant. The lack of a significant relation was probably related to differences in the percentage mass of silts and clays in surface runoff relative to soil. The concentration of suspended phosphorus in surface runoff was also not significantly correlated to volume of surface runoff or any variables associated with precipitation energy and intensity (table 6).

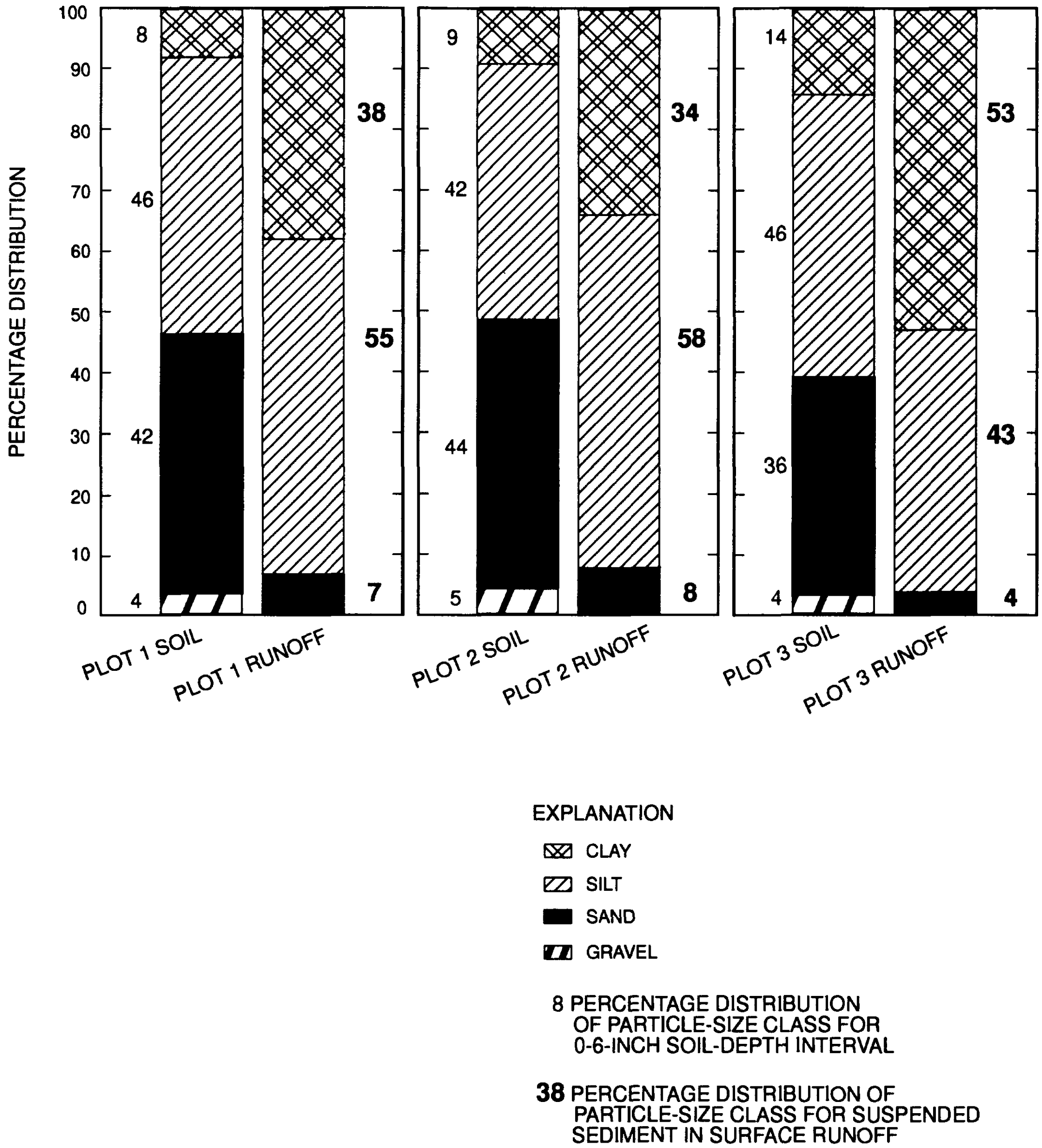
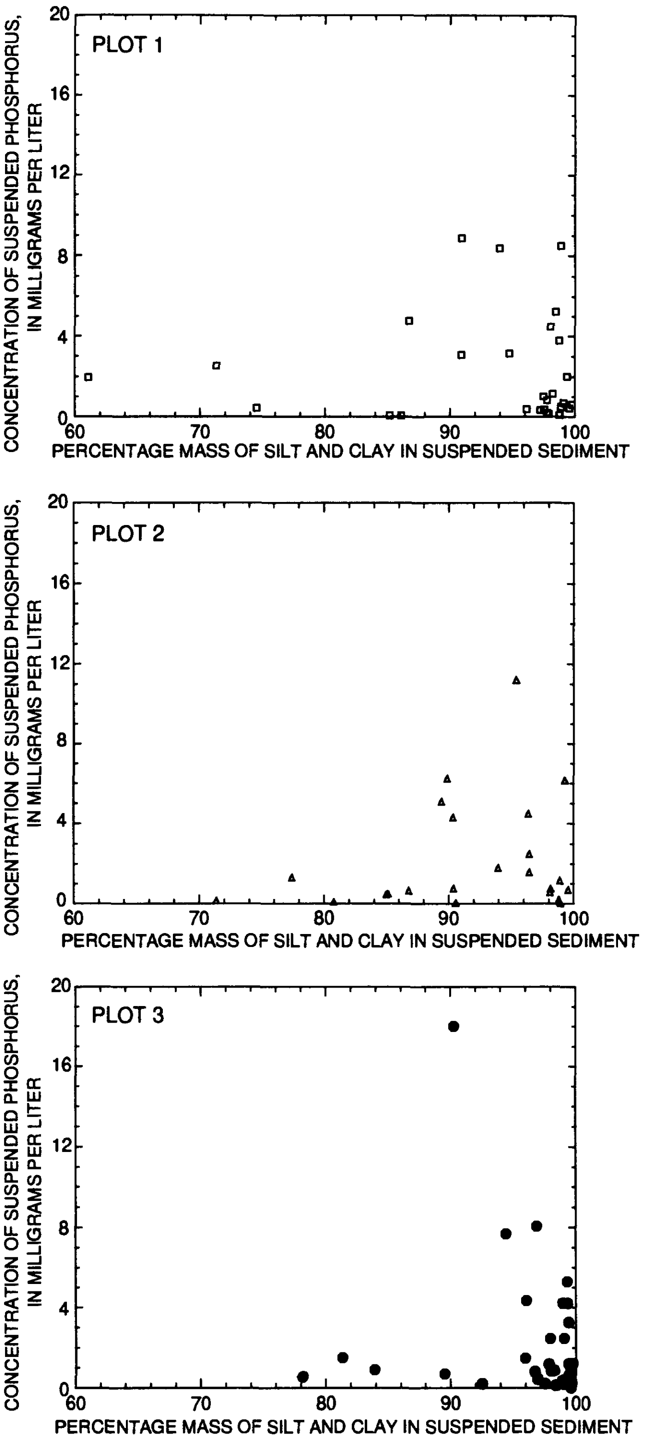


Figure 25. Percentage distribution of particle-size classes for 0-6-inch depth interval of soil and for suspended sediment in surface runoff for three study plots.



NOTE: Observations for plot 3 for (percentage mass of silt and clay = 81.15 and suspended phosphorus = 150 milligrams per liter), (percentage mass of silt and clay = 90.27 and suspended phosphorus =18 milligrams per liter), and (percentage mass of silt and clay = 95.19 and suspended phosphorus = 135 milligrams per liter) are not plotted.

Figure 26. Concentrations of suspended phosphorus and percentage mass of silt and clay in suspended sediment in surface runoff for three study plots.

Subsurface Flow

Dissolved concentrations of phosphorus in subsurface flow were significantly correlated to specific conductance, dissolved organic carbon, and concentrations of dissolved Ca, Mg, Na, and K (fig. 27). The significant correlations for the concentration of dissolved phosphorus in subsurface flow were similar to the significant correlations for the concentration of dissolved phosphorus in surface runoff (fig. 24). Similarities in relations of dissolved phosphorus in surface runoff and subsurface flow to other chemical constituents could be because of (1) similarities in mineralogic controls at the surface and 18 in. below land surface and (2) macropore flow from surface to subsurface. As with surface runoff, the relation of dissolved phosphorus to cations may also be related to recent and past applications of manure to the study plots.

Regressions of concentrations of dissolved phosphorus in subsurface flow against concentration of soil PAP were markedly different depending on whether the concentrations of soil PAP for 0-6-in. depth interval of soil or the concentrations of soil PAP for the 0-24-in. depth interval of soil were used in the regression (fig. 27). Only the regression for the concentrations for the 0-6-in. depth interval of soil is reported because the model with concentrations of soil PAP for the 0-24-in. depth interval was not significant. The model for the 0-6-in. depth interval of soil indicated that dissolved concentrations of phosphorus in subsurface flow would exceed 0.1 mg/L if soil concentrations of PAP were greater than 49 ppm. All study plots had soil concentrations of PAP greater than 49 ppm in the 0-6-in. depth interval. The significance of the model for concentrations of soil PAP for the 0-6-in. depth interval may indicate that macropore flow was affecting concentrations of dissolved phosphorus in subsurface flow. If infiltrating water was not passing through large pores, a better relation would be expected between concentrations of soil PAP in the 0-24-in. depth interval and concentrations of dissolved phosphorus in subsurface flow collected at 18 in. Another factor that may indicate the occurrence of macropore flow were results from the soil-flask experiments (fig. 9). These experiments showed that the soil had the capacity to retain more phosphorus in the form of phosphate. If phosphate was being adsorbed from solution, concentrations of dissolved phosphorus in subsurface flow would decrease relative to concentrations in surface runoff. However, because dissolution of phosphorus is an equilibrium process (Taylor and Kunishi, 1971) and concentrations of soil PAP are high even at depths of 12-24 in. in soil, it is possible that phosphorus would not be sorbed to soil as it moved downward with infiltrating water. The fact that soil-flask experiments maximized contact with soil and water make comparisons to field conditions difficult.

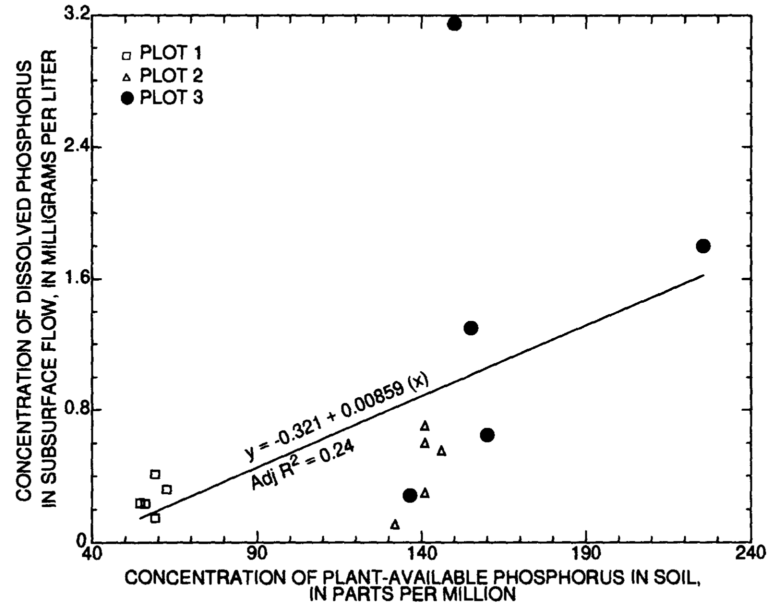
Differences in (1) the regression equations of dissolved concentrations of phosphorus in surface runoff (fig. 24) and subsurface flow (fig. 27) against concentrations of soil PAP and (2) actual concentrations of dissolved phosphorus in surface runoff (fig. 13) and subsurface flow (fig. 22) did indicate that macropore flow was not the only factor affecting concentrations of dissolved phosphorus in subsurface flow. The equations indicated that predicted concentrations of dissolved phosphorus would be greater in subsurface flow than surface runoff for concentrations of soil PAP greater than 75 ppm. All concentrations of soil PAP for the 0-6-in. depth interval for plots 2 and 3 exceeded 75 ppm. Other potential effects on the concentration of dissolved phosphorus in subsurface flow were the mineralization of organic phosphorus to dissolved forms of phosphorus and mineralogic controls. The saturation indices (SI) for Fe oxides and strengite were lower for the subsurface-flow data relative to surface-runoff data for each of the study plots (table 13). Values of SI below zero indicated that strengite, if present, was dissolving. Dissolution of strengite would release phosphorus from the mineral phase.

REGRESSIONS

A) Regression of dissolved phosphorus against subsurface-flow parameters.
Dissolved phosphorus = 0.329 - 0.0228 (dissolved calcium) + 0.00334 (specific conductance, in microsiemens per centimeter)

Number of observations = 41 Adj $R^2 = 0.72$

B) Regression of the concentration of dissolved phosphorus in subsurface flow against the concentration of plant-available phosphorus (PAP) in the 0-6-inch depth interval of soil. Median values for the concentration of dissolved phosphorus in subsurface flow for each time interval (see table 15) were regressed against the concentration of PAP in soil for that time interval. The graph below includes the regression equation and the values used to generate the regression equation.



CORRELATIONS		
Parameter	Number of observations	Spearman coefficient
Specific conductance (microsiemens per centimeter)	66	0.83
Dissolved organic carbon	45	.59
Dissolved calcium	41	.72
Dissolved magnesium	41	.80
Dissolved sodium	41	.65
Dissolved potassium	39	.75

All parameters and models are significant at alpha = 0.05.

Figure 27. Relation of the concentrations of dissolved phosphorus in subsurface flow to other chemical parameters measured in subsurface flow and soil at three study plots. [Unless otherwise noted, all units are in milligrams per liter; Adj R^2, coefficient of determination]

SUMMARY AND CONCLUSIONS

The U.S. Geological Survey, in cooperation with the Bureau of Land and Water Conservation within the Pennsylvania Department of Environmental Protection, conducted a field-scale study to evaluate the effects of manure application and concentrations of soil phosphorus on phosphorus transport from a minimum-till farm site in Lancaster County, Pa. The study was conducted in the Mill Creek Basin, which is within the drainage of the Conestoga River and Chesapeake Bay. Identification of factors affecting phosphorus transport from agricultural areas was necessary because excessive concentrations of phosphorus in surface-water bodies cause eutrophication and promotes the excessive growth of algal communities. Research during the 1980's indicated that 50 percent of the controllable load of phosphorus to the Chesapeake Bay originates from agricultural sources.

The purpose of the investigation was to quantify and determine the significance of chemical, physical, and hydrologic factors that affect phosphorus transport. The field and laboratory study was conducted from September 1992 to March 1995 at three plots less than 1 acre in size located at a farm site planted in silage corn. The study period for collection of field data encompassed the time intervals from March 30, 1993, through December 31, 1993, and March 10, 1994, through August 31, 1994. Phosphorus in the form of manure was applied by injection to a depth of 6-8 in. on two of the three study plots during May 1993 and May 1994. Plot 1 received no manure or commercial fertilizer over the study period. Approximately 11,000 and 30,000 L of liquid swine-dairy manure were applied to plots 2 and 3, respectively, during both years. During the study period, concentrations of phosphorus and selected cation inputs to soil from precipitation and manure were measured, as were concentrations of phosphorus and selected cation outputs from soil in surface runoff, subsurface flow, and plant harvest. Laboratory soil-flask experiments and geochemical modeling analysis were conducted to determine the maximum phosphate retention capacity of soil and primary mineralogic controls in soil that affect phosphate equilibrium processes. Physical characteristics such as particle-size distributions in soil and surface runoff and surface topography were quantified. Hydrologic characteristics such as infiltration rate of soil, precipitation-energy variables, and the volume of surface runoff also were monitored during the study period.

Particle-size distributions of soil for plot 3 indicated that the silt-clay (fines) size fraction to a depth of 24 in. was about 60 percent; the fines fraction for plots 1 and 2 was 46 to 48 percent. The higher fines fraction and bulk density for plot 3 were reflected in the lower soil infiltration rate for plot 3 relative to plots 1 and 2.

Precipitation amounts and intensities varied from 1993 to 1994. From May through August, about 10 and 20 in. of precipitation were measured at the study site during 1993 and 1994, respectively. The first 2 in.-per-day storm took place in November 1993; three such storms took place during summer 1994.

The volume of surface runoff from the study plots differed by plot and season. About 90 percent of the total runoff volume during the study period occurred after October 1993 because of the lack of intense precipitation from late March 1993 to late November 1993. For any one precipitation amount, volumes of surface runoff increased with an increase in the kinetic energy and maximum intensity of precipitation and decreased with an increase in the duration of a storm. The significantly higher volume of surface runoff for plot 3 relative to plots 1 and 2 was probably caused by lower infiltration rates on plot 3.

Optimum concentrations of plant-available phosphorus (PAP) for silage corn are 30-50 ppm. Soil concentrations of PAP on all three study plots were optimum or above optimum for silage corn both before and after the study period. This was true to a depth of 24 in. on each plot except for plot 3 for the 12-24-in. depth interval of soil. The high concentrations of soil PAP made it difficult to identify changes in the concentration of soil PAP when phosphorus was input to the treated plots in the form of manure. Increased concentrations of soil PAP were evident during the study period for the plot (plot 3) that received the largest manure applications over the study period. The percentages of total phosphorus in plant-available and organic forms were about 5 and 20 percent, respectively, over the 0-24-in. depth interval of soil on the study plots, with a general decrease in PAP with an increase in soil depth and generally no change in the percentage of organic phosphorus with depth.

Particle-size distributions in the soil and the concentration of soil phosphorus on the different particle-size classes indicated that about 70 percent of the total mass of phosphorus in soil to a depth of 24 in. was associated with silt and clay particles. The overall concentrations of phosphorus on sand, silt, and clay particles were 700, 1,000, and 3,400 ppm, respectively. As particle size decreases, the concentration of phosphorus per mass for that particle-size class increases. Thus, erosion control to reduce phosphorus losses from these study plots would increase efficiency by reducing the loss of fines from soil.

Results of soil-flask experiments indicated that soil from the study plots was not saturated with respect to phosphorus. Soils had the capacity to retain about 694 to 1,160 mg of phosphorus per kg of soil for plots 2 and 1, respectively. The measured retention capacity probably exceeded actual retention capacity because laboratory conditions optimized the contact time between soil and the test solutions.

Results of geochemical modeling indicated that the primary mineralogical controls on the concentration of dissolved phosphorus in surface runoff and subsurface flow were aluminum and iron oxides and strengite (if it exists). Aluminum and iron oxides bind phosphate in solution and strengite is an iron-phosphate mineral. Because of the large fraction of organic phosphorus in soil, it is possible that the mineralization of organic phosphorus into dissolved inorganic forms was also affecting the concentration of dissolved phosphorus in solution.

Phosphorus inputs to the plots during the study period were from precipitation and manure. Phosphorus inputs from precipitation were 0.42 kg/acre to each plot. Phosphorus loads to the plots from manure were 112 and 251 kg/acre for plots 2 and 3, respectively. About 60 percent of the phosphorus load from manure was applied in 1994.

Phosphorus outputs in surface runoff differed between study plots. The cumulative yields of total phosphorus in surface runoff for plots 1, 2, and 3 during the study period were 1.12, 1.24, and 1.69 kg/acre, respectively. Differences between plots were primarily evident for yields of dissolved phosphorus. The percentage of the output of total phosphorus in surface runoff that was dissolved ranged from 6 percent for plot 1 to 26 percent for plot 3. The cumulative yields of dissolved phosphorus from plots 2 and 3 were about 135 and 500 percent, respectively, greater than the dissolved yield from plot 1. After the second manure application on plots 2 and 3, concentrations of dissolved phosphorus in surface runoff on those plots were significantly higher than the concentration for plot 1. Thus, yields of dissolved phosphorus in surface runoff were affected by manure applications. Yields of suspended phosphorus in surface runoff from the study plots were similar over the study period. Because of differences in precipitation and subsequent volumes of surface runoff, approximately 80 percent of the cumulative yield of suspended phosphorus occurred after mid-May 1994. The yield of suspended phosphorus in surface runoff was not significantly affected by manure applications.

Subsurface-flow samples, which were collected 18 in. below land surface, showed that concentrations of dissolved phosphorus from plots 2 and 3 increased after manure applications during the study period. The mean concentrations of dissolved phosphorus in subsurface flow after the first manure application were 0.29, 0.57, and 1.45 mg/L of phosphorus for plots 1, 2, and 3, respectively.

The loss of dissolved phosphorus from soil through a surface-runoff mechanism was affected by the concentration of PAP in soil. The total volume of surface runoff and energy and intensity variables related to precipitation did not significantly affect the concentration of dissolved phosphorus in surface runoff. The regression model relating dissolved phosphorus in surface runoff to soil PAP indicated that concentrations of dissolved phosphorus in surface runoff would exceed 0.1 mg/L if soil concentrations of PAP exceeded 9 ppm. More than 50 percent of the variation of dissolved phosphorus in surface runoff was explained by soil concentrations of PAP in the 0-6-in. depth interval.

The primary factor that affected the output of phosphorus in suspended forms in surface runoff was the particle-size distribution of suspended sediment in surface runoff. Surface runoff was enriched with fines (silt- and clay-size particles) relative to the soil matrix. Generally, more than 90 percent of sediment in runoff was fines; only 50-60 percent of particle sizes from the intact soil matrix in the 0-6-in. depth interval were in the silt- to clay-size range. Most of the highest concentrations of suspended phosphorus in runoff were associated with samples that contained near or greater than 90 percent fines. Concentrations of suspended phosphorus in surface runoff were not significantly related to soil concentrations of total phosphorus in the 0-6-in. depth interval. This was probably caused by differences in the percent mass of silts and clays in surface runoff relative to soil.

Concentrations of dissolved phosphorus in subsurface flow also were related to soil concentrations of PAP. The relation indicated that dissolved concentrations of phosphorus in subsurface flow would exceed 0.1 mg/L if soil concentrations of PAP in the 0-6-in. depth interval of soil were greater than 49 ppm. In addition to soil concentrations of PAP, other potential effects on the relatively high concentrations (greater than 0.1 mg/L) of dissolved phosphorus in subsurface flow were macropore flow, mineralization of organic phosphorus to dissolved inorganic phosphorus, and mineralogic controls. The relatively high concentrations of dissolved phosphorus evident at 18 in. below land surface indicate that phosphorus is moving through the soil matrix. The lack of available data for dissolved phosphorus in subsurface waters indicates that further work is necessary to determine typical concentrations of dissolved phosphorus at different depths below land surface. This is especially important in areas that have relatively high concentrations of soil PAP.

The significant relation of high concentrations of dissolved phosphorus to soil concentrations of PAP indicated that soils with comparable concentrations of soil PAP would be potential sources of dissolved phosphorus to surface water and to shallow ground water. Thus, the application of manure (and phosphorus) to a system that has soil concentrations of PAP greater than optimum for plant uptake would probably not benefit the crop and would likely have a detrimental impact on water bodies through eutrophication by inputs of dissolved phosphorus.

As soil concentrations of PAP increased, the percentage of the total phosphorus lost from a system in the dissolved form increased. This indicates that best-management practices to reduce phosphorus losses from this system need to target both suspended and dissolved forms of phosphorus. Practices aimed at reducing the loss of dissolved phosphorus from the system increase in importance with an increase in soil PAP. Suspended forms of phosphorus were primarily associated with fines. Important hydrologic outputs of dissolved phosphorus were surface runoff and subsurface flow to a depth of 18 in. below land surface.

REFERENCES CITED

Bachmann, R.W., 1980, The role of agricultural sediments and chemicals in eutrophication: Journal Water Pollution Control Federation, v. 52, p. 2425-2431, 2600.

Baker, D.E., and Amacher, M.C., 1981, The development and interpretation of a diagnostic soil-testing program: The Pennsylvania State University, College of Agriculture, University Park, Pennsylvania, Agricultural Experiment Station Bulletin 826, 18 p.

Ball, J.W., and Nordstrom, D.K., 1991, User's manual for WATEQ4F, with revised thermodynamic data base and test cases for calculating speciation of major, trace, and redox elements in natural waters: U.S. Geological Survey Open-File Report 91-183, 189 p.

Blake, G.R., and Hartge, K.H., 1986, Bulk density, *in* Klute, Arnold, ed., Methods of soil analysis, Part 1. Physical and mineralogical methods, Agronomy Monograph no. 9 (2d ed.): Madison, Wis., American Society of Agronomy-Soil Science Society of America, p. 363-375.

Bouwer, Herman, 1986, Intake rate: cylinder infiltrometer, *in* Klute, Arnold, ed., Methods of soil analysis, Part 1. Physical and mineralogical methods, Agronomy Monograph no. 9 (2nd ed.): Madison, Wis., American Society of Agronomy-Soil Science Society of America, p. 825-844.

Brady, N.C., 1974, The nature and properties of soils (8th ed.): New York, Macmillan Publishing Co., 639 p.

Chesapeake Bay Program, 1992, Nutrient reduction strategy reevaluation workgroup report #1: Nonpoint source baseline nutrient loading inventory: Nonpoint Source Subcommittee, 84 p.

Custer, B.H., 1985, Soil survey of Lancaster County, Pennsylvania: U.S. Department of Agriculture, Soil Conservation Service, 152 p.

Dalal, R.C., 1977, Soil organic phosphorus: Advances in Agronomy, v. 29, p. 83-117.

Drever, J.L., 1982, The geochemistry of natural waters: Englewood Cliffs, N.J., Prentice-Hall, Inc., 388 p.

Edwards, A.P., and Bremner, J.M., 1967, Dispersion of soil particles by sonic vibration: Journal of Soil Science, v. 18, p. 47-63.

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

Gardner, W.H., 1986, Water content, *in* Klute, Arnold, ed., Methods of soil analysis, Part 1. Physical and mineralogical methods, Agronomy Monograph no. 9 (2nd ed.): Madison, Wis., American Society of Agronomy-Soil Science Society of America, p. 493-544.

Gartley, K.L., and Sims, J.T., 1994, Phosphorus soil testing: Environmental uses and implications: Communications in Soil Science and Plant Analysis, v. 25, p. 1565-1582.

Guy, H.P., 1969, Laboratory theory and methods for sediment analysis: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. C1, 58 p.

Helsel, D.R., and Hirsch, R.M., 1992, Statistical methods in water resources: Amsterdam, Elsevier Science Publishing Co., Inc., 522 p.

Hem, J.D., 1985, Study and interpretation of the chemical characteristics of natural water: U.S. Geological Survey Water-Supply Paper 2254, 263 p.

Holford, I.C.R., and Mattingly, G.E.G., 1976, A model for the behaviour of labile phosphate in soil: Plant and Soil, v. 44, p. 219-229.

Khaleel, R.R., Reddy, K.R., and Overcash, M.R., 1981, Changes in soil physical properties due to organic waste applications—A review: Journal of Environmental Quality, v. 10, p. 133-141.

Kohnke, Helmut, and Bertrand, A.R., 1959, Soil conservation: New York, McGraw-Hill Book Co., 298 p.

REFERENCES CITED—Continued

Krumbein, W.C., and Pettijohn, F.J., 1938, Manual of sedimentary petrography: New York, Appleton-Century-Crofts, 549 p.

Langland, M.J., 1992, Atmospheric deposition of ammonia from open manure-storage lagoons in south-central Pennsylvania: The Environmental Professional, v. 14, p. 28-37.

Larsen, Sigurd, 1967, Soil phosphorus: Advances in Agronomy, v. 19, p. 151-210.

Lee, G.F., 1973, Role of phosphorus in eutrophication and diffuse source control: Water Research, v. 7, p. 111-128.

Lindsay, W.L., and Moreno, E.C., 1960, Phosphate phase equilibria in soils: Soil Science Society Proceedings, v. 24, p. 177-182.

Mehlich, Adolph, 1984, Mehlich no. 3 extractant—A modification of Mehlich no. 2 extractant: Communications in Soil Science and Plant Analysis, v. 15, p. 1409-1416.

Nagpal, N.K., 1986, Effect of soil and effluent characteristics on phosphorus sorption in dosed columns: Journal of Environmental Quality, v. 15, p. 73-78.

National Oceanic and Atmospheric Administration, 1993, Climatological Data - Annual Summary - Pennsylvania 1993: Asheville, N.C., National Climate Data Center, v. 98, 34 p.

Olsen, S.R., and Watanabe, F.S., 1957, A method to determine a phosphorus adsorption maximum of soils as measured by the Langmuir isotherm: Soil Science Society Proceedings, v. 21, p. 144-149.

Page, A.L., Miller, R.H., and Keeney, D.R., eds., 1982, Methods of soil analysis, Part 2. Chemical and microbiological properties, Agronomy Monograph No. 9 (2nd ed.): Madison, Wis., American Society of Agronomy-Soil Science Society of America, 1159 p.

Pennsylvania State University, 1991, The agronomy guide 1991-1992, Chambers, R.D., ed.: University Park, Pa., Pennsylvania State University, 164 p.

Peperzak, Paul, Caldwell, A.G., Hunziker, R.R., and Black, C.A., 1959, Phosphorus fractions in manures: Soil Science, v. 87, p. 293-302.

Petersen, R.G., and Calvin, L.D., 1986, Sampling, *in* Klute, Arnold, ed., Methods of soil analysis, Part 1. Physical and mineralogical methods, Agronomy Monograph no. 9 (2nd ed.): Madison, Wis., American Society of Agronomy-Soil Science Society of America, p. 33-51.

Poth, C.W., 1977, Summary ground-water resources of Lancaster County, Pennsylvania: Pennsylvania Geological Survey, Water Resources Report 43, 80 p.

Romkens, M.J.M., and Nelson, D.W., 1974, Phosphorus relationships in runoff from fertilized soils: Journal of Environmental Quality, v. 3, p. 10-13.

Salisbury, F.B., and Ross, C.W., 1985, Plant physiology (3rd ed.): Belmont, Calif., Wadsworth Publishing Co., 540 p.

Saly, Rudolf, 1967, Use of ultrasonic vibration for dispersing soil samples: Soviet Soil Science, 1967, p. 1547-1559.

Sample, E.C., Soper, R.J., and Racz, G.J., 1980, Reactions of phosphate fertilizers in soil, *in* Stelly, Matthias, and Dinauer, R.C., eds., The role of phosphorus in agriculture: Madison, Wis., The American Society of Agronomy, p. 263-310.

Sharpley, A.N., 1980, The enrichment of soil phosphorus in runoff sediments: Journal of Environmental Quality, v. 9, p. 521-526.

Sharpley, A.N., 1985, The selective erosion of plant nutrients in runoff: Soil Science Society of America Journal, v. 49, p. 1527-1534.

REFERENCES CITED—Continued

Sharpley, A.N., Carter, B.J., Wagner, B.J., Smith, S.J., Cole, E.L., and Sample, G.A., 1991, Impact of long-term swine and poultry manure application on soil and water resources in eastern Oklahoma: Oklahoma State University Technical Bulletin, T169, 51 p.

Sharpley, A.N., Chapra, S.C., Wedepohl, Richard, Sims, J.T., Daniel, T.C., and Reddy, K.R., 1994, Managing agricultural phosphorus for protection of surface waters: Issues and options: Journal of Environmental Quality, v. 23, p. 437-451.

Sherman, L.K., and Musgrave, G.W., 1942, Infiltration, *in* Meinzer, O.E., ed., Hydrology: New York, Dover Publications, p. 244-258.

Syers, J.K., Browman, M.G., Smillie, G.W., and Corey, R.B., 1973, Phosphate sorption by soils evaluated by the Langmuir adsorption equation: Soil Science Society of America Proceedings, v. 37, p. 358-363.

Taylor, A.W., and Kunishi, H.M., 1971, Phosphate equilibria on stream sediment and soil in a watershed draining an agricultural region: Journal of Agricultural and Food Chemistry, v. 19, p. 827-831.

Thornthwaite, C.W., and Mather, J.R., 1957, Instructions and tables for computing potential evapotranspiration and the water balance: Centerton, N.J., Drexel Institute of Technology, Laboratory of Climatology, Publications in Climatology, v. 10, 311 p.

U.S. Department of Agriculture, 1992, Conestoga headwaters project - Pennsylvania - Rural clean water program - 10-year report, 1981-1991: Agricultural Stabilization and Conservation Service, 329 p.

U.S. Environmental Protection Agency, 1986, Quality criteria for water, 1986: USEPA-440/5-86-001, 256 p.

U.S. Geological Survey, 1990, National water summary 1987—Hydrologic events and water supply and use: U.S. Geological Survey Water-Supply Paper 2350, 553 p.

Whittig, L.D., and Allardice, W.R., 1986, X-ray diffraction techniques, *in* Klute, Arnold, ed., Methods of soil analysis, Part 1. Physical and mineralogical methods, Agronomy Monograph no. 9 (2nd ed.): Madison, Wis., American Society of Agronomy-Soil Science Society of America, p. 331-362.

Wischmeier, W.H., and Smith, D.D., 1978, Predicting rainfall erosion processes - a guide to conservation planning: U.S. Department of Agriculture, Agricultural Handbook no. 537, 58 p.

Witt, E.C., III, Hippe, D.J., and Giovannitti, R.M., 1992, Evaluation of nutrient quality-assurance data for Alexanders and Mount Rock Springs Basins, Cumberland County, Pennsylvania: U.S. Geological Survey Open-File Report 92-165, 31 p.

Woodruff, J.R. and Kamprath, E.J., 1965, Phosphorus adsorption maximum as measured by the Langmuir isotherm and its relationship to phosphorus availability: Soil Science Society Proceedings, v. 29, p. 148-150.

APPENDIXES

APPENDIX 1

Appendix 1. Precipitation quantity, duration, maximum intensity, and energy data at study site during study period and surface-runoff volumes for each study plot

Date	Precipitation (inches)	Storm duration (hours)	Maximum storm intensity (inches per hour)	Kinetic energy of storm (foot-tons per acre per inch of rain)	Plot 1 surface-runoff volume (liters)	Plot 2 surface-runoff volume (liters)	Plot 3 surface-runoff volume (liters)
19930401	1.19	13	0.25	6,149	0	0	105
19930410	1.37	24	.28	10,470	13	25	13
19930416	1.04	5.0	.44	3,298	14	513	297
19930421	2.52	22	.30	10,710	11	424	1,412
19930422	.02	2.0	.01	508	0	0	0
19930505	.11	2.0	.10	839	0	0	0
19930505	.11	1.0	.11	599	0	0	0
19930512	.51	1.0	.51	819	0	43	92
19930513	.04	2.0	.03	666	0	0	0
19930516	.03	3.0	.01	762	0	0	0
19930518	.22	9.0	.07	3,096	0	0	8
19930520	.08	3.0	.04	1,119	0	0	0
19930524	.03	1.0	.03	412	0	0	0
19930531	.56	3.0	.45	1,640	11	9	7
19930601	.02	2.0	.01	508	0	0	0
19930602	.03	2.0	.02	312	0	0	0
19930604	.05	1.0	.05	485	0	0	0
19930605	.02	1.0	.02	354	0	0	0
19930608	.03	8.0	.01	431	0	0	0
19930609	.17	2.0	.12	1,097	0	0	0
19930609	.10	1.0	.10	585	0	0	0
19930619	.19	2.0	.10	1,155	0	0	0
19930620	.15	2.0	.10	1,070	0	0	0
19930621	.09	3.0	.05	1,151	0	0	0
19930622	.03	1.0	.03	412	0	0	0
19930627	.05	7.0	.02	858	0	0	0
19930629	.13	15	.07	1,020	0	0	0
19930701	.04	1.0	.04	453	0	0	0
19930702	.56	11	.15	4,783	0	0	0
19930703	.03	2.0	.02	608	0	0	0
19930707	1.09	3.5	.78	2,249	47	1,232	3,301
19930714	.57	1.0	.57	935	471	356	1,215
19930719	.42	8.5	.30	2,987	0	0	0
19930726	.03	1.0	.03	412	0	0	0
19930729	.36	5.0	.33	1,419	0	0	0
19930804	.08	2.0	.04	907	0	0	0
19930806	1.46	9.0	.29	5,007	0	0	0
19930811	.08	1.0	.08	553	0	0	0
19930813	.65	2.0	.57	1,388	0	102	1,400
19930816	.24	2.0	.22	1,052	0	0	0
19930817	.43	3.0	.20	1,840	0	0	0
19930820	1.69	.7	2.52	1,049	5,034	3,823	4,296
19930828	.32	2.0	.58	1,545	0	0	0
19930904	1.75	12	.98	4,697	2,922	655	3,407
19930908	.17	3.0	.15	1,151	0	0	0

Appendix 1. Precipitation quantity, duration, maximum intensity, and energy data at study site during study period and surface-runoff volumes for each study plot—Continued

Date	Precipitation (inches)	Storm duration (hours)	Maximum storm intensity (inches per hour)	Kinetic energy of storm (foot-tons per acre per inch of rain)	Plot 1 surface-runoff volume (liters)	Plot 2 surface-runoff volume (liters)	Plot 3 surface-runoff volume (liters)
19930909	0.47	6.0	0.60	2,750	0	0	0
19930915	.67	3.0	.56	1,798	0	0	500
19930916	.05	1.0	.05	485	0	0	0
19930916	.29	7.5	.30	2,075	0	0	0
19930917	.07	5.0	.04	1,116	0	0	0
19930918	.03	2.0	.02	312	0	0	0
19930921	.26	7.5	.19	1,719	0	0	0
19930924	.02	1.0	.02	353	0	0	0
19930926	1.77	19	1.00	6,748	106	34	1,457
19931003	.44	8.0	.25	2,466	257	0	1,522
19931012	1.12	14	.30	5,011	1,590	170	4,580
19931018	.06	7.5	.03	775	0	0	0
19931020	.68	13	.27	4,653	0	0	2,101
19931021	.22	3.5	.16	1,772	0	0	0
19931030	1.42	21	.20	10,460	0	0	4,939
19931105	.03	4.0	.01	408	0	0	0
19931113	.22	18	.09	1,663	0	0	0
19931117	.23	4.0	.06	505	0	0	0
19931119	.03	1.0	.03	412	0	0	0
19931128	3.50	14	.79	9,121	32,250	17,750	31,260
19931205	3.19	30	.47	14,830	20,530	9,595	32,060
19931210	.18	5.0	.14	1,395	0	0	276
19931219	.07	3.0	.04	1,061	0	0	0
19931221	.97	15	.17	7,039	295	0	3,350
19940312[1]	1.38	27	.22	9,639	0	2,498	4,201
19940316[1]	.08	11	.04	1,080	0	0	0
19940319[1]	.24	21	.06	2,884	0	0	4,353
19940325[1]	.81	56	.14	5,420	3,123	0	34,770
19940328	2.25	69	.23	19,130	95	0	341
19940403	.07	9.0	.01	1,579	0	0	0
19940405	.02	2.0	.01	508	0	0	0
19940406	.03	7.0	.01	405	0	0	0
19940407	.48	7.0	.34	2,900	0	0	0
19940410	.32	11	.06	3,802	0	0	0
19940411	.03	10	.01	273	0	0	0
19940413	.76	10	.26	4,029	0	0	530
19940416	.38	8.0	.23	2,119	45	0	189
19940427	.15	5.0	.14	688	0	0	0
19940429	.04	4.0	.02	762	0	0	0
19940501	.27	9.5	.48	1,142	38	0	0
19940504	.22	8.0	.08	2,575	0	0	0
19940506	.05	3.0	.02	961	0	0	0
19940508	1.28	17	.30	6,641	246	0	738
19940511	.02	1.0	.02	354	0	0	0
19940512	.26	7.0	.15	1,881	0	0	0

Appendix 1. Precipitation quantity, duration, maximum intensity, and energy data at study site during study period and surface-runoff volumes for each study plot—Continued

Date	Precipitation (inches)	Storm duration (hours)	Maximum storm intensity (inches per hour)	Kinetic energy of storm (foot-tons per acre per inch of rain)	Plot 1 surface-runoff volume (liters)	Plot 2 surface-runoff volume (liters)	Plot 3 surface-runoff volume (liters)
19940516	0.09	9.0	0.05	1,144	0	0	0
19940520	.12	10	.07	1,241	0	0	0
19940520	.05	2.0	.02	386	0	0	0
19940525	1.72	3.0	1.36	3,236	5,489	246	4,315
19940606	.10	.2	.40	784	0	0	0
19940606	.25	1.5	.21	1,245	0	0	0
19940611	.10	6.0	.04	1,569	0	0	0
19940612	2.43	.3	7.36	1,203	15,560	7,248	22,560
19940619	.31	.5	.62	847	852	38	1,041
19940627	.91	6.0	.28	4,927	3,161	568	3,445
19940629	.44	.7	.97	1,683	4,278	2,044	4,542
19940630	.07	.3	.21	693	0	0	0
19940703	.17	.8	.26	1,375	0	0	0
19940706	.59	4.0	.33	2,329	0	0	114
19940709	.04	1.0	.04	453	0	0	0
19940714	2.18	5.8	2.12	3,215	6,889	5,678	9,274
19940715	.04	1.0	.04	453	0	0	0
19940718	.56	2.7	1.12	3,303	0	0	0
19940723	.81	1.0	.81	886	2,080	1,079	2,195
19940725	2.09	4.2	3.35	4,815	10,070	7,646	16,460
19940728	.07	5.0	.05	640	0	0	0
19940805	.33	3.0	.21	1,698	0	0	0
19940812	.69	.8	1.12	1,819	360	132	700
19940817	2.58	8.0	1.48	5,098	31,170	1,735	30,790
19940821	2.00	27	.34	8,919	662	0	2,422
19940824	.27	2.0	.15	1,254	0	0	0
19940827	.13	2.0	.07	1,045	0	0	0

[1] Surface runoff partially caused by snowmelt.

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APPENDIX 2

Appendix 2. Chemistry data for soil samples

[WH, whole soil sample; SA, sand; SC, silt and clay; SI, silt; CL, clay; date is month and year; lbs/acre, pounds per acre; meq/100g, milliequivalents per 100 grams; mg/kg, milligrams per kilogram; mmhos/cm, millimhos per centimeter; <, less than; --, no data]

Plot	Depth (inches)	Particle size	Date	Plant-available phosphorus (lb/acre of P_2O_5)	Exchange-able potassium (meq/ 100g)	Exchange-able magnesium (meq/100g)	Exchange-able calcium (meq/100g)	Cation exchange capacity (meq/ 100g)	Calcium, total (in percen-tage mass)	Sodium, total (in percen-tage mass)	Magnesium, total (in percen-tage mass)	Potas-sium, total (in percen-tage mass)
1	6-12	WH	493	83	0.10	1.8	8.5	10.4	0.579	0.025	1.65	1.29
1	12-24	WH	493	78	.12	1.8	6.8	8.7	.260	.019	1.67	1.18
1	0-6	WH	493	125	.15	2.2	6.5	8.8	.273	.016	1.54	.99
1	0-6	SA	493	90	.09	1.6	5.4	7.0	.267	.004	1.32	.60
1	6-12	SA	493	--	--	--	--	--	--	--	--	--
1	12-24	SA	493	--	--	--	--	--	--	--	--	--
1	0-6	SC	493	144	.15	2.2	6.5	8.8	.361	.037	1.98	1.72
1	0-6	SI	493	148	.09	1.8	6.3	8.1	.302	<.001	1.82	1.12
1	12-24	SC	493	--	--	--	--	--	--	--	--	--
1	6-12	SC	493	--	--	--	--	--	--	--	--	--
1	6-12	SI	493	81	.06	1.0	5.5	6.5	--	--	--	--
1	12-24	SI	493	76	.09	1.6	6.0	9.7	--	--	--	--
1	0-6	CL	493	--	--	--	--	--	--	--	--	--
2	6-12	WH	493	103	.09	1.3	6.0	7.4	.255	.025	1.48	1.01
2	12-24	WH	493	72	.06	1.0	4.5	5.5	.374	.027	1.59	1.12
2	0-6	WH	493	264	.15	2.3	8.8	11.2	.436	.022	1.44	1.18
2	0-6	SA	493	243	.07	1.4	7.0	8.5	.881	.005	1.30	.63
2	6-12	SA	493	--	--	--	--	--	--	--	--	--
2	12-24	SA	493	--	--	--	--	--	--	--	--	--
2	0-6	SC	493	256	.14	1.7	7.8	11.6	.414	.035	1.74	1.62
2	0-6	SI	493	230	.09	1.3	6.8	8.2	.335	<.001	1.65	1.18
2	6-12	SC	493	--	--	--	--	--	--	--	--	--
2	12-24	SC	493	--	--	--	--	--	--	--	--	--
2	6-12	SI	493	95	.06	.7	4.3	5.1	--	--	--	--
2	12-24	SI	493	64	.05	.8	3.5	4.3	--	--	--	--
2	0-6	CL	493	--	--	--	--	--	--	--	--	--
3	0-6	WH	493	273	.16	2.6	6.3	9.0	.239	.028	1.21	1.09
3	6-12	WH	493	72	.10	1.8	4.8	6.6	.163	.028	1.28	1.08
3	12-24	WH	493	43	.09	1.4	5.5	6.9	.189	.021	1.34	1.25
3	0-6	SA	493	230	.06	1.5	4.3	5.8	.200	.001	.90	.53
3	6-12	SA	493	--	--	--	--	--	--	--	--	--
3	12-24	SA	493	--	--	--	--	--	--	--	--	--
3	0-6	SC	493	256	.14	2.0	5.5	7.7	.297	.046	1.50	1.69
3	0-6	SI	493	214	.07	1.3	4.3	5.6	.230	<.001	1.44	1.31
3	12-24	SC	493	--	--	--	--	--	--	--	--	--
3	6-12	SC	493	--	--	--	--	--	--	--	--	--
3	6-12	SI	493	62	.07	1.1	3.5	6.7	--	--	--	--
3	12-24	SI	493	43	.07	.8	3.5	6.3	--	--	--	--
3	0-6	CL	493	--	--	--	--	--	--	--	--	--
1	6-12	WH	793	83	.11	2.0	8.8	10.9	.391	.011	1.72	1.52
1	12-24	WH	793	83	.10	1.5	10.0	11.6	.521	.024	1.69	1.12
1	0-6	WH	793	118	.14	2.2	7.5	9.9	.361	.021	1.67	1.24
1	12-24	SA	793	--	--	--	--	--	--	--	--	--
1	0-6	SA	793	--	--	--	--	--	--	--	--	--
1	6-12	SA	793	--	--	--	--	--	--	--	--	--
1	12-24	SI	793	--	--	--	--	--	--	--	--	--
1	6-12	SI	793	85	.07	1.2	6.3	7.5	--	--	--	--
1	0-6	SI	793	129	.09	1.5	6.0	7.6	--	--	--	--
2	6-12	WH	793	132	.10	1.4	7.0	8.5	.342	.023	1.57	1.18
2	12-24	WH	793	103	.07	1.3	6.5	7.9	.315	.024	1.73	1.41

Appendix 2. Chemistry data for soil samples—Continued

Plot	Iron, total (in percentage mass)	Aluminum, total (in percentage mass)	Phosphorus, total (in percentage mass)	Phosphorus, organic (mg/kg)	Phosphorus, inorganic (mg/kg)	Exchangeable aluminum (mg/kg of Al)	Exchangeable sodium (mg/kg of Na)	pH (standard units)	Electrical conductivity (mmhos/cm)	Carbon, total, organic (in percentage mass)	Free iron oxides (in percentage mass)
1	4.44	4.28	0.114	278	848	0.4	16.4	7.3	0.7	0.41	1.80
1	4.46	4.22	.109	45	1,045	.4	11.6	7.0	.3	.22	2.62
1	3.79	3.97	.103	219	811	.1	11.4	7.0	1.0	.88	2.35
1	2.66	2.32	.100	501	504	34	2.6	--	.2	.65	.92
1	--	--	.063	132	498	--	--	--	--	--	--
1	--	--	.071	164	546	--	--	--	--	--	--
1	5.02	5.73	.150	565	935	2.2	8.8	--	.8	1.00	2.06
1	4.17	4.53	.117	355	815	1.1	3.6	--	.1	.80	1.08
1	--	--	.148	438	1,037	--	--	--	--	--	--
1	--	--	.145	510	940	--	--	--	--	--	--
1	--	--	.090	254	646	--	--	--	--	--	--
1	--	--	.102	232	788	--	--	--	--	--	--
1	--	--	.339	1,546	1,844	--	--	--	--	--	--
2	5.00	4.06	.101	200	810	.1	18.4	7.2	.6	.45	2.94
2	4.55	3.99	.113	250	880	.2	18.0	7.2	.3	.23	2.68
2	4.15	4.15	.132	470	850	.1	15.9	7.2	1.1	.98	2.93
2	3.03	2.54	.085	228	622	4.9	5.1	--	.3	.50	.82
2	--	--	.062	154	466	--	--	--	--	--	--
2	--	--	.069	146	542	--	--	--	--	--	--
2	4.62	5.63	.153	567	963	1.5	8.2	--	.8	.90	1.61
2	3.67	4.50	.112	343	777	1.2	3.3	--	.3	.70	.90
2	--	--	.157	593	977	--	--	--	--	--	--
2	--	--	.154	549	991	--	--	--	--	--	--
2	--	--	.093	209	721	--	--	--	--	--	--
2	--	--	.109	219	871	--	--	--	--	--	--
2	--	--	.348	1,430	2,050	--	--	--	--	--	--
3	3.90	4.61	.127	258	1,012	.1	17.8	6.9	1.1	1.10	2.87
3	4.28	4.78	.091	339	571	.2	18.6	6.9	.4	.51	3.59
3	4.68	4.67	.087	298	572	.2	16.3	7.2	.4	.35	3.59
3	3.59	2.21	.101	428	582	3.2	.8	--	.1	.70	1.08
3	--	--	.046	145	320	--	--	--	--	--	--
3	--	--	.053	177	353	--	--	--	--	--	--
3	4.47	6.50	.163	681	949	1.8	18.9	--	.8	.90	1.91
3	3.26	4.74	.099	418	572	.3	3.6	--	.3	.80	.74
3	--	--	.112	429	696	--	--	--	--	--	--
3	--	--	.128	583	697	--	--	--	--	--	--
3	--	--	.068	254	426	--	--	--	--	--	--
3	--	--	.066	240	420	--	--	--	--	--	--
3	--	--	.333	1,439	1,891	--	--	--	--	--	--
1	5.10	4.86	.104	260	785	.4	15.1	7.1	.7	.47	2.85
1	4.21	3.88	.111	170	940	.2	14.4	7.3	.7	.27	2.38
1	4.42	4.31	.114	99	1,041	.1	14.0	7.1	.7	.92	2.46
1	--	--	.072	106	614	--	--	--	--	--	--
1	--	--	.064	191	449	--	--	--	--	--	--
1	--	--	.060	113	487	--	--	--	--	--	--
1	--	--	.117	294	876	--	--	--	--	--	--
1	--	--	.100	270	730	--	--	--	--	--	--
1	--	--	.116	362	798	--	--	--	--	--	--
2	4.83	4.35	.113	327	803	.1	19.3	7.3	.7	.55	3.09
2	4.20	4.52	.126	124	1,136	.1	21.1	7.2	.7	.26	2.70

Appendix 2. Chemistry data for soil samples—Continued

Plot	Depth (inches)	Particle size	Date	Plant-available phosphorus (lb/acre of P_2O_5)	Exchangeable potassium (meq/100g)	Exchangeable magnesium (meq/100g)	Exchangeable calcium (meq/100g)	Cation exchange capacity (meq/100g)	Calcium, total (in percentage mass)	Sodium, total (in percentage mass)	Magnesium, total (in percentage mass)	Potassium, total (in percentage mass)
2	0-6	WH	793	282	0.17	2.4	8.0	10.5	0.407	0.027	1.48	0.97
2	12-24	SA	793	--	--	--	--	--	--	--	--	--
2	6-12	SA	793	--	--	--	--	--	--	--	--	--
2	0-6	SA	793	--	--	--	--	--	--	--	--	--
2	12-24	SI	793	--	--	--	--	--	--	--	--	--
2	0-6	SI	793	256	.09	1.5	6.8	8.3	--	--	--	--
2	6-12	SI	793	125	.06	.8	5.5	6.4	--	--	--	--
3	6-12	WH	793	109	.15	2.0	4.8	8.9	.163	.031	1.24	.87
3	12-24	WH	793	63	.12	1.5	4.8	6.4	.179	.019	1.48	1.03
3	0-6	WH	793	300	.34	2.9	6.3	11.4	.232	.032	1.26	1.06
3	0-6	SA	793	--	--	--	--	--	--	--	--	--
3	6-12	SA	793	--	--	--	--	--	--	--	--	--
3	12-24	SA	793	--	--	--	--	--	--	--	--	--
3	12-24	SI	793	--	--	--	--	--	--	--	--	--
3	6-12	SI	793	--	--	--	--	--	--	--	--	--
3	0-6	SI	793	--	--	--	--	--	--	--	--	--
1	0-6	WH	1093	112	.14	2.6	6.5	9.2	.325	.009	1.60	.73
1	6-12	WH	1093	83	.10	2.0	5.8	7.8	.306	.022	1.72	.09
1	12-24	WH	1093	83	.09	1.6	8.8	10.4	.488	.019	1.78	.84
1	0-6	SA	1093	72	.06	1.4	4.5	5.9	.213	<.001	1.27	.57
1	6-12	SA	1093	--	--	--	--	--	--	--	--	--
1	12-24	SA	1093	--	--	--	--	--	--	--	--	--
1	0-6	SC	1093	148	.14	2.1	6.5	8.7	.355	.035	1.98	1.64
1	0-6	SI	1093	132	.07	1.7	5.5	7.3	.295	<.001	1.87	1.16
1	6-12	SC	1093	--	--	--	--	--	--	--	--	--
1	12-24	SC	1093	--	--	--	--	--	--	--	--	--
1	12-24	SI	1093	83	.06	1.0	7.0	10.1	--	--	--	--
1	6-12	SI	1093	72	.06	1.2	4.3	7.5	--	--	--	--
1	0-6	CL	1093	--	--	--	--	--	--	--	--	--
2	6-12	WH	1093	88	.11	1.5	6.3	7.8	.286	.025	1.59	.87
2	12-24	WH	1093	78	.08	1.1	10.6	11.8	.639	.018	1.64	.89
2	0-6	WH	1093	282	.23	2.5	8.5	11.2	.354	.014	1.43	.75
2	0-6	SA	1093	198	.07	1.2	5.5	6.8	.509	<.001	1.08	.51
2	12-24	SA	1093	--	--	--	--	--	--	--	--	--
2	6-12	SA	1093	--	--	--	--	--	--	--	--	--
2	0-6	SC	1093	282	.17	2.0	7.3	9.4	.378	.035	1.69	1.38
2	0-6	SI	1093	230	.09	1.4	5.8	7.2	.309	<.001	1.62	1.19
2	6-12	SC	1093	--	--	--	--	--	--	--	--	--
2	12-24	SC	1093	--	--	--	--	--	--	--	--	--
2	6-12	SI	1093	85	.06	.8	4.8	5.6	--	--	--	--
2	12-24	SI	1093	83	.05	.5	8.3	8.8	--	--	--	--
2	0-6	CL	1093	--	--	--	--	--	--	--	--	--
3	12-24	WH	1093	44	.09	1.4	4.5	6.0	.136	.023	1.30	.83
3	6-12	WH	1093	81	.12	1.9	4.8	8.8	.147	.027	1.19	.95
3	0-6	WH	1093	310	.26	2.5	6.0	8.7	.231	.028	1.16	.96
3	0-6	SA	1093	191	.07	.9	2.8	5.7	.152	<.001	.78	.46
3	12-24	SA	1093	--	--	--	--	--	--	--	--	--
3	6-12	SA	1093	--	--	--	--	--	--	--	--	--
3	0-6	SC	1093	310	.25	2.4	6.0	8.6	.286	.044	1.46	1.70
3	0-6	SI	1093	282	.14	1.6	4.8	6.5	.241	<.001	1.42	1.25

Appendix 2. Chemistry data for soil samples—Continued

Plot	Iron, total (in percentage mass)	Aluminum, total (in percentage mass)	Phosphorus, total (in percentage mass)	Phosphorus, organic (mg/kg)	Phosphorus, inorganic (mg/kg)	Exchangeable aluminum (mg/kg of Al)	Exchangeable sodium (mg/kg of Na)	pH (standard units)	Electrical conductivity (mmhos/cm)	Carbon, total, organic (in percentage mass)	Free iron oxides (in percentage mass)
2	4.06	4.38	0.127	353	917	0.2	21.9	7.1	1.4	0.83	2.80
2	--	--	.086	252	612	--	--	--	--	--	--
2	--	--	.062	135	485	--	--	--	--	--	--
2	--	--	.074	185	555	--	--	--	--	--	--
2	--	--	.122	298	922	--	--	--	--	--	--
2	--	--	.119	420	770	--	--	--	--	--	--
2	--	--	.102	317	703	--	--	--	--	--	--
3	4.27	4.72	.106	410	650	.2	31.5	6.2	2.0	.64	3.21
3	4.52	4.59	.096	268	692	.2	16.4	6.3	1.2	.30	3.16
3	4.20	4.58	.132	347	973	.2	48.9	6.4	3.5	.95	2.96
3	--	--	.084	287	553	--	--	--	--	--	--
3	--	--	.068	316	364	--	--	--	--	--	--
3	--	--	.064	238	402	--	--	--	--	--	--
3	--	--	.076	219	541	--	--	--	--	--	--
3	--	--	.087	303	567	--	--	--	--	--	--
3	--	--	.104	366	669	--	--	--	--	--	--
1	4.06	3.98	.106	136	924	.2	7.9	7.2	.5	.82	2.52
1	4.53	4.26	.108	200	884	.2	10.8	6.8	.3	.33	2.46
1	4.26	3.81	.115	140	1,010	.4	8.6	7.4	.3	.16	2.27
1	2.52	2.15	.071	168	542	3.0	.4	--	.3	.50	.68
1	--	--	.066	114	546	--	--	--	--	--	--
1	--	--	.088	93	787	--	--	--	--	--	--
1	5.07	5.72	.153	622	908	2.4	10.0	--	.3	1.10	1.40
1	4.16	4.65	.111	371	739	1.1	3.3	--	.1	.80	.97
1	--	--	.164	516	1,124	--	--	--	--	--	--
1	--	--	.173	349	1,381	--	--	--	--	--	--
1	--	--	.128	248	1,032	--	--	--	--	--	--
1	--	--	.099	254	736	--	--	--	--	--	--
1	--	--	.308	1,171	1,909	--	--	--	--	--	--
2	4.06	4.29	.105	383	667	.2	33.9	7.2	1.2	.48	2.47
2	4.02	3.97	.107	241	829	.1	19.5	7.6	.8	.27	2.68
2	3.96	4.06	.123	279	951	.2	27.1	7.3	.8	1.10	2.69
2	2.64	2.11	.077	196	574	5.1	4.4	--	.3	.80	.59
2	--	--	.090	301	599	--	--	--	--	--	--
2	--	--	.059	195	395	--	--	--	--	--	--
2	4.77	5.65	.155	569	981	1.4	24.3	--	.6	1.00	2.01
2	3.57	4.48	.107	359	711	1.3	5.6	--	.3	.80	1.30
2	--	--	.152	536	980	--	--	--	--	--	--
2	--	--	.158	438	1,142	--	--	--	--	--	--
2	--	--	.091	260	650	--	--	--	--	--	--
2	--	--	.114	264	876	--	--	--	--	--	--
2	--	--	.355	1,462	2,088	--	--	--	--	--	--
3	4.51	4.71	.083	213	617	.1	21.5	6.7	.8	.17	3.21
3	3.85	4.29	.086	313	547	.1	40.3	6.5	1.4	.42	3.04
3	3.72	4.50	.129	414	876	.2	35.2	6.7	.9	.95	2.58
3	2.79	1.87	.080	207	593	5.5	1.4	--	.4	.60	.62
3	--	--	.042	135	285	--	--	--	--	--	--
3	--	--	.054	185	355	--	--	--	--	--	--
3	4.54	6.45	.174	713	1,032	2.7	28.4	--	.6	1.15	1.42
3	3.77	5.02	.127	553	717	1.1	8.5	--	.1	.90	.94

Appendix 2. Chemistry data for soil samples—Continued

Plot	Depth (inches)	Particle size	Date	Plant-available phosphorus (lb/acre of P_2O_5)	Exchange-able potassium (meq/100g)	Exchange-able magnesium (meq/100g)	Exchange-able calcium (meq/100g)	Cation exchange capacity (meq/100g)	Calcium, total (in percen-tage mass)	Sodium, total (in percen-tage mass)	Magnesium, total (in percen-tage mass)	Potas-sium, total (in percen-tage mass)
3	6-12	SC	1093	--	--	--	--	--	--	--	--	--
3	12-24	SC	1093	--	--	--	--	--	--	--	--	--
3	6-12	SI	1093	68	0.09	1.0	3.3	6.4	--	--	--	--
3	12-24	SI	1093	43	.09	.9	3.5	6.5	--	--	--	--
3	0-6	CL	1093	--	--	--	--	--	--	--	--	--
1	6-12	WH	494	95	.09	1.8	6.3	8.1	--	--	--	--
1	12-24	WH	494	81	.09	2.0	9.3	11.3	--	--	--	--
1	0-6	WH	494	118	.14	2.3	7.8	10.2	--	--	--	--
2	6-12	WH	494	103	.10	1.4	6.8	8.2	--	--	--	--
2	12-24	WH	494	83	.09	1.2	9.0	10.3	--	--	--	--
2	0-6	WH	494	282	.20	2.3	7.9	10.4	--	--	--	--
3	0-6	WH	494	320	.35	2.4	6.3	11.0	--	--	--	--
3	12-24	WH	494	58	.07	1.2	4.5	7.8	--	--	--	--
3	6-12	WH	494	83	.14	1.8	4.3	8.2	--	--	--	--
1	0-6	WH	794	109	.12	2.1	7.3	9.5	--	--	--	--
1	6-12	WH	794	85	.10	1.9	7.8	9.8	--	--	--	--
1	12-24	WH	794	88	.09	1.6	9.8	11.5	--	--	--	--
2	0-6	WH	794	292	.23	2.2	7.3	11.7	--	--	--	--
2	6-12	WH	794	129	.12	1.6	7.3	8.9	--	--	--	--
2	12-24	WH	794	70	.09	1.1	13.3	14.5	--	--	--	--
3	12-24	WH	794	66	.10	1.2	3.6	5.9	--	--	--	--
3	0-6	WH	794	451	.56	2.8	6.5	11.9	--	--	--	--
3	6-12	WH	794	125	.24	1.9	4.8	8.9	--	--	--	--

Appendix 2. Chemistry data for soil samples—Continued

Plot	Iron, total (in percentage mass)	Aluminum, total (in percentage mass)	Phosphorus, total (in percentage mass)	Phosphorus, organic (mg/kg)	Phosphorus, inorganic (mg/kg)	Exchangeable aluminum (mg/kg of Al)	Exchangeable sodium (mg/kg of Na)	pH (standard units)	Electrical conductivity (mmhos/cm)	Carbon, total, organic (in percentage mass)	Free iron oxides (in percentage mass)
3	--	--	0.135	539	811	--	--	--	--	--	--
3	--	--	.125	521	729	--	--	--	--	--	--
3	--	--	.069	254	436	--	--	--	--	--	--
3	--	--	.087	390	480	--	--	--	--	--	--
3	--	--	.334	1,346	1,994	--	--	--	--	--	--
1	--	--	.109	87	1,003	--	--	--	0.3	0.35	--
1	--	--	.114	86	1,054	--	--	--	.4	.24	--
1	--	--	.113	207	923	--	--	--	.4	.91	--
2	--	--	.108	334	746	--	--	--	.6	.42	--
2	--	--	.107	133	939	--	--	--	.7	.31	--
2	--	--	.122	160	1,059	--	--	--	.8	.87	--
3	--	--	.142	248	1,172	--	--	--	.7	1.01	--
3	--	--	.091	313	597	--	--	--	1.0	.15	--
3	--	--	.095	111	839	--	--	--	.9	1.41	--
1	--	--	.102	143	877	--	--	--	.6	.81	--
1	--	--	.103	47	983	--	--	--	.4	.50	--
1	--	--	.108	236	844	--	--	--	.4	.19	--
2	--	--	.125	269	981	--	--	--	1.0	.98	--
2	--	--	.097	144	826	--	--	--	.7	.59	--
2	--	--	.120	112	1,088	--	--	--	.6	.39	--
3	--	--	.088	93	784	--	--	--	1.0	.26	--
3	--	--	.140	205	1,195	--	--	--	2.9	1.21	--
3	--	--	.103	173	857	--	--	--	1.3	.50	--

APPENDIX 3

Appendix 3. Water-quality data for precipitation, surface-runoff, and subsurface-flow samples

[Site variable is local identifier; PRE is precipitation station; 1SR and 1SS are surface-runoff and subsurface-flow stations, respectively, for plot 1; 2SR and 2SS are surface-runoff and subsurface-flow stations, respectively, for plot 2; 3SR and 3SS are surface-runoff and subsurface-flow stations, respectively, for plot 3; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; °C, degrees Celsius; µg/L, micrograms per liter; mm, millimeters; --, no data]

Site	Date	Time	Phosphorus, total (mg/L as P)	Phosphorus, dissolved (mg/L as P)	Phosphorus, ortho, dissolved (mg/L as P)	Phosphorus, hydrolyzable and ortho, dissolved (mg/L as P)	Phosphorus, hydrolyzable and ortho, total (mg/L as P)	Specific conductance (µS/cm)	pH, whole water field (standard units)	Temperature, water (°C)
3SR	19930402	0800	1.9	0.43	--	0.59	1.3	41	7.00	12.6
3SS	19930402	0830	--	.26	--	.40	--	165	7.00	17.9
PRE	19930402	1200	.16	--	--	--	--	20	5.05	12.0
3SR	19930411	0715	150	.32	--	.37	170	105	7.05	18.0
3SS	19930411	0730	--	.31	--	.34	--	177	7.35	9.3
2SR	19930411	0830	1.8	.43	--	.48	--	98	7.05	19.9
1SR	19930411	0915	2.1	.13	--	.18	4.8	62	7.30	17.8
PRE	19930411	0945	.08	--	--	--	--	16	6.45	18.4
3SR	19930417	0800	1.7	.84	--	.85	5.2	55	7.00	19.9
2SR	19930417	1000	1.6	.85	--	.83	5.2	54	6.90	18.9
2SS	19930417	1030	--	.14	--	.12	--	66	--	--
1SR	19930417	1130	2.7	.16	--	.11	7.0	75	7.10	19.6
1SS	19930417	1200	--	.37	--	.34	--	54	6.75	--
1SS	19930422	1045	--	.28	--	.23	--	31	6.85	19.5
3SR	19930513	0800	1.7	1.0	--	.72	3.4	156	7.15	14.6
2SR	19930513	1000	2.1	1.6	--	1.2	1.6	191	7.08	15.2
3SR	19930519	0800	38	20	--	21	100	1,480	7.45	14.8
PRE	19930519	0900	.09	--	--	--	.05	52	4.50	17.7
3SR	19930601	0745	140	4.7	--	5.0	140	378	7.45	16.4
2SR	19930601	0815	.72	.56	--	.47	.66	222	7.70	14.6
1SR	19930601	0900	.76	.30	--	3.0	.53	101	6.55	14.9
PRE	19930601	0915	.10	--	--	--	.06	24	5.55	14.7
PRE	19930630	1000	.13	--	--	--	--	--	--	--
3SR	19930708	0800	.99	.78	--	.81	.75	125	6.35	26.2
3SS	19930708	0830	--	4.7	--	2.1	--	4,120	6.65	24.4
2SR	19930708	1000	.93	.36	--	.32	1.1	115	6.60	26.4
2SS	19930708	1030	--	.32	--	.31	--	219	7.05	29.3
1SR	19930708	1300	.81	.73	--	.76	.69	69	6.55	24.7
PRE	19930708	1400	.08	--	--	--	.07	44	3.95	27.1
3SR	19930715	0800	5.0	.67	--	.72	.84	130	6.50	23.9
2SR	19930715	1000	1.2	.73	--	.79	.03	95	6.70	23.6
1SR	19930715	1200	.98	.29	--	.31	.63	88	6.50	23.2
1SS	19930715	1215	--	.55	--	.53	--	--	--	--
PRE	19930715	1330	.13	--	--	--	--	52	4.00	21.0
2SS	19930807	0930	--	1.2	1.1	--	--	174	7.60	28.7
PRE	19930807	1030	.01	--	--	--	--	19	4.35	27.7
3SR	19930814	1030	.60	.48	.21	--	--	76	6.25	22.5
2SR	19930814	1200	.50	.48	.21	--	--	82	6.45	22.0
PRE	19930818	0900	.09	--	--	--	--	76	3.85	25.4
2SS	19930818	0900	--	.90	.87	--	--	--	--	--

Appendix 3. Water-quality data for precipitation, surface-runoff, and subsurface-flow samples—Continued

Site	Date	Carbon, organic, total (mg/L as C)	Carbon, organic, dissolved (mg/L as C)	Calcium, total (mg/L as Ca)	Calcium, dissolved (mg/L as Ca)	Magnesium, total (mg/L as Mg)	Magnesium, dissolved (mg/L as Mg)	Sodium, total (mg/L as Na)	Sodium, dissolved (mg/L as Na)
3SR	19930402	23.5	--	25.5	4.1	32	1.7	0.5	--
3SS	19930402	--	4.2	--	19	--	7.7	--	1.8
PRE	19930402	5.9	--	.3	--	.05	--	2.1	--
3SR	19930411	870	--	320	12	190	4.4	1.7	.9
3SS	19930411	--	4.1	--	19	--	8.3	--	2.0
2SR	19930411	600	--	140	10	170	2.6	.8	.4
1SR	19930411	500	--	90	7.4	190	1.9	.8	.5
PRE	19930411	8.0	--	.3	--	.05	--	2.2	--
3SR	19930417	140	--	18	4.4	31	2.2	1.0	.9
2SR	19930417	82	--	12	4.3	22	1.6	.8	.8
2SS	19930417	--	--	--	--		--	--	--
1SR	19930417	690	--	120	7.4	140	2.5	1.6	1.3
1SS	19930417	--	--	--	--	--	--	--	--
1SS	19930422	--	3.1	--	2.7	--	1.0	--	.2
3SR	19930513	250	18	59	10	70	4.3	1.5	1.4
2SR	19930513	230	31	47	13	58	4.0	1.1	1.0
3SR	19930519	830	--	130	19	65	17	66	69
PRE	19930519	21	--	.8	--	.20	--	3.1	--
3SR	19930601	560	--	200	--	110	--	13	--
2SR	19930601	300	--	400	32	150	5.9	2.0	1.9
1SR	19930601	480	--	72	9.0	120	2.9	.9	.7
PRE	19930601	12	--	1.2	--	.40	--	1.3	--
PRE	19930630	--	--	--	--	--	--	--	--
3SR	19930708	21	--	9.8	8.5	9.2	3.1	1.5	1.6
3SS	19930708	--	23	--	450	--	170	--	91
2SR	19930708	48	--	14	9.7	21	2.7	.8	1.6
2SS	19930708	--	11	--	26	--	3.8	--	1.8
1SR	19930708	200	--	34	9.7	91	1.8	.4	.3
PRE	19930708	45	--	.4	--	.10	--	1.1	--
3SR	19930715	24	--	14	10	13	3.5	1.1	1.3
2SR	19930715	85	--	28	8.0	51	2.6	.6	.6
1SR	19930715	480	--	16	7.0	46	2.7	.3	.4
1SS	19930715	--	--	--	--	--	--	--	--
PRE	19930715	--	--	--	--	--	--	--	--
2SS	19930807	--	--	--	--	--	--	--	--
PRE	19930807	--	--	--	--	--	--	--	--
3SR	19930814	20	--	5	4.5	5.8	2.1	.3	.3
2SR	19930814	49	--	6.9	4.6	16	2.1	.2	.2
PRE	19930818	6.5	--	.4	--	.05	--	1.0	--
2SS	19930818	--	--	--	--	--	--	--	--

Appendix 3. Water-quality data for precipitation, surface-runoff, and subsurface-flow samples—Continued

Site	Date	Potassium, total (mg/L as K)	Potassium, dissolved (mg/L as K)	Iron, total (µg/L as Fe)	Iron, dissolved (µg/L as Fe)	Aluminum, total (µg/L as Al)	Aluminum, dissolved (µg/L as Al)	Sediment, suspended (mg/L)	Sediment, suspended fall diameter (percentage finer than 0.004 mm)	Sediment, suspended fall diameter (percentage finer than 0.062 mm)
3SR	19930402	8.7	1.5	90,000	140	28,000	120	6,960	36.39	95.93
3SS	19930402	--	1.2	--	180	--	170	--	--	--
PRE	19930402	.1	--	100	--	40	--	--	--	--
3SR	19930411	26	2.3	160,000	100	310,000	220	74,000	26.97	81.15
3SS	19930411	--	1.3	--	390	--	410	--	--	--
2SR	19930411	22	4.8	160,000	430	220,000	290	35,200	17.11	77.43
1SR	19930411	14	1.5	220,000	320	280,000	190	38,200	16.86	61.07
PRE	19930411	.1	--	70	--	7	--	--	--	--
3SR	19930417	8.4	3.3	62,000	240	56,000	280	5,940	48.98	98.25
2SR	19930417	8.6	5.4	37,000	660	32,000	680	2,860	42.19	98.14
2SS	19930417	--	--	--	--	--	--	--	--	--
1SR	19930417	15	2.0	140,000	200	220,000	400	26,000	21.13	71.28
1SS	19930417	--	--	--	--	--	--	--	--	--
1SS	19930422	--	1.6	--	100	--	70	--	--	--
3SR	19930513	27	15	140,000	580	110,000	540	16,000	25.22	89.48
2SR	19930513	36	26	87,000	750	79,000	600	12,500	25.06	85.10
3SR	19930519	160	130	110,000	190	77,000	40	7,660	36.27	90.27
PRE	19930519	.2	--	170	--	530	--	--	--	--
3SR	19930601	6.3	--	160,000	--	200,000	--	51,600	27.15	95.19
2SR	19930601	18	6.1	160,000	310	200,000	360	84,100	15.72	71.36
1SR	19930601	11	6.5	180,000	250	180,000	180	27,500	14.88	74.49
PRE	19930601	--	40	--	40	--	--	--	--	--
PRE	19930630	--	--	--	--	--	--	--	--	--
3SR	19930708	4.9	3.5	18,000	140	14,000	90	4,100	59.90	98.99
3SS	19930708	--	49	--	5	--	20	--	--	--
2SR	19930708	1.0	3.4	39,000	130	96,000	140	9,430	38.25	98.08
2SS	19930708	--	6.9	--	130	--	90	--	--	--
1SR	19930708	1.1	2.5	130,000	370	300,000	260	74,950	25.49	85.15
PRE	19930708	1.6	--	20	--	30	--	--	--	--
3SR	19930715	5.0	3.8	28,000	140	20,000	80	7,310	45.30	96.02
2SR	19930715	9.7	3.6	83,000	300	83,000	200	54,600	29.69	84.98
1SR	19930715	8.5	2.8	79,000	240	76,000	110	20,900	45.33	99.08
1SS	19930715	--	--	--	--	--	--	--	--	--
PRE	19930715	--	--	--	--	--	--	--	--	--
2SS	19930807	--	--	--	--	--	--	--	--	--
PRE	19930807	--	--	--	--	--	--	--	--	--
3SR	19930814	5.6	5.0	9,100	110	7,700	100	481	46.26	98.39
2SR	19930814	8.9	6.8	23,000	430	20,000	100	1,180	10.96	98.92
PRE	19930818	.2	--	130	--	30	--	--	--	--
2SS	19930818	--	--	--	--	--	--	--	--	--

Appendix 3. Water-quality data for precipitation, surface-runoff, and subsurface-flow samples—Continued

Site	Date	Time	Phosphorus, total (mg/L as P)	Phosphorus, dissolved (mg/L as P)	Phosphorus, ortho, dissolved (mg/L as P)	Phosphorus, hydrolyzable and ortho, dissolved (mg/L as P)	Phosphorus, hydrolyzable and ortho, total (mg/L as P)	Specific conductance (µS/cm)	pH, whole water field (standard units)	Temperature, water (°C)
3SR	19930821	0900	0.72	0.52	0.52	--	--	74	6.35	20.9
3SS	19930821	1000	--	1.6	1.4	--	--	2,400	7.05	18.2
2SR	19930821	1100	.82	.61	.58	--	--	57	6.55	19.6
2SS	19930821	1200	--	.51	.48	--	--	94	7.35	17.7
1SR	19930821	1300	.58	.42	.38	--	--	107	6.95	18.3
1SS	19930821	1400	--	.28	.25	--	--	71	6.38	23.9
PRE	19930821	1500	.03	--	--	--	--	18	--	--
3SR	19930905	0730	.77	.65	.66	--	--	73	6.25	17.8
3SS	19930905	0800	--	1.4	1.4	--	--	2,910	6.85	10.5
2SR	19930905	1000	.82	.69	.71	--	--	79	6.50	18.1
1SR	19930905	1300	.45	.35	.35	--	--	45	6.25	11.6
1SS	19930905	1330	--	.42	.42	--	--	88	6.65	14.2
PRE	19930905	1500	.02	--	--	--	--	17	4.55	14.1
3SR	19930916	0800	1.3	1.0	.96	--	--	113	6.55	19.2
3SS	19930916	0830	--	2.5	2.3	--	--	621	7.40	19.5
2SS	19930916	0930	--	.66	.68	--	--	129	6.70	19.3
3SR	19930927	0800	1.1	.72	.74	--	--	110	6.55	18.4
3SS	19930927	0830	--	1.2	1.2	--	--	1,360	6.65	14.1
2SR	19930927	0930	1.3	.64	.65	--	--	89	7.05	16.0
2SS	19930927	1000	--	.49	.51	--	--	160	6.90	16.9
1SR	19930927	1030	1.5	1.0	1.1	--	--	111	7.00	14.8
PRE	19930927	1100	.03	--	--	--	--	20	4.50	16.8
1SS	19930927	1130	--	.14	.13	--	--	112	6.95	14.7
3SR	19931004	0800	5.1	.89	.75	--	--	475	6.97	16.1
3SS	19931004	0900	--	1.3	1.2	--	--	913	7.03	13.1
2SS	19931004	0945	--	.96	.95	--	--	279	7.12	12.0
1SR	19931004	1000	9.6	1.1	1.0	--	--	246	6.49	16.2
PRE	19931004	1100	.04	--	--	--	--	33	4.09	15.6
3SR	19931013	0730	1.8	.60	.59	--	--	213	6.42	12.9
3SS	19931013	0830	--	1.3	1.3	--	--	658	6.53	13.5
2SR	19931013	0930	1.7	.54	.53	--	--	108	6.46	13.3
2SS	19931013	1030	--	.75	.72	--	--	292	6.39	13.6
1SR	19931013	1130	1.5	.48	.47	--	--	52	6.29	13.9
1SS	19931013	1230	--	.55	.56	--	--	100	6.29	11.4
3SR	19931021	0800	1.5	.64	.63	--	--	205	6.71	16.6
3SS	19931021	0830	--	1.3	1.3	--	--	496	6.75	15.5
2SS	19931021	1000	--	.60	.59	--	--	215	6.67	15.3
3SR	19931031	0800	.53	.52	.53	--	--	139	6.73	10.1
3SS	19931031	0900	--	1.3	1.0	--	--	450	6.75	10.4
2SS	19931031	1000	--	.63	.60	--	--	174	6.67	10.9

Appendix 3. Water-quality data for precipitation, surface-runoff, and subsurface-flow samples—Continued

Site	Date	Carbon, organic, total (mg/L as C)	Carbon, organic, dissolved (mg/L as C)	Calcium, total (mg/L as Ca)	Calcium, dissolved (mg/L as Ca)	Magnesium, total (mg/L as Mg)	Magnesium, dissolved (mg/L as Mg)	Sodium, total (mg/L as Na)	Sodium, dissolved (mg/L as Na)
3SR	19930821	22	--	6.3	5.2	7.1	2.2	0.6	0.7
3SS	19930821	--	15	--	300	--	110	--	64
2SR	19930821	25	--	6.2	4.1	12	1.6	.2	.2
2SS	19930821	--	6.7	--	11	--	1.9	--	.5
1SR	19930821	28	--	11	8.5	13	3.0	.7	.7
1SS	19930821	--	4.9	--	6.2	--	2.5	--	.4
PRE	19930821	--	--	--	--	--	--	--	--
3SR	19930905	30	--	6.3	5.0	9.2	2.5	.4	.5
3SS	19930905	--	14	--	310	--	120	--	76
2SR	19930905	90	--	12	5.3	30	2.5	.5	.6
1SR	19930905	16	--	4.0	3.6	8.5	1.5	.2	.4
1SS	19930905	--	7.9	--	8.2	--	3.6	--	.5
PRE	19930905	--	--	--	--	--	--	--	--
3SR	19930916	49	--	9.4	6.5	15	3.7	.5	.7
3SS	19930916	--	11	--	58	--	23	--	11
2SS	19930916	--	10	--	12	--	3.1	--	.3
3SR	19930927	2.9	--	6.8	5.4	8.8	3.2	.5	.6
3SS	19930927	--	12	--	150	--	55	--	35
2SR	19930927	110	--	41	5.9	65	2.7	.3	.3
2SS	19930927	--	10	--	18	--	3.8	--	1.9
1SR	19930927	70	--	10	6.1	23	2.9	.9	.9
PRE	19930927	3.7	--	.05	--	.05	--	.7	--
1SS	19930927	--	12	--	13	--	5.5	--	.9
3SR	19931004	64	--	23	21	26	17	1.0	1.4
3SS	19931004	--	15	--	82	--	34	--	23
2SS	19931004	--	21	--	22	--	7.6	--	.7
1SR	19931004	110	--	19	13	48	9.0	.4	.4
PRE	19931004	--	--	--	--	--	--	--	--
3SR	19931013	23	--	12	10	14	7.1	1.4	1.1
3SS	19931013	--	13	--	60	--	24	--	15
2SR	19931013	20	--	13	5.9	20	3.6	.3	.5
2SS	19931013	--	31	--	22	--	9.1	--	.5
1SR	19931013	31	--	4.9	3.1	14	2.0	1.0	.3
1SS	19931013	--	9.4	--	8.6	--	3.8	--	.6
3SR	19931021	26	--	11	11	11	6.8	1.2	1.3
3SS	19931021	--	11	--	46	--	18	--	12
2SS	19931021	--	18	--	18	--	6.7	--	.6
3SR	19931031	12	--	7.2	7.7	6.7	4.6	1.3	1.3
3SS	19931031	--	8.9	--	42	--	18	--	9.9
2SS	19931031	--	14	--	1.2	--	2.2	--	.4

Appendix 3. Water-quality data for precipitation, surface-runoff, and subsurface-flow samples—Continued

Site	Date	Potassium, total (mg/L as K)	Potassium, dissolved (mg/L as K)	Iron, total (µg/L as Fe)	Iron, dissolved (µg/L as Fe)	Aluminum, total (µg/L as Al)	Aluminum, dissolved (µg/L as Al)	Sediment, suspended (mg/L)	Sediment, suspended fall diameter (percentage finer than 0.004 mm)	Sediment, suspended fall diameter (percentage finer than 0.062 mm)
3SR	19930821	4.1	3.8	13,000	70	12,000	85	425	--	99.04
3SS	19930821	--	23	--	10	--	5	--	--	--
2SR	19930821	5.6	4.6	21,000	110	18,000	140	1,350	41.85	98.80
2SS	19930821	--	4.8	--	160	--	190	--	--	--
1SR	19930821	8.4	7.7	19,000	110	18,000	150	701	--	97.88
1SS	19930821	--	2.3	--	45	--	20	--	--	--
PRE	19930821	--	--	--	--	--	--	--	--	--
3SR	19930905	5.9	1.2	19,000	180	16,000	350	1,360	49.18	99.60
3SS	19930905	--	--	--	5	--	10	--	--	--
2SR	19930905	8.5	9.0	49,000	240	44,000	400	4,390	36.33	98.85
1SR	19930905	4.1	.05	13,000	240	11,000	290	339	--	98.75
1SS	19930905	--	4.6	--	190	--	280	--	--	--
PRE	19930905	--	--	--	--	--	--	--	--	--
3SR	19930916	9.8	.05	32,000	150	26,000	670	2,310	53.80	99.29
3SS	19930916	--	--	--	5	--	20	--	--	--
2SS	19930916	--	9.5	--	40	--	90	--	--	--
3SR	19930927	14	11	19,000	120	14,000	140	906	65.16	98.96
3SS	19930927	--	12	--	20	--	40	--	--	--
2SR	19930927	21	9.1	100,000	260	99,000	380	13,600	30.39	86.79
2SS	19930927	--	8.6	--	200	--	180	--	--	--
1SR	19930927	10	7.3	35,000	140	29,000	120	1,780	42.09	98.88
PRE	19930927	.05	--	20	--	5	--	--	--	--
1SS	19930927	--	1.3	--	200	--	190	--	--	--
3SR	19931004	62	56	3,500	150	29,000	180	1,290	88.66	98.95
3SS	19931004	--	10	--	50	--	30	--	--	--
2SS	19931004	--	25	--	340	--	220	--	--	--
1SR	19931004	41	36	81,000	670	60,000	250	3,550	77.23	98.87
PRE	19931004	--	--	--	--	--	--	--	--	--
3SR	19931013	27	23	22,000	140	19,000	220	1,060	93.71	99.41
3SS	19931013	--	8.8	--	100	--	110	--	--	--
2SR	19931013	22	12	42,000	190	40,000	320	4,040	58.94	98.87
2SS	19931013	--	31	--	110	--	140	--	--	--
1SR	19931013	27	6.5	23,000	170	17,000	130	435	--	97.48
1SS	19931013	--	7.4	--	180	--	20	--	--	--
3SR	19931021	21	22	15,000	220	12,000	220	500	--	98.20
3SS	19931021	--	11	--	90	--	60	--	--	--
2SS	19931021	--	29	--	270	--	210	--	--	--
3SR	19931031	13	12	9,900	310	7,500	320	225	--	99.62
3SS	19931031	--	8.2	--	120	--	90	--	--	--
2SS	19931031	--	17	--	150	--	150	--	--	--

Appendix 3. Water-quality data for precipitation, surface-runoff, and subsurface-flow samples—Continued

Site	Date	Time	Phos-phorus, total (mg/L as P)	Phos-phorus, dissolved (mg/L as P)	Phosphorus, ortho, dissolved (mg/L as P)	Phosphorus, hydrolyzable and ortho, dissolved (mg/L as P)	Phosphorus, hydrolyzable and ortho, total (mg/L as P)	Specific conduct-ance (μS/cm)	pH, whole water field (standard units)	Temper-ature, water (°C)
1SS	19931031	1030	--	0.66	0.67	--	--	--	--	--
3SR	19931129	0800	1.7	.48	.50	--	--	41	6.83	12.4
3SS	19931129	0900	--	.90	.85	--	--	169	6.89	11.7
2SR	19931129	1000	2.0	.42	.44	--	--	29	7.05	13.4
2SS	19931129	1100	--	.42	.43	--	--	111	6.84	12.8
1SR	19931129	1300	.52	.13	.15	--	--	58	6.93	16.7
1SS	19931129	1330	--	.23	.23	--	--	46	7.03	11.8
3SR	19931206	0800	1.1	.35	.30	--	--	31	6.81	14.5
3SS	19931206	0900	--	1.0	.84	--	--	75	6.91	12.2
2SR	19931206	1000	1.1	.32	.30	--	--	26	6.97	15.1
2SS	19931206	1100	--	.25	.24	--	--	57	7.01	11.9
1SR	19931206	1200	.33	.12	.12	--	--	30	7.13	13.8
1SS	19931206	1300	--	.22	.25	--	--	16	7.21	12.8
PRE	19931206	1330	.01	--	--	--	--	4	5.55	12.0
3SR	19931211	0800	1.4	.36	.37	--	--	82	6.89	10.1
3SR	19931222	0800	.71	.46	.41	--	--	129	6.90	12.8
3SS	19931222	0900	--	.68	.68	--	--	238	6.99	14.1
2SS	19931222	1000	--	.26	.27	--	--	74	7.09	12.6
PRE	19931222	1130	.05	--	--	--	--	14	5.10	12.6
1SR	19931222	1200	.80	.18	.18	--	--	25	6.97	14.0
1SS	19931222	1230	--	.17	.19	--	--	25	6.96	12.8
3SR	19940313	1000	.73	.53	.53	--	--	60	7.13	15.0
2SR	19940313	1100	.29	.24	.23	--	--	25	6.58	14.4
2SS	19940313	1130	--	.24	.23	--	--	52	6.01	16.8
1SS	19940313	1300	--	.65	.63	--	--	69	5.97	5.8
3SR	19940320	0800	.82	.32	.32	--	--	48	6.73	16.3
3SS	19940320	0830	--	.65	.59	--	--	241	7.43	17.1
3SR	19940326	0800	.85	.42	.40	--	--	79	6.98	8.5
3SS	19940326	0900	--	.48	.45	--	--	267	7.25	10.3
1SR	19940326	1100	.51	.13	.13	--	--	27	6.70	8.4
3SR	19940329	0800	2.8	.36	.35	--	--	38	6.65	10.6
3SS	19940329	0930	--	.65	.62	--	--	163	7.15	11.5
2SS	19940329	1030	--	.36	.34	--	--	--	--	--
1SR	19940329	1200	1.0	.17	.15	--	--	25	6.70	10.6
1SS	19940329	1300	--	.16	.13	--	--	30	6.80	10.6
3SR	19940414	0800	1.9	.38	.40	--	--	58	6.60	18.7
3SS	19940414	0830	--	.78	.81	--	--	151	7.25	17.9
1SS	19940414	0900	--	.14	.14	--	--	35	6.48	18.0
PRE	19940414	1000	.03	--	--	--	--	24	4.53	18.3
3SR	19940417	0800	3.8	.55	.54	--	--	86	6.85	19.6

Appendix 3. Water-quality data for precipitation, surface-runoff, and subsurface-flow samples—Continued

Site	Date	Carbon, organic, total (mg/L as C)	Carbon, organic, dissolved (mg/L as C)	Calcium, total (mg/L as Ca)	Calcium, dissolved (mg/L as Ca)	Magnesium, total (mg/L as Mg)	Magnesium, dissolved (mg/L as Mg)	Sodium, total (mg/L as Na)	Sodium, dissolved (mg/L as Na)
1SS	19931031	--	9.1	--	--	--	--	--	--
3SR	19931129	21	5.4	7.6	3.1	12	1.7	0.5	0.5
3SS	19931129	--	7.5	--	13	--	6.1	--	43
2SR	19931129	51	9.5	14	2.6	23	1.3	.4	.4
2SS	19931129	--	7.0	--	3.9	--	1.8	--	45
1SR	19931129	31	12	9.3	5.5	22	1.9	.5	.5
1SS	19931129	--	3.0	--	4.0	--	1.8	--	44
3SR	19931206	12	--	5.0	2.5	9.0	1.2	.3	.4
3SS	19931206	--	3.8	--	6.5	--	2.7	--	1.4
2SR	19931206	22	--	7.6	2.0	14	.8	.2	.3
2SS	19931206	--	3.6	--	5.7	--	1.8	--	.2
1SR	19931206	12	--	3.3	3.2	7.3	1.1	.2	.3
1SS	19931206	--	4.3	--	6.7	--	1.2	--	.2
PRE	19931206	--	--	--	--	--	--	--	--
3SR	19931211	20	--	7.2	5.8	8.0	2.7	.9	1.1
3SR	19931222	18	--	6.1	3.9	7.9	2.0	1.0	1.2
3SS	19931222	--	3.8	--	17	--	7.6	--	3.3
2SS	19931222	--	5.8	--	7.9	--	2.2	--	.3
PRE	19931222	--	--	--	--	--	--	--	--
1SR	19931222	40	--	8.1	1.7	31	.7	.1	.4
1SS	19931222	--	2.2	--	2.0	--	1.0	--	.1
3SR	19940313	6.8	--	1.9	2.0	1.4	1.1	.7	.6
2SR	19940313	4.7	--	1.6	1.4	1.6	.5	.4	.4
2SS	19940313	77	3.2	--	4.7	--	1.4	--	.4
1SS	19940313	--	4.2	--	3.8	--	1.8	--	.7
3SR	19940320	11	--	3.4	2.0	5.6	.9	.6	.6
3SS	19940320	--	6.4	--	--	--	--	--	--
3SR	19940326	8.3	--	4.0	3.8	3.5	1.9	.9	.9
3SS	19940326	--	11	--	24	--	11	--	3.8
1SR	19940326	6.5	--	2.4	2.2	4.5	1.0	.3	.3
3SR	19940329	34	--	6.0	1.6	12	.8	.7	.5
3SS	19940329	--	3.9	--	15	--	5.9	--	2.3
2SS	19940329	--	--	--	--	--	--	--	--
1SR	19940329	27	--	13	1.9	44	.9	.5	.2
1SS	19940329	--	2.4	--	2.6	--	1.2	--	.05
3SR	19940414	77	--	11	2.9	16	1.3	.6	.6
3SS	19940414	--	5.8	--	13	--	5.2	--	2.8
1SS	19940414	--	3.8	--	2.8	--	1.3	--	.1
PRE	19940414	--	--	--	--	--	--	--	--
3SR	19940417	320	--	--	--	--	--	--	--

Appendix 3. Water-quality data for precipitation, surface-runoff, and subsurface-flow samples—Continued

Site	Date	Potassium, total (mg/L as K)	Potassium, dissolved (mg/L as K)	Iron, total (µg/L as Fe)	Iron, dissolved (µg/L as Fe)	Aluminum, total (µg/L as Al)	Aluminum, dissolved (µg/L as Al)	Sediment, suspended (mg/L)	Sediment, suspended fall diameter (percentage finer than 0.004 mm)	Sediment, suspended fall diameter (percentage finer than 0.062 mm)
1SS	19931031	--	--	--	--	--	--	--	--	--
3SR	19931129	3.6	3.6	29,000	30	28,000	30	1,830	70.61	99.74
3SS	19931129	--	7.3	--	40	--	30	--	--	--
2SR	19931129	1.9	1.9	42,000	40	47,000	30	4,910	43.53	96.43
2SS	19931129	--	8.3	--	50	--	40	--	--	--
1SR	19931129	3.2	3.2	32,000	160	25,000	150	2,020	30.78	96.13
1SS	19931129	--	2.6	--	20	--	10	--	--	--
3SR	19931206	3.9	2.3	27,000	160	20,000	200	1,010	74.39	99.60
3SS	19931206	--	3.6	--	450	--	1,200	--	--	--
2SR	19931206	3.4	1.2	36,000	80	28,000	110	1,920	51.53	90.39
2SS	19931206	--	4.4	--	105	--	110	--	--	--
1SR	19931206	2.9	2.0	15,000	280	10,000	230	393	63.01	97.77
1SS	19931206	--	4.0	--	100	--	100	--	--	--
PRE	19931206	--	--	--	--	--	--	--	--	
3SR	19931211	5.4	5.0	20,000	190	15,000	200	810	80.60	99.55
3SR	19931222	25	21	19,000	190	12,000	240	931	87.92	99.67
3SS	19931222	--	11	--	50	--	70	--	--	--
2SS	19931222	--	2.0	--	80	--	90	--	--	--
PRE	19931222	--	--	--	--	--	--	--	--	--
1SR	19931222	5.7	1.0	55,000	150	39,000	160	2,280	59.71	99.76
1SS	19931222	--	.95	--	20	--	30	--	--	--
3SR	19940313	9.4	10	1,400	260	1,100	280	61	92.53	--
2SR	19940313	3.2	3.3	2,100	78	1,700	80	159	--	90.56
2SS	19940313	--	2.1	--	45	--	30	--	--	--
1SS	19940313	--	2.2	--	39	--	30	--	--	--
3SR	19940320	7.0	6.6	12,000	140	11,000	2,100	616	--	99.31
3SS	19940320	--	--	--	--	--	--	--	--	--
3SR	19940326	9.7	10	5,300	330	4,200	2,200	139	--	96.95
3SS	19940326	--	8.1	--	170	--	180	--	--	--
1SR	19940326	1.7	1.6	5,900	100	4,300	90	231	--	97.53
3SR	19940329	8.8	6.0	32,000	200	35,000	240	2,440	62.24	99.06
3SS	19940329	.	5.7	--	260	--	270	--	--	--
2SS	19940329	--	--	--	--	--	--	--	--	--
1SR	19940329	7.1	1.3	75,000	200	71,000	330	5,080	44.50	97.76
1SS	19940329	--	1.3	--	210	--	290	--	--	--
3SR	19940414	11	7.7	49,000	94	37,000	90	3,980	51.68	81.32
3SS	19940414	--	6.3	--	53	--	50	--	--	--
1SS	19940414	--	1.4	--	55	--	40	--	--	--
PRE	19940414	--	--	--	--	--	--	--	--	--
3SR	19940417	--	--	--	--	--	--	13,700	46.10	99.41

Appendix 3. Water-quality data for precipitation, surface-runoff, and subsurface-flow samples—Continued

Site	Date	Time	Phosphorus, total (mg/L as P)	Phosphorus, dissolved (mg/L as P)	Phosphorus, ortho, dissolved (mg/L as P)	Phosphorus, hydrolyzable and ortho, dissolved (mg/L as P)	Phosphorus, hydrolyzable and ortho, total (mg/L as P)	Specific conductance (µS/cm)	pH, whole water field (standard units)	Temperature, water (°C)
3SS	19940417	0830	--	0.85	0.83	--	--	145	7.35	21.1
1SR	19940417	0900	2.2	.18	.16	--	--	45	6.87	20.5
1SS	19940417	0930	--	.16	.15	--	--	41	6.64	19.4
1SR	19940502	0900	1.3	.15	.10	--	--	102	6.89	15.5
1SS	19940502	0930	--	.11	.10	--	--	118	6.64	16.5
3SR	19940509	0800	1.1	.43	.45	--	--	46	6.34	19.2
3SS	19940509	0900	--	.62	.65	--	--	101	6.91	18.9
1SR	19940509	1000	.52	.08	.10	--	--	37	6.43	19.7
1SS	19940509	1100	--	.09	.09	--	--	38	6.34	19.2
PRE	19940509	1130	--	--	--	--	--	21	4.37	17.7
3SR	19940526	0800	6.5	1.2	1.2	--	--	108	6.76	18.2
3SS	19940526	0900	--	1.8	1.6	--	--	549	6.71	14.8
2SR	19940526	1000	6.9	.74	.77	--	--	76	6.87	18.0
2SS	19940526	1100	--	.60	.57	--	--	128	7.23	22.4
1SR	19940526	1200	4.7	.21	.15	--	--	89	6.63	17.5
3SR	19940613	0800	1.8	.95	.92	--	--	190	6.21	24.6
3SS	19940613	0900	--	1.1	1.1	--	--	825	6.39	25.3
2SR	19940613	1000	12	.80	.74	--	--	93	6.43	24.8
1SR	19940613	1200	8.6	.23	.17	--	--	102	6.39	24.5
1SS	19940613	1300	--	.28	.24	--	--	161	6.40	23.5
3SR	19940620	0800	1.4	.77	.71	--	--	678	6.59	20.4
2SR	19940620	1000	7.2	.95	.84	--	--	448	7.16	19.4
1SR	19940620	1200	3.9	.12	.08	--	--	226	6.81	19.8
3SR	19940628	0800	1.5	.95	.88	--	--	128	6.51	20.9
2SR	19940628	1000	1.8	1.1	.98	--	--	126	6.93	20.3
1SR	19940628	1200	.57	.22	.17	--	--	61	6.63	20.3
1SS	19940628	1300	--	.22	.17	--	--	90	6.53	17.1
3SR	19940630	0800	8.9	.84	.78	--	--	114	6.58	20.7
3SS	19940630	0900	--	1.3	1.2	--	--	558	7.93	22.0
2SR	19940630	1000	3.4	.89	.81	--	--	82	6.89	20.6
1SR	19940630	1200	5.4	.17	.15	--	--	49	6.65	19.9
3SR	19940707	0800	2.0	.83	.81	--	--	139	6.31	23.0
3SR	19940715	0800	8.5	.81	.75	--	--	70	6.28	22.7
3SS	19940715	0900	--	1.7	1.5	--	--	--	--	--
2SR	19940715	1000	5.1	.61	.58	--	--	66	6.16	22.8
2SS	19940715	1100	--	.48	.46	--	--	240	6.40	23.8
1SR	19940715	1200	9.2	.31	.27	--	--	103	6.50	23.0
3SR	19940724	0800	1.4	.48	.47	--	--	53	6.74	15.3
3SS	19940724	0900	--	1.9	2.0	--	--	405	7.43	16.2
2SR	19940724	1000	5.6	.50	.52	--	--	43	6.79	15.5

Appendix 3. Water-quality data for precipitation, surface-runoff, and subsurface-flow samples—Continued

Site	Date	Carbon, organic, total (mg/L as C)	Carbon, organic, dissolved (mg/L as C)	Calcium, total (mg/L as Ca)	Calcium, dissolved (mg/L as Ca)	Magnesium, total (mg/L as Mg)	Magnesium, dissolved (mg/L as Mg)	Sodium, total (mg/L as Na)	Sodium, dissolved (mg/L as Na)
3SS	19940417	--	--	--	--	--	--	--	--
1SR	19940417	220	--	--	--	--	--	--	--
1SS	19940417	--	8.4	--	--	--	--	--	--
1SR	19940502	210	--	--	--	--	--	--	--
1SS	19940502	--	9.0	--	--	--	--	--	--
3SR	19940509	--	--	--	--	--	--	--	--
3SS	19940509	--	--	--	--	--	--	--	--
1SR	19940509	--	--	--	--	--	--	--	--
1SS	19940509	--	--	--	--	--	--	--	--
PRE	19940509	--	--	--	--	--	--	--	--
3SR	19940526	16	--	--	--	--	--	--	--
3SS	19940526	--	16	--	--	--	--	--	--
2SR	19940526	17	--	--	--	--	--	--	--
2SS	19940526	--	--	--	--	--	--	--	--
1SR	19940526	29	--	--	--	--	--	--	--
3SR	19940613	--	--	--	--	--	--	--	--
3SS	19940613	--	--	--	--	--	--	--	--
2SR	19940613	--	--	--	--	--	--	--	--
1SR	19940613	--	--	--	--	--	--	--	--
1SS	19940613	--	--	--	--	--	--	--	--
3SR	19940620	140	--	--	--	--	--	--	--
2SR	19940620	770	--	--	--	--	--	--	--
1SR	19940620	160	--	--	--	--	--	--	--
3SR	19940628	--	--	--	--	--	--	--	--
2SR	19940628	--	--	--	--	--	--	--	--
1SR	19940628	--	--	--	--	--	--	--	--
1SS	19940628	--	--	--	--	--	--	--	--
3SR	19940630	84	--	19	7.5	21	2.7	1.5	1.5
3SS	19940630	--	--	--	--	--	--	--	--
2SR	19940630	130	--	25	7.3	39	2.6	1.0	.9
1SR	19940630	63	--	13	4.5	36	1.6	.2	.2
3SR	19940707	--	--	--	--	--	--	--	--
3SR	19940715	--	--	--	--	--	--	--	--
3SS	19940715	--	--	--	--	--	--	--	--
2SR	19940715	--	--	--	--	--	--	--	--
2SS	19940715	--	--	--	--	--	--	--	--
1SR	19940715	--	--	--	--	--	--	--	--
3SR	19940724	--	--	--	--	--	--	--	--
3SS	19940724	--	--	--	--	--	--	--	--
2SR	19940724	--	--	--	--	--	--	--	--

Appendix 3. Water-quality data for precipitation, surface-runoff, and subsurface-flow samples—Continued

Site	Date	Potassium, total (mg/L as K)	Potassium, dissolved (mg/L as K)	Iron, total (µg/L as Fe)	Iron, dissolved (µg/L as Fe)	Aluminum, total (µg/L as Al)	Aluminum, dissolved (µg/L as Al)	Sediment, suspended (mg/L)	Sediment, suspended fall diameter (percentage finer than 0.004 mm)	Sediment, suspended fall diameter (percentage finer than 0.062 mm)
3SS	19940417	--	--	--	--	--	--	--	--	--
1SR	19940417	--	--	--	--	--	--	7,060	35.91	99.35
1SS	19940417	--	--	--	--	--	--	--	--	--
1SR	19940502	--	--	--	--	--	--	5,390	35.61	98.22
1SS	19940502	--	--	--	--	--	--	--	--	--
3SR	19940509	--	--	--	--	--	--	2,010	55.60	99.61
3SS	19940509	--	--	--	--	--	--	--	--	--
1SR	19940509	--	--	--	--	--	--	4,860	45.13	99.54
1SS	19940509	--	--	--	--	--	--	--	--	--
PRE	19940509	--	--	--	--	--	--	--	--	--
3SR	19940526	--	--	--	--	--	--	9,090	57.20	99.33
3SS	19940526	--	--	--	--	--	--	--	--	--
2SR	19940526	--	--	--	--	--	--	12,200	53.32	99.28
2SS	19940526	--	--	--	--	--	--	--	--	--
1SR	19940526	--	--	--	--	--	--	10,800	45.77	98.05
3SR	19940613	--	--	--	--	--	--	6,930	42.67	98.00
3SS	19940613	--	--	--	--	--	--	--	--	--
2SR	19940613	--	--	--	--	--	--	5,350	38.48	95.40
1SR	19940613	--	--	--	--	--	--	18,200	25.12	94.00
1SS	19940613	--	--	--	--	--	--	--	--	--
3SR	19940620	--	--	--	--	--	--	7,530	49.54	99.41
2SR	19940620	--	--	--	--	--	--	53,700	26.64	89.88
1SR	19940620	--	--	--	--	--	--	5,850	26.20	98.76
3SR	19940628	--	--	--	--	--	--	5,710	46.50	78.15
2SR	19940628	--	--	--	--	--	--	27,900	22.84	99.53
1SR	19940628	--	--	--	--	--	--	4,480	48.12	97.22
1SS	19940628	--	--	--	--	--	--	--	--	--
3SR	19940630	13	8.5	59,000	430	44,000	570	4,400	51.47	96.90
3SS	19940630	--	--	--	--	--	--	--	--	--
2SR	19940630	9.7	3.4	80,000	460	62,000	520	6,450	40.33	96.44
1SR	19940630	5.6	.90	74,000	410	47,000	580	2,860	47.58	98.44
3SR	19940707	--	--	--	--	--	--	3,530	62.45	97.82
3SR	19940715	--	--	--	--	--	--	4,840	34.59	94.43
3SS	19940715	--	--	--	--	--	--	--	--	--
2SR	19940715	--	--	--	--	--	--	2,620	41.27	96.36
2SS	19940715	--	--	--	--	--	--	--	--	--
1SR	19940715	--	--	--	--	--	--	8,940	30.32	90.95
3SR	19940724	--	--	--	--	--	--	2,590	35.17	83.88
3SS	19940724	--	--	--	--	--	--	--	--	--
2SR	19940724	--	--	--	--	--	--	8,190	27.29	89.42

Appendix 3. Water-quality data for precipitation, surface-runoff, and subsurface-flow samples—Continued

Site	Date	Time	Phosphorus, total (mg/L as P)	Phosphorus, dissolved (mg/L as P)	Phosphorus, ortho, dissolved (mg/L as P)	Phosphorus, hydrolyzable and ortho, dissolved (mg/L as P)	Phosphorus, hydrolyzable and ortho, total (mg/L as P)	Specific conductance (µS/cm)	pH, whole water field (standard units)	Temperature, water (°C)
2SS	19940724	1100	--	0.51	0.53	--	--	88	6.85	20.8
3SR	19940728	0800	4.7	.50	.48	--	--	49	6.31	21.6
3SS	19940728	0900	--	1.5	1.4	--	--	260	6.32	23.5
2SR	19940728	1000	2.3	.49	.46	--	--	58	6.13	22.1
1SR	19940728	1200	3.3	.13	.11	--	--	41	6.21	22.3
1SS	19940728	1300	--	.14	.12	--	--	79	5.95	22.2
3SR	19940813	0800	.97	.77	.77	--	--	79	6.25	18.0
3SS	19940813	0900	--	1.8	1.7	--	--	232	6.57	18.8
2SR	19940813	1000	.66	.56	.56	--	--	103	6.47	16.7
1SR	19940813	1200	.23	.15	.15	--	--	77	6.59	18.7
3SR	19940818	0800	1.4	.60	.54	--	--	29	6.17	21.0
3SS	19940818	0900	--	2.7	2.7	--	--	383	6.60	22.1
2SR	19940818	1000	4.8	.48	.41	--	--	28	6.43	21.5
2SS	19940818	1100	--	.68	.59	--	--	213	7.18	21.5
1SR	19940818	1200	5.1	.33	.29	--	--	56	6.55	22.0
1SS	19940818	1300	--	.26	.22	--	--	49	6.03	22.0
3SR	19940822	0800	3.1	.65	.62	--	--	33	6.30	22.0
3SS	19940822	0900	--	2.0	1.8	--	--	356	6.87	23.4
1SR	19940822	1200	3.3	.21	.19	--	--	27	6.43	22.9

Appendix 3. Water-quality data for precipitation, surface-runoff, and subsurface-flow samples—Continued

Site	Date	Carbon, organic, total (mg/L as C)	Carbon, organic, dissolved (mg/L as C)	Calcium, total (mg/L as Ca)	Calcium, dissolved (mg/L as Ca)	Magnesium, total (mg/L as Mg)	Magnesium, dissolved (mg/L as Mg)	Sodium, total (mg/L as Na)	Sodium, dissolved (mg/L as Na)
2SS	19940724	--	--	--	--	--	--	--	--
3SR	19940728	--	--	--	--	--	--	--	--
3SS	19940728	--	--	--	--	--	--	--	--
2SR	19940728	--	--	--	--	--	--	--	--
1SR	19940728	--	--	--	--	--	--	--	--
1SS	19940728	--	--	--	--	--	--	--	--
3SR	19940813	--	--	--	--	--	--	--	--
3SS	19940813	--	--	--	--	--	--	--	--
2SR	19940813	--	--	--	--	--	--	--	--
1SR	19940813	--	--	--	--	--	--	--	--
3SR	19940818	--	--	--	--	--	--	--	--
3SS	19940818	--	--	--	--	--	--	--	--
2SR	19940818	--	--	--	--	--	--	--	--
2SS	19940818	--	--	--	--	--	--	--	--
1SR	19940818	--	--	--	--	--	--	--	--
1SS	19940818	--	--	--	--	--	--	--	--
3SR	19940822	--	--	--	--	--	--	--	--
3SS	19940822	--	--	--	--	--	--	--	--
1SR	19940822	--	--	--	--	--	--	--	--

Appendix 3. Water-quality data for precipitation, surface-runoff, and subsurface-flow samples—Continued

Site	Date	Potassium, total (mg/L as K)	Potassium, dissolved (mg/L as K)	Iron, total (µg/L as Fe)	Iron, dissolved (µg/L as Fe)	Aluminum, total (µg/L as Al)	Aluminum, dissolved (µg/L as Al)	Sediment, suspended (mg/L)	Sediment, suspended fall diameter (percentage finer than 0.004 mm)	Sediment, suspended fall diameter (percentage finer than 0.062 mm)
2SS	19940724	--	--	--	--	--	--	--	--	--
3SR	19940728	--	--	--	--	--	--	7,260	27.62	99.33
3SS	19940728	--	--	--	--	--	--	--	--	--
2SR	19940728	--	--	--	--	--	--	4,360	32.47	93.96
1SR	19940728	--	--	--	--	--	--	2,260	32.09	94.76
1SS	19940728	--	--	--	--	--	--	--	--	--
3SR	19940813	--	--	--	--	--	--	1,410	--	97.53
3SS	19940813	--	--	--	--	--	--	--	--	--
2SR	19940813	--	--	--	--	--	--	7,620	21.05	80.76
1SR	19940813	--	--	--	--	--	--	4,060	23.31	86.07
3SR	19940818	--	--	--	--	--	--	1,440	41.47	96.70
3SS	19940818	--	--	--	--	--	--	--	--	--
2SR	19940818	--	--	--	--	--	--	2,610	--	90.32
2SS	19940818	--	--	--	--	--	--	--	--	--
1SR	19940818	--	--	--	--	--	--	2,960	--	86.68
1SS	19940818	--	--	--	--	--	--	--	--	--
3SR	19940822	--	--	--	--	--	--	919	--	97.96
3SS	19940822	--	--	--	--	--	--	--	--	--
1SR	19940822	--	--	--	--	--	--	1,590	41.94	90.96

APPENDIX 4

Appendix 4. Chemistry data for manure samples collected during manure application and study plot to which manure was applied
[ppm; parts per million]

Year	Plot	Nitrogen, (ppm as N)	P_2O_5 (ppm as P_2O_5)	K_2O (ppm as K_2O)	Calcium (ppm as Ca)	Magnesium (ppm as Mg)	Copper (ppm as Cu)	Iron (ppm as Fe)	Manganese (ppm as Mn)	Zinc (ppm as Zn)	Aluminum (ppm as Al)	Sodium (ppm as Na)
[1] 1993	2	2,400	2,000	1,400	800	200	11	240	12	30	<0.5	374
[1] 1993	2	2,400	2,100	1,300	800	200	12	248	13	31	<.5	370
[1] 1993	3	2,800	2,200	1,500	800	200	12	251	13	31	<.5	428
[1] 1993	3	2,900	2,200	1,500	800	200	12	248	13	31	<.5	433
[1] 1993	3	2,900	2,300	1,600	900	200	13	262	14	33	<.5	451
[1] 1993	3	2,900	2,200	1,600	800	200	12	252	13	33	<.5	424
[2] 1994	2,3	3,600	3,400	1,900	1,800	600	19	686	26	55	329	447
[2] 1994	2,3	3,200	2,900	1,600	1,300	500	16	562	21	45	265	370

[1] 100 percent swine manure.

[2] 70 percent swine manure and 30 percent dairy-cow manure.

APPENDIX 5

Appendix 5. Chemistry data for corn-plant samples collected immediately prior to harvest from the study plots during 1993 and 1994 [µg/g, micrograms per gram]

Plot	Year	Plant material	Phosphorus (in percentage mass)	Potassium (in percentage mass)	Calcium (in percentage mass)	Magnesium (in percentage mass)	Manganese (µg/g)	Iron (µg/g)	Copper (µg/g)	Boron (µg/g)	Aluminum (µg/g)	Zinc (µg/g)	Sodium (µg/g)
1	1993	husk	0.16	1.08	0.14	0.18	20	316	26	6	218	22	58
1	1993	leaf	.29	.80	.72	.58	56	694	26	8	434	34	64
1	1993	root	.22	1.04	.14	.18	49	1,738	37	2	1,134	27	66
1	1993	corn	.26	.48	.01	.09	4	37	11	2	18	15	10
1	1993	stem	.19	.60	.18	.31	9	142	18	3	96	23	19
2	1993	husk	.04	1.28	.12	.11	12	156	18	5	110	9	44
2	1993	leaf	.16	.90	.84	.62	70	785	28	10	544	30	66
2	1993	root	.11	1.19	.28	.30	54	1,822	28	3	1,376	23	212
2	1993	corn	.22	.41	.01	.08	4	32	10	2	14	14	8
2	1993	stem	.08	1.02	.34	.44	12	173	12	4	110	12	24
3	1993	husk	.06	1.39	.12	.10	24	379	17	5	322	14	47
3	1993	leaf	.19	1.13	.75	.52	98	581	31	9	487	47	68
3	1993	root	.14	1.60	.28	.41	70	1,948	27	3	1,899	24	360
3	1993	corn	.24	.46	.01	.08	4	32	7	1	125	16	5
3	1993	stem	.09	1.44	.32	.52	12	136	12	4	101	14	29
1	1994	husk	.10	.82	.14	.17	28	652	165	6	372	36	49
1	1994	leaf	.28	.84	.68	.54	74	1,278	24	11	770	51	62
1	1994	root	.19	1.36	.15	.21	70	2,500	40	3	1,808	40	116
1	1994	corn	.28	.46	.01	.10	4	46	14	2	20	18	11
1	1994	stem	.24	.80	.11	.22	7	150	13	4	80	27	16
2	1994	husk	.08	1.17	.15	.14	18	327	11	6	206	14	36
2	1994	leaf	.24	1.80	.78	.48	60	556	20	10	377	45	55
2	1994	root	.14	2.21	.30	.30	52	1,637	16	3	1,152	21	526
2	1994	corn	.31	.48	.01	.10	4	38	4	2	16	18	7
2	1994	stem	.12	1.58	.26	.26	7	84	10	3	46	19	23
3	1994	husk	.14	1.50	.17	.12	40	450	24	6	382	24	47
3	1994	leaf	.24	1.96	.82	.30	119	837	25	12	668	60	56
3	1994	root	.12	2.54	.28	.28	64	1,224	18	3	1,060	21	779
3	1994	corn	.30	.46	.01	.09	4	34	5	2	14	20	6
3	1994	stem	.13	2.33	.28	.28	13	155	14	3	88	28	24