EVALUATION OF AGRICULTURAL BEST-MANAGEMENT PRACTICES IN THE CONESTOGA RIVER HEADWATERS, PENNSYLVANIA:

Characterization of Surface-Runoff and Ground-Water Quantity and Quality in a Small Carbonate Basin Near Churchtown, Pennsylvania, Prior to Terracing and Implementation of Nutrient Management

WATER-QUALITY STUDY OF THE CONESTOGA RIVER HEADWATERS, PENNSYLVANIA

By Patricia L. Lietman, David W. Hall, Michael J. Langland, Douglas C. Chichester, and Janice R. Ward

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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
square foot (ft^2)	0.09294	square meter
square mile (mi^2)	2.590	square kilometer
	Discharge	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon per minute per foot (gal/min)/ft	0.2070	liter per second per meter
	Volume	
cubic foot (ft^3)	0.02832	cubic meter
quart (qt)	0.9463	liter
gallon (gal)	3.785	liter
bushel (dry)	35.24	liter
	Mass	
pound (lb)	0.4536	kilogram
ton (short, 2,000 pounds)	0.9072	metric ton
pound per acre (lb/acre)	1.123	kilogram per hectare
ton per acre (ton/acre)	2.241	metric ton per hectare
	Temperature	
degree Fahrenheit (°F)	°C=5/9 (°F-32)	degree Celsius

Other Abbreviations

Abbreviated water-quality units used in report:

- μg/kg micrograms per kilograms
- μg/L micrograms per liter
- μS/cm microsiemens per centimeter at 25 degrees Celsius
- mg/kg milligrams per kilograms
- mg/L milligrams per liter

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.

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Characterization of Surface-Runoff and Ground-Water Quantity and Quality in a Small Carbonate Basin Near Churchtown, Pennsylvania, Prior to Terracing and Implementation of Nutrient Management

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ABSTRACT

The U.S. Geological Survey, in cooperation with the Pennsylvania Department of Environmental Protection[1], conducted a study as part of the U.S. Department of Agriculture's Rural Clean Water Program to determine the effects of agricultural best-management practices on surface-water and ground-water quality in the Conestoga River headwaters basin. This report describes Field-Site 1 and characterizes the surface-runoff and ground-water quantity and quality at the site from January 1983 through September 1984, before the implementation of terracing and nutrient-management best-management practices. The 22.1-acre site, part of two dairy farms, was cropland used primarily for the production of corn and alfalfa, and is underlain by carbonate rock.

During the 21-month study period, 91.2 inches of precipitation fell, of which 66 percent occurred during the 1984 water year. Of the 169 storms of 0.10 inch or larger, 97 produced measurable runoff.

The average annual application of nutrients to the 14.4 acres of cornfields was 410 pounds per acre of nitrogen and 110 pounds per acre of phosphorus. About three times more nutrients were applied during 1984 water year than during the 1983 water year. The approximate soil-nitrate concentration as nitrogen for the study period was 8.2 milligrams per kilogram in the top 8 inches of soil.

Runoff for the study period totalled 714,000 cubic feet, or 9.8 percent of total precipitation. Eighty-eight percent of the runoff occurred during the 1984 water year. Regression analyses indicate that total runoff was controlled primarily by total precipitation amounts during storms and by antecedent moisture conditions; mean event and maximum instantaneous discharges are controlled by precipitation intensity and by antecedent moisture conditions. Regression analyses also suggest that crop cover on the corn acreage affected runoff amounts and rates.

Mean concentrations in runoff ranged from 24 to 73,000 milligrams per liter for suspended sediment, 0.45 to 24 milligrams per liter for total phosphorus, and 1.5 to 55 milligrams per liter for total nitrogen. Of the total nitrogen in instantaneous runoff samples, a median of 72 percent was total organic nitrogen.

Results of multiple regression analyses suggest that mean nitrogen concentrations in runoff (1) increased with increased surface-nitrogen applications made prior to runoff, and (2) were diluted with increased precipitation duration. Runoff from storms on frozen ground produced the highest loads of nitrogen in runoff. Over the 21-month study period, an estimated 258 tons of suspended sediment, 314 pounds of nitrogen, and 176 pounds of phosphorus were transported with runoff from the site. Of this, 88 percent of the nitrogen and phosphorus loads and 94 percent of the suspended-sediment load were discharged during the wet 1984 water year. The loads for the study period represent 2.5 percent of the total nitrogen and 5.5 percent of the total phosphorus applied to the site as manure and commercial fertilizer.

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[1] Prior to 1995, the Pennsylvania Department of Environmental Protection (PaDEP) was known as the Pennsylvania Department of Environmental Resources (PaDER).

The ground-water basin at the site is slightly larger than the surface-water basin. Ground-water levels, except at one well, responded quickly to recharge; water levels peaked several hours to a day after precipitation. Surface-applied materials moved rapidly to the water table through macropores and slowly by transport through micropores in the unsaturated zone.

Median concentrations of dissolved nitrate ranged from 9.2 to 13 milligrams per liter as nitrogen for ground-water samples collected monthly from five wells and a spring. Dissolved nitrate comprised 93 percent (median percentage) of the total nitrogen in ground-water samples. The effect of recharge on ground-water nitrate concentrations was affected by variations in nutrient availability at the land surface and in the unsaturated zone. A lag time of 1 to 3 months was observed between the time that nitrogen was applied to the land surface and local maximums in nitrate concentrations were detected in ground water unaffected by recharge events. Approximately 3,187,000 cubic feet of ground water and an associated 2,200 pounds of nitrate-nitrogen discharged from the site during the study period.

For the study period, 42 percent of the precipitation recharged to ground water, 10 percent became runoff, and 48 percent evapotranspired. Inputs of nitrogen to the study area were estimated to be 93 percent from manure, 5 percent from commercial fertilizer, and 2 percent from precipitation. Nitrogen outputs from the system were estimated to be 38 percent to crop uptake, 39 percent to volatilization, 20 percent to ground-water discharge, and 3 percent to surface runoff.

INTRODUCTION

The U.S. Geological Survey (USGS), in cooperation with the Pennsylvania Department of Environmental Protection (PaDEP)[2], conducted a study to determine the effects of agricultural best-management practices (BMP's) on surface-water and ground-water quality in the Conestoga River headwaters, Lancaster County, Pa. This study was one of five comprehensive monitoring and evaluation projects in the U.S. Department of Agriculture's (USDA) Rural Clean Water Program (RCWP) (U.S. Department of Agriculture, 1980).

In 1979, the U.S. Congress enacted the RCWP. This program designated the Conestoga River headwaters basin as 1 of 20 project areas approved for remedial action to improve surface-water and ground-water quality. This area was chosen because the Conestoga River had been designated as the top priority basin in need of further study on nonpoint-source contamination in Pennsylvania's Agricultural 208 Plan (Schueller, 1983, Lancaster County Conservation District, 1982). This designation had been made because the project area contains 132 mi of streams that have considerable existing or potential use for water supply, livestock watering, fish and wildlife habitats, and recreation as well as significant ground-water use for public-water supplies. In addition, studies (U.S. Department of Agriculture, 1982; Lancaster County Conservation District, 1982; Pennsylvania Department of Environmental Resources, 1983) in the area have shown a trend toward increasing degradation of surface-water and ground-water quality caused by large nonpoint discharges of suspended sediment and nutrients. The major water-quality problems include nutrients from manure, pesticides from applications to crop land, and sediment from intensive cropping.

The objective of the RCWP is to improve surface-water and ground-water quality by voluntary implementation of agricultural best-management practices, such as terracing, manure storage, grassy waterways, and nutrient and pesticide management. Cost-share funds have been allocated to the 20 selected projects nationwide to initiate implementation of these practices, and to monitor the effects of implementation on water quality.

Water-quality monitoring in the Conestoga River headwaters area was conducted over a 10-year period and at three levels: regional, small watershed, and field. Each level involved monitoring before and after implementation of BMP's to determine their effects on surface-water and ground-water quality. A detailed description of the overall study can be found in "Evaluation of Agricultural Best-Management Practices in the Conestoga River Headwaters, Pennsylvania: Methods of Data Collection and Analysis, and Description of Study Areas" (Chichester, 1988).

Purpose and Scope

This report describes the results of studies at Field-Site 1 in the Conestoga River headwaters, a 22.1-acre field site in carbonate terrane, and describes the surface-runoff and ground-water quantity and quality from January 1983 through September 1984, before implementation of BMP's (pre-BMP). The environmental conditions and factors influencing water quality and the relation between those factors and surface-runoff and ground-water quantity and quality at Field-Site 1 are also described.

For surface runoff, quantity and concentrations and loads of suspended sediment, nutrients, and selected herbicides are discussed. For ground water, water levels and nutrient and herbicide concentrations are discussed. Land use, soil, and manure-use data are analyzed to determine the sources and timing of loadings of nutrients and herbicides in surface runoff and ground water. Precipitation quantity, intensity, and chemistry data are used to determine the influence of precipitation on water quality. Data presented in this report will be compared to data collected for 5 years after implementation of BMP's (post-BMP) to determine the effects of terracing, manure storage, and nutrient management on surface-runoff and ground-water quality.

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[2] Prior to 1995, the Pennsylvania Department of Environmental Protection (PaDEP) was known as the Pennsylvania Department of Environmental Resources (PaDER).

In this report, concentrations and loads of all species of nitrogen and phosphorus are expressed in their elemental form. For example, all concentrations are expressed as nitrogen whether discussing ammonium or nitrate. The term ammonium refers to the ammonium ion plus free ammonia. Nitrogen species are reported according to reporting procedures and methods used at the time of data collection. Total concentration of nutrients represent concentration found in a raw water sample and dissolved represent those found in a sample passed through a 0.45 μm (micron) filter. The growing season, for the purposes of this report, is defined as May through October, and the nongrowing season as November through April.

This report is one in a series of nine USGS reports that describe the Conestoga River headwaters project. The occurrence and significance of nitrate and herbicides in water in the Conestoga River basin is described by Fishel and Lietman (1986). Other reports describe the overall project, the specific study sites before implementation of BMP's, and the effects of BMP's on water quality, and summarize results of the entire project.

Acknowledgments

The authors acknowledge the efforts of many people who made this study possible. John Hauenstein, Charles Takita, and Gary Lesher of the Susquehanna River Basin Commission provided field assistance and surveyed and mapped the site. Many employees of the U.S. Soil Conservation Service and the U.S. Agricultural Stabilization and Conservation Service at the State and local levels provided assistance in the planning and implementation of management practices on the site, and provided technical assistance to the project. Donald Robinson and Robert Anderson of the Eastern Lancaster County School District assisted in the selection of the site and provided field and technical assistance. Dr. Dale Baker from The Pennsylvania State University provided assistance and equipment for collecting soil samples. The authors also wish to acknowledge Titus Zimmerman and Paul Zeiset for allowing us to conduct this study on their farms and for providing land-use information.

SAMPLING NETWORK AND DATA ANALYSIS

Location and Description

The 22.1-acre site, which is underlain by carbonate rock, is located in the Conestoga River headwaters, between Churchtown and Goodville, Lancaster County, Pa. (fig. 1). The site, part of two dairy farms, was conventionally tilled cropland and was planted primarily in corn and alfalfa during the study period. The silt loam soils are up to 60 in. deep and are moderately to well drained. The site has an average slope of about 6 percent.

Data Collection and Analysis

Detailed information on methods of data collection and sample analysis is presented in Chichester (1988). A summary of the data-collection network is given in table 1 and shown in figure 2. The list of characteristics and chemical constituents for which water samples were analyzed, associated laboratory detection limits, and U.S. Environmental Protection Agency (USEPA) Primary Drinking-Water Regulations are shown in table 2.

For this study, all water-quality and some initial soil-quality and manure samples were analyzed by the PaDEP, Bureau of Laboratories; all suspended-sediment and particle-size samples were analyzed by the USGS Sediment Laboratory in Harrisburg, Pa. Most soil samples were analyzed by The Pennsylvania State University, Soils and Environmental Chemistry Laboratory, University Park, Pa., and most manure samples were analyzed by A&L Eastern Agricultural Laboratories, Inc., Richmond, Va.

Water-quality data from this study were published in USGS Water-Resources Data Reports PA-83-2 (1984) and PA-84-2 (1985) and are stored in the USGS WATSTORE and USEPA STORET data bases. The data were catalogued by the USGS local identification numbers used in this report. All data are on file in the USGS office in Harrisburg, Pa.

Precipitation-quantity data were collected continuously during storms at 5-minute intervals by use of a rain gage equipped with an analog digital recorder (ADR) sensitive to precipitation amounts as little as 0.014 in. Precipitation samples were analyzed periodically for dissolved-nitrogen species and phosphorus.

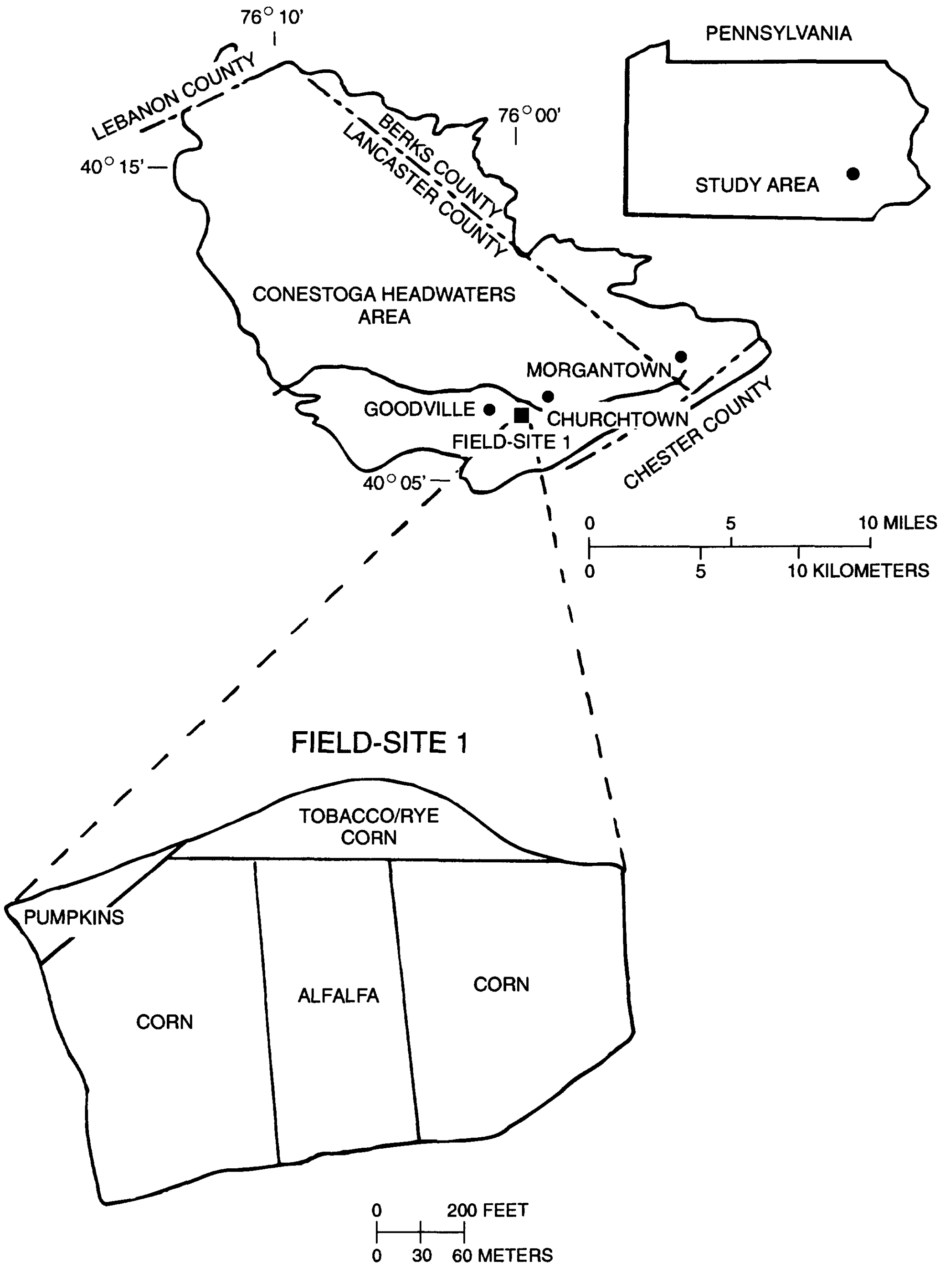

Figure 1. Location of Field-Site 1 and types of crops.

Table 1. Data-collection network at Field-Site 1
[NA, not applicable]

Activity or resource	Number of locations	Sampling frequency	Analysis performed
Precipitation	1	5-minute intervals during storms	Volume
		3 times during study period	Nutrients
Agricultural activities	Entire site	Biweekly	NA
Manure	NA	At selected major applications	Nutrients
Soil	Varied	Spring, summer, fall	Nutrients and herbicides
Soil water	17 initially; 5 for study period	During storms	Nutrients
Runoff	1	All runoff events	Volume
		Most runoff events	Suspended sediment and nutrients
		Most runoff events from May-September 1984	Herbicides
Ground water	6 wells	Continuous	Water level
	8 wells	Intermittent	Water level
	6 wells and 1 spring	Monthly plus 3 recharge events per year	Temperature, specific conductance, and nutrients
	2 wells	Monthly, during April-November, plus 3 recharge events per year	Herbicides

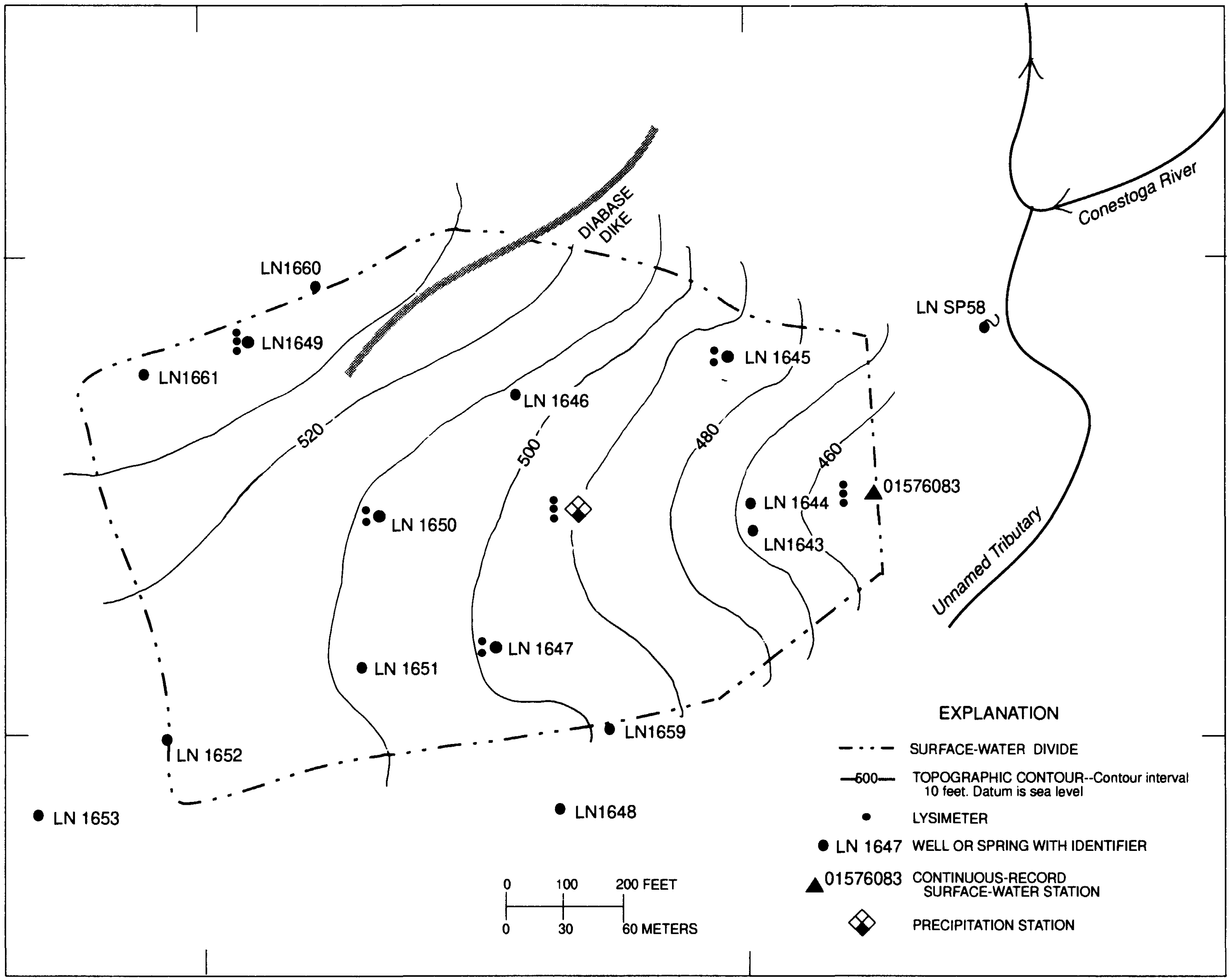

Figure 2. Topography and data-collection locations at Field-Site 1.

Table 2. Primary characteristics and chemical constituents for which precipitation, surface-runoff, or ground-water samples from Field-Site 1 were analyzed
[°C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligram per liter; µg/L, micrograms per liter; mL, milliliter]

Characteristic or constituent	Detection limit	U.S. Environmental Protection Agency Primary Drinking-Water Regulation
Temperature (field)	Measured to nearest 0.5 °C	
Specific conductance (field)	1 to 10 µS/cm dependent on value	
Suspended sediment	1 mg/L	
Total and dissolved nutrients:		
Ammonium[1] plus organic nitrogen	.2 mg/L	
Ammonium[1]	.01 mg/L	
Organic nitrogen (calculated)	.2 mg/L	
Nitrate plus nitrite	.01 mg/L	
Nitrite	.01 mg/L	
Nitrate (calculated)	.01 mg/L	[2] 10 µg/L
Phosphorus	.01 mg/L	
Total herbicides: [3]		
Atrazine	.2 mg/L for 1983	[2] 3 µg/L
	.1 mg/L for 1984	[4] 3 µg/L
Cyanazine	.2 mg/L	[4] 1 µg/L
Propazine	.2 mg/L	[4] 10 µg/L
Alachlor	.05 mg/L	[2] 0 µg/L
		[4] 2 µg/L
Metolachlor	.1 mg/L	[4] 100 µg/L

[1] Ammonium in this report represents ammonia plus ammonium.
[2] Maximum Contaminant Level (U.S. Environmental Protection Agency, 1992).
[3] The detection limit of herbicides is as described above if the recommended 1,900 mL of sample is used in analysis. For samples with substantial sediment concentrations, such as was the case with many runoff samples, a smaller volume of sample was used for analysis because of interferences caused by the suspended material. For samples with less than 1,900 mL of sample, the detection limit varied proportionately with the amount of sample used for analysis.
[4] Lifetime health advisory level (U.S. Environmental Protection Agency, 1992).

Land-use data were provided by the farmers for each 2-week period. Information on commercial-fertilizer, manure, and herbicide applications including the amount, time, and location of application, was collected. Data also were collected on time of plowing, planting, and harvesting. Manure samples were collected at the time of selected major manure applications to the site. These samples were analyzed for total ammonia plus organic nitrogen and total phosphorus.

Shallow soil samples were collected three times a year. Initially, soil was collected from a 2-in. depth at 13 locations distributed over the site, and was composited in a 1-qt glass bottle. These soil samples were analyzed for particle-size distribution, pH, major ions, nutrients, and triazine herbicides (atrazine, simazine, prometone, prometryne, and propazine). The major ions and nutrients in the shallow soil samples were analyzed by use of methods for bottom material described by Skougstad and others (1979). (All other methods are described in Chichester, 1988.) Soil samples for particle-size and herbicide analyses continued to be collected by this procedure throughout the study period. However, beginning in the fall of 1983, soil samples for soluble nitrogen and soluble phosphorus analysis were collected in the spring and fall, by use of a deep-soil probe. In the fall of 1983, 2-ft-deep soil samples were collected at 13 locations; each 2-ft core was split into two 1-ft sections for analysis. In the spring of 1984, 8-in.-deep soil samples were collected at three locations.

Samples to determine the nutrient content of soil water in the top 9 ft of soil were collected by means of 17 porous-cup lysimeters at depths of 3, 6, or 9 ft. Because of the large percentage of clay in the soils at the site, the large hydrostatic pressure of the clays, and clogging of the porous cups by clay particles, many of the lysimeters failed to collect soil-water samples soon after installation. Seven lysimeters operated for more than 1 month, and 5 operated for the study period. The 3-, 6-, and 9-ft lysimeters all operated simultaneously at only one location; however, the 6-ft lysimeter only collected samples for 2 months, but the other two remained useful for the study period.

Surface runoff from the site was diverted through a 9-in. Parshall[3] flume located beside the gage house. Stage was recorded continuously with a graphic recorder and an ADR. Runoff samples were collected with a float/stage-triggered PS-69 automatic sampler modified with a refrigeration unit. Perforated intakes for the automatic sampler were positioned in the center of the flume. Each time a sample was collected, a mark was automatically made on the graphic runoff record to identify the stage associated with that sample. Runoff from snowmelt or from rainfall on snow-covered, frozen ground was difficult to measure and sample precisely. Small volumes of water moving through the flume over long periods sometimes amounted to substantial runoff volumes, but were at the lower limits of the recording capacity. When the water level in the flume was very low, air entering the sampling tube caused loss of vacuum to lift the samples into the automatic sampler. Also, freezing temperatures occasionally caused recording and sampling equipment to perform sluggishly or malfunction, and ice contributed to data-collection error. Selected discrete runoff samples were analyzed for suspended sediment, total and dissolved nutrients, and sometimes herbicides. Flow-weighted mean storm concentrations and loads were calculated from continuous graphs of discharge and constituent concentrations constructed by use of recorded stage and laboratory data from the discrete storm samples analyzed. Flow-weighted mean event concentrations and event loads were calculated by use of methods described by Porterfield (1972).

Suspended-sediment and nutrient loads for unsampled runoff events were estimated by use of regression equations derived from log-transformed calculated suspended-sediment and nutrient loads from sampled runoff events as a function of log-transformed total runoff (table 3). The runoff and load data were normalized by log transformations. Regression analyses for suspended sediment, total nitrogen, total ammonium plus organic nitrogen, total nitrate plus nitrite, and total phosphorus were performed separately for data from the growing season (May through October) and the nongrowing season (November through April) and were used to make estimations on the basis of runoff occurring during similar field conditions. Scatter plots were used to verify all the regression analysis, as demonstrated by the total-nitrogen loads plots in figure 3. For the 21-month study period, 22 percent of the total runoff of 714,000 ft^3 was used to estimate 23 percent of the suspended-sediment load, and 32 percent of the total runoff was used to estimate 25 percent of the total nitrogen, 24 percent of the total ammonium plus organic nitrogen, 32 percent of the total nitrate plus nitrite, and 29 percent of the total phosphorus loads. The sum of the individually estimated loads of total ammonium plus organic nitrogen and total nitrate plus nitrite approximated the individually estimated total-nitrogen load to within 3.0 percent. Data for estimated and sampled individual runoff events were summed to estimate monthly and annual loads.

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[3] Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Table 3. Regression statistics for the log of suspended-sediment load, in tons, and the log of total nutrient load, in pounds, as a function of the log of total runoff, in cubic feet
[<, less than]

Season [1]	Dependent variable	Degrees of freedom	Regression coefficient	t-statistic	p-value	Intercept	Coefficient of determination	Standard error of estimates		
			Log of total runoff				(Adjusted R^2) [2]	(Log units)	(in percent plus/minus) [3]	
Growing	Suspended sediment	23	1.389	12.923	<0.001	-4.931	0.88	0.397	149	60
Nongrowing	Suspended sediment	47	.965	10.229	<.001	-4.130	.69	.570	272	73
Growing	Total nitrogen	19	.875	10.618	<.001	-2.995	.85	.300	100	50
Nongrowing	Total nitrogen	32	1.028	13.468	<.001	-3.566	.82	.400	151	60
Growing	Total ammonium plus organic nitrogen	19	.906	9.603	<.001	-3.222	.83	.343	120	55
Nongrowing	Total ammonium plus organic nitrogen	32	1.035	12.772	<.001	-3.636	.80	.426	167	62
Growing	Total nitrate plus nitrite	19	1.007	7.429	<.001	-4.303	.74	.487	207	67
Nongrowing	Total nitrate plus nitrite	29	.896	15.483	<.001	-4.315	.82	.314	106	52
Growing	Total phosphorus	19	1.178	16.023	<.001	-4.280	.93	.267	85	46
Nongrowing	Total phosphorus	33	.927	10.913	<.001	-3.531	.78	.437	174	63

[1] Growing season is May through October. Nongrowing season is November through April.
[2] R^2 adjusted for degrees of freedom to allow more valid comparison between seasons.
[3] Calculated as described by Tasker (1978).

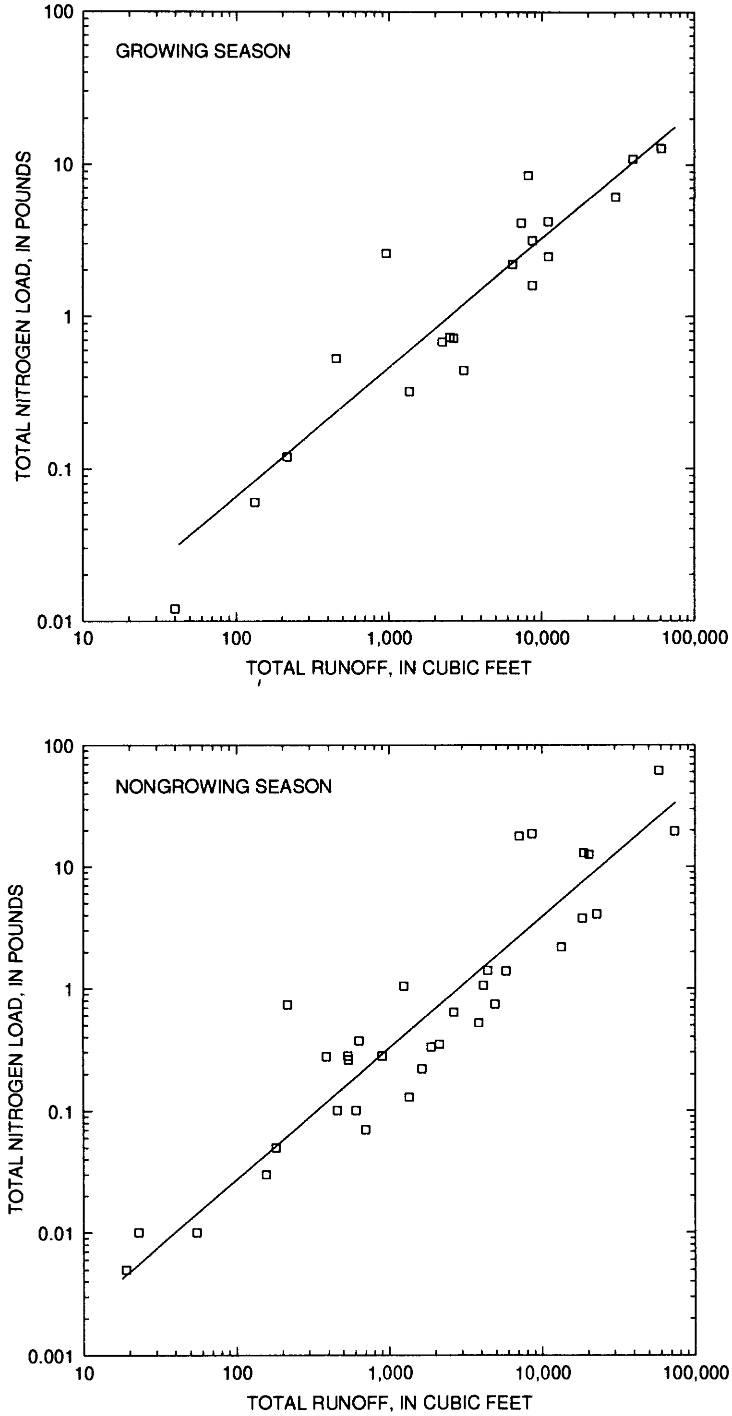

Figure 3. Total nitrogen load as a function of total runoff for runoff events at Field-Site 1 during the growing (top) and nongrowing (bottom) seasons. (Regression line statistics are shown in table 3.)

Fourteen wells were drilled at the site by air-rotary methods, cased to bedrock, then continued as open holes to the first major water-bearing zone in the unconfined, carbonate-rock aquifer. The 6-in. (inner diameter) steel well casings were grouted in place and bentonite was used as an additional surface seal. Water levels were measured continuously at six wells (referred to as primary observation wells) and intermittently at the other wells (table 4). Initially, water from all wells was sampled according to methods described by Lietman, Gerhart, and Wetzel (1989); then, six wells and the spring were selected for continued sampling. Water samples from wells were measured for specific conductance and analyzed for nutrient concentrations every 3 to 4 weeks during nonrecharge periods and more frequently during several recharge periods, and for selected herbicides periodically throughout the study period. Additionally, water temperature was measured and major-ion concentrations in well-water samples were analyzed several times during the 1983 water year.[4]

In this report, statistical procedures were used for summarizing data, making statistically supported inferences about the data, and defining explanatory relations between various data sets. Data summarization was accomplished with descriptive statistics such as means, medians, ranges, standard deviations, and percentiles. Statistical inferences about data normality, differences between data set means or medians, and linear-regression analyses were based on the results of hypothesis testing. All hypothesis tests were performed at the 95-percent confidence level. Data normality was tested by use of the Shapiro-Wilk method. Differences between central values of data sets were tested with nonparametric procedures: the Wilcoxon Signed-rank for match-pair data, and the Mann-Whitney Rank Sum test for independent observations. These procedures do not require an assumption of normality or transformation of the data. Explanatory relations between hydrologic, climatic, and agricultural-activities data were explored with linear regression. The Mallows' C_p statistic and the adjusted R^2 values (adjusted for degrees of freedom and number of independent variables) were used to choose the best regression models. The F-test was used to test for overall regression significance, and the t-test was used for significance of regression coefficients. In addition, residual plots and diagnostics for outliers, influence, and leverage were evaluated for each regression.

A more complete discussion of basic descriptive, parametric, and nonparametric procedures used can be found in Iman and Conover (1983) and Conover (1980). All statistical procedures were run on software from the Statistical Analysis System (SAS) Institute, Inc. (1982a, 1982b), P-STAT, Inc. (1986), and SYSTAT, Inc. (Wilkenson, 1988).

Quality Assurance

The quality of nutrient and atrazine laboratory analyses was evaluated by use of several types of samples. Blank samples of distilled water, routinely submitted for analysis, were used to evaluate the potential contamination of samples during preparation and analysis at the laboratory. USGS round-robin standard-reference water samples (V.J. Janzer, U.S. Geological Survey, written commun., 1983, 1984; Janzer, 1983; Janzer and Latal, 1984) were used to determine laboratory accuracy. Field-split duplicate water samples were used to measure the laboratory precision of the analysis for the individual constituents.

The Wilcoxon Signed-Rank test and the Mann-Whitney Rank Sum test were used to evaluate the nutrient data collected at all surface-water and ground-water data-collection locations for the Conestoga project during the Field-Site 1 study period. Table 5 shows the constituents analyzed and summary statistics used in the quality-assurance analysis.

For each blank sample, the difference between the reported concentrations and the detection limit was calculated for each constituent. The results of a Wilcoxon Signed-Rank test indicated that the median of the analytical concentrations of the blanks varied significantly from the detection limit at the 95-percent confidence level for two of the five dissolved nutrient constituents--ammonium and ammonium plus organic nitrogen. This suggests either a positive bias for reported concentrations near the detection limit for these constituents or less than pure distilled-water blanks.

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[4] Water year is the 12-month period beginning on October 1 and ending on September 30; it is designated by the calendar year in which it ends.

Table 4. Ground-water data-collection locations and descriptions

[All depths shown in feet below land surface; (gal/min)/ft, gallon per minute per foot; <, less than; E, estimated value; °, degrees; ', minutes; ", seconds; NA, not applicable; --, no data; N, nutrient data only; I, sampled for major ions; NWL, nutrient and continuous water-level data; WL, intermittent water-level data only; NWLP, nutrient, continuous water-level, and herbicide data]

Well number	Latitude	Longitude	Total depth of well	Depth of bottom of casing (overburden thickness)	Depth to bedrock	Depth of water table surface: Maximum (lowest water level)	Depth of water table surface: Minimum (highest water level)	Specific capacity (gal/min)/ft	Data collected	Sampling depth
LN SP58	40°07'44"	75°58'39"	spring	NA	NA	NA	NA	NA	N + I	NA
LN 1643	40°07'41"	75°58'43"	100	68.9	20	38.75	33.66	20	NWL + I	82
LN 1644	40°07'42"	75°58'43"	75	77.6	22	--	--	30	WL	43
LN 1645	40°07'46"	75°58'43"	80	24.2	7	52.53	49.00	160	NWLP + I	62
LN 1646	40°07'44"	75°58'47"	125	99.4	5	73.21	69.47	130	NWLP + I	107
LN 1647	40°07'40"	75°58'49"	75	37.3	17	--	--	<.25	WL + I	65
LN 1648	40°07'38"	75°58'46"	100	7.2	2	--	--	.50	WL + I	72
LN 1649	40°07'44"	75°58'54"	85	38.7	35	37.94	29.35	14	NWL + I	72
LN 1650	40°07'41"	75°58'51"	125	89.7	63	74.52	70.14	36	NWL + I	112
LN 1651	40°07'39"	75°58'51"	105	71.7	68	71.27	62.65	20	NWL + I	92
LN 1652	40°07'38"	75°58'53"	125	79.5	12	--	--	<.25	WL + I	83
LN 1653	40°07'37"	75°58'56"	132	105.1	27	--	--	3.0	WL + I	117
LN 1659	40°07'39"	75°58'45"	142	E84	18	--	--	.50	WL	98
LN 1660	40°07'45"	75°58'53"	150	39.2	12	--	--	.75	WL	73
LN 1661	40°07'44"	75°58'56"	75	38.5	20	--	--	3.0	WL	63

Table 5. Summary statistics for quality-assurance analyses
[All values are shown in milligrams per liter as nitrogen or phosphorus; Min, minimum; Max, maximum; n, number of samples; <, less than; --, no data]

Constituent	Detection limits	Concentrations of all samples		Blanks				Standards						Duplicates					
					Concentration		Median difference from detection limit		Concentration		Difference between known and measured values				Concentration		Difference between pairs		
		Min	Max	n	Min	Max		n	Min	Max	Min	Max	Median	n	Min	Max	Min	Max	Median
Total nitrate plus nitrite	0.04	<0.04	36	--	--	--	--	--	--	--	--	--	--	119	<0.04	36	-5.0	4.0	0.00
Dissolved nitrate plus nitrite	.04	<.04	34	8	<0.04	0.06	0.00	--	--	--	--	--	--	128	<.04	34	-4.0	8.5	.00
Total nitrate	.04	--	--	--	--	--	--	6	2.5	4.0	-2.6	0.50	0.20	--	--	--	--	--	--
Dissolved nitrate	.04	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Total nitrite	.01	<.01	1.5	--	--	--	--	--	--	--	--	--	--	119	<.01	6.9	-1.2	.50	.00
Dissolved nitrite	.01	<.01	2.2	8	<.01	<.01	.00	--	--	--	--	--	--	134	<.01	6.0	-1.0	.70	.00
Total ammonium plus organic nitrogen	.20	<.20	79	--	--	--	--	1	1.1	1.1	.30	.30	.30	111	<.20	10	-1.9	2.0	.00
Dissolved ammonium plus organic nitrogen	.20	<.20	25	8	<.20	1.0	.13	--	--	--	--	--	--	116	<.20	9.2	-2.4	1.9	-.05
Total ammonium	.02	.06	21	--	--	--	--	3	.16	1.9	-.01	.30	.03	120	<.02	5.7	-5.0	.60	.00
Dissolved ammonium	.02	.03	18	8	<.02	.13	.04	--	--	--	--	--	--	136	<.02	5.3	-5.1	3.1	.00
Total phosphorus	.02	<.02	20	--	--	--	--	6	.50	1.4	-.03	.03	.01	114	<.02	.62	-.33	.30	.00
Dissolved phosphorus	.02	<.02	8.0	8	<.02	.03	.00	--	--	--	--	--	--	123	<.02	.45	-.12	.12	.00

For reference samples, evaluation of the Wilcoxon Signed-Rank test results for total nitrate and total phosphorus revealed no significant differences from their expected concentrations at the 95-percent confidence level for six samples analyzed for each. This indicates an acceptable degree of accuracy for these constituents. Since there were fewer reference samples analyzed for the other two constituents, they were not evaluated by this statistical method. The PaDEP reported concentrations for total ammonium within 1.5, 0.5, and 0.5 standard deviations of the mean for three samples reported by all the laboratories participating in these standards, and for total ammonium plus organic nitrogen, the reported concentration for one sample was within 0.5 standard deviations of the mean.

The duplicate data were compared by use of the Mann-Whitney Rank Sum test, which compares the data as two independent groups. The results of this test showed no significant difference at the 95-percent confidence level between groups for any of the constituents, indicating an acceptable degree of laboratory repeatability.

For atrazine, three distilled-water blanks were analyzed by PaDEP and all had concentrations less than the detection limit of 0.2 μg/L. Concentrations of two atrazine standards prepared by the USGS laboratory in Atlanta, Ga., were 0.9 and 3.6 μg/L. These standards were analyzed by the PaDEP laboratory, which determined concentrations of 0.7 and 3.2 μg/L, respectively. Four samples were submitted to both the PaDEP and USGS laboratories; concentrations of two of these samples were reported to be 0.2 μg/L by both labs, and the other two concentrations were reported to be less than the detection limit by PaDEP and 0.4 and 0.1 μg/L by the USGS lab. Twenty-four duplicate samples also were submitted to the PaDEP laboratory; concentrations of all but six samples were at or less than the detection limit for both the sample and its duplicate. Concentrations for the other six pairs are 0.6 and 0.6, 0.3 and less than 0.2, 0.4 and 0.4, 0.3 and 0.3, 0.2 and 0.5, and less than 0.2 and 0.3 μg/L. The concentrations of the data pairs are near the detection limit and differ only slightly, and the degree of repeatability was acceptable.

The Kemmerer-type point sampler (used for well sampling) was washed with distilled water and, periodically, the wash water (sampler blanks) was analyzed for nutrients (eight samples) and herbicides (three samples). The mean nutrient concentrations in the nutrient sampler blanks were similar to those in laboratory distilled water, and all of the herbicide sampler blanks had nutrient concentrations less than the detection limit. Therefore, the cleaning procedure used for the point sampler was considered to be sufficient to prevent contamination of the samples.

FACTORS THAT CAN AFFECT QUANTITY AND QUALITY OF WATER

Topography

Field-Site 1 is a gentle to moderately sloping surface-water basin (fig. 2) with a total relief of 84 ft. Surface elevation ranges from 451 ft above sea level at the eastern edge of the site to 535 ft at its northern edge. The slope of the land surface ranges from 2 percent in the southwestern part of the site to 22 percent in the northeastern part. The median slope of the land surface is about 6 percent.

Physiography and Geology

The site is located within the Piedmont Physiographic Province in the Conestoga Valley Section (U.S. Department of Agriculture, 1985). The Conestoga Valley Section consists predominantly of carbonate and shale rocks that have been deformed repeatedly by folding and faulting.

The site is underlain by dolomitic rocks of the Zooks Corner Formation of Cambrian age. This formation consists primarily of interbedded, thin- to thick-bedded, white to medium-dark gray, finely crystalline dolomite, silty and sandy dolomite, and dolomitic sandstone (Meisler and Becher, 1971). Lithologic logs developed during the drilling of 14 wells indicate that soils are underlain by a 10- to 100-ft-thick weathered zone, which, in turn, rests on relatively fresh dolomite of the Zooks Corner Formation (fig. 4, table 4). Numerous cavities and voids, in some areas filled with silt or clay, are present at all depths in both the weathered and fresh dolomite.

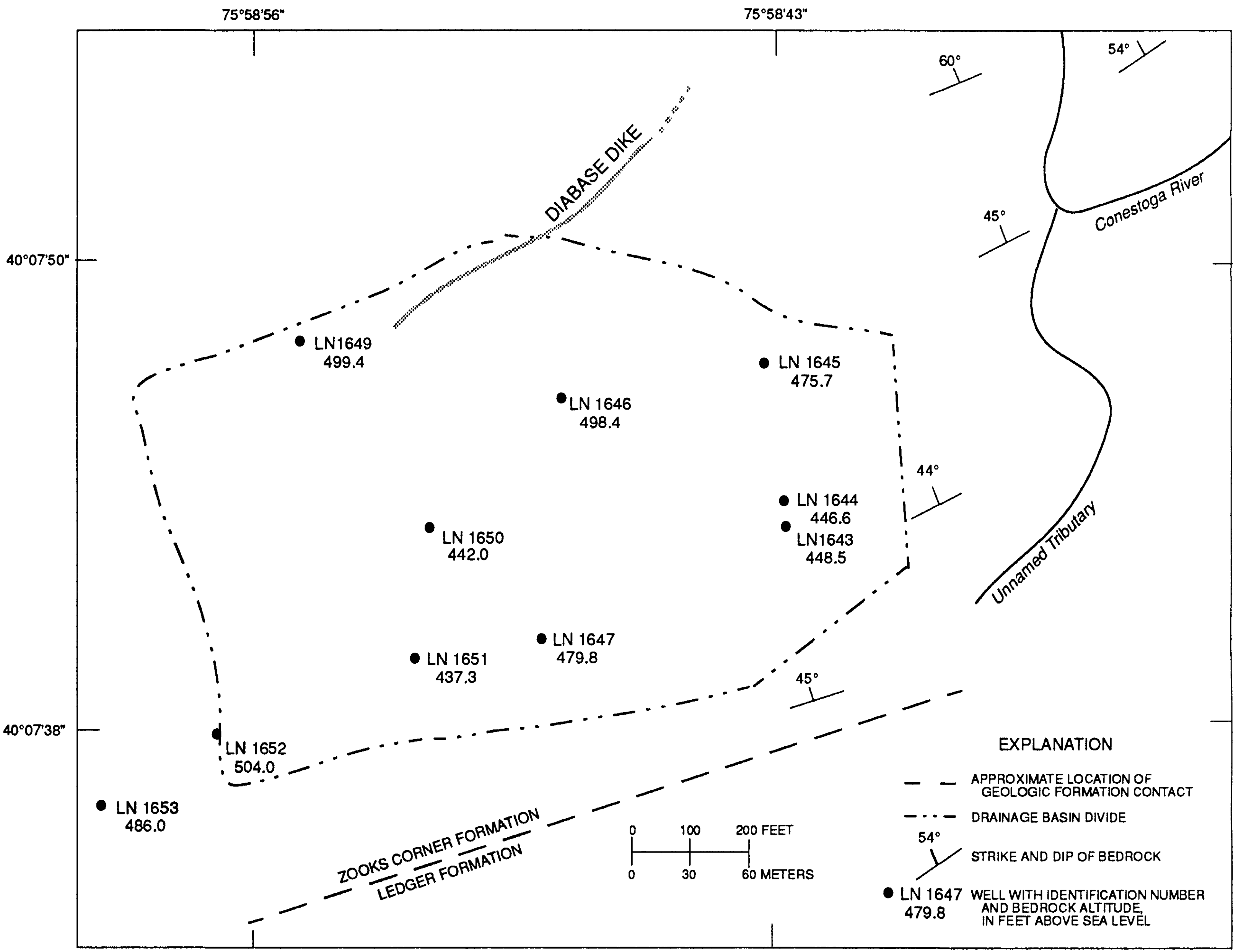


Figure 4. Bedrock altitudes, bedding orientation, and geologic-formation boundaries at Field-Site 1.

Although no outcrops of the Zooks Corner Formation are exposed at the site, nearby outcrops of the Ledger Formation were used for field measurements (fig. 4). The Ledger Formation, which conformably overlies the Zooks Corner Formation, has a similar depositional history and structural features. Jointing of the rock in this area has a preferential NE to SW trend. Strike of the formation ranges from N. 60° E. to N. 70° E. and dip ranges from 40° NW. to 70° NW. Mean values for strike and dip are N. 65° E. and 54° NW., respectively.

The Pennsylvania State Geologic Map (Berg and others, 1980) shows a diabase dike of Triassic age that protrudes into the northern edge of the site (fig. 2). Diabase float and hydrologic anomalies confirm the existence of this dike. A ground-magnetic geophysical survey showed that the diabase dike trends east-northeast and extends approximately 300 ft into the north-central part of the site.

Precipitation and Evapotranspiration

Quantity

Precipitation at the field site averages about 41.5 in. per year on the basis of 30 years of record at Morgantown, Pa.—a nearby National Oceanic and Atmospheric Administration (NOAA) station. Total precipitation for the study period at the site was 91.2 in., and, as shown below, approximately equalled the annual long-term average for the partial 1983 water year and was about 44 percent wetter than the annual long-term average for the 1984 water year (National Oceanic and Atmospheric Administration, 1982, 1983, 1984).

	Precipitation, in inches	
Period	Field-Site 1	Morgantown (1951-80)
Jan. 1 - Sept. 30, 1983	31.4	31.9
Oct. 1, 1983 - Sept. 30, 1984	59.8	41.5

Some reference point is needed to compare climatic data from year to year and to determine whether a year or season is wet or dry. A comparison of total monthly precipitation (fig. 5) to evapotranspiration is helpful in estimating how much precipitation was available for crop growth, ground-water recharge, and runoff. An estimate of potential evapotranspiration was made by use of techniques described by Thornthwaite (1948) and mean monthly air temperatures at the Morgantown NOAA station. Potential evapotranspiration is the amount of water available for evapotranspiration if all soil-moisture requirements in a recharge area are met by precipitation (Freeze and Cherry, 1979). Because this generally does not occur, actual evapotranspiration is usually less than potential evapotranspiration.

Potential evapotranspiration for the site was estimated to be 27.7 in. or 70 percent of the total precipitation for the 1983 water year, and 25.7 in. or 43 percent of total precipitation for the 1984 water year (fig. 6). Although total precipitation for 1983 was about equal to the 1951-80 mean, serious soil-moisture deficiencies were observed at the site from June through September--most of the primary growing season. For these 4 months, total precipitation was 8.7 in. less than potential evapotranspiration. In 1984, monthly precipitation exceeded or nearly met potential evapotranspiration from May through July, providing sufficient water for the crops.

The number and distribution of storms (fig. 7), as well as their intensities and durations, affect the amount of runoff and recharge. During the study period, 169 storms occurred. For the purpose of this report, a storm is defined as a minimum of 0.10 in. of precipitation bounded by an interval of 1 hour or more of less than 0.014 in. (the minimum measurable amount) of precipitation. Total precipitation was measured for 64 percent of the storms and estimated for part or all of the other storms from records of nearby USGS raingages or the Morgantown NOAA station.

Storms occurred most frequently during the spring (March through May). For both 1983 and 1984, 10 to 16 storms occurred on 12 to 16 days of each spring month, accounting for 41 percent of the storms during the study period.

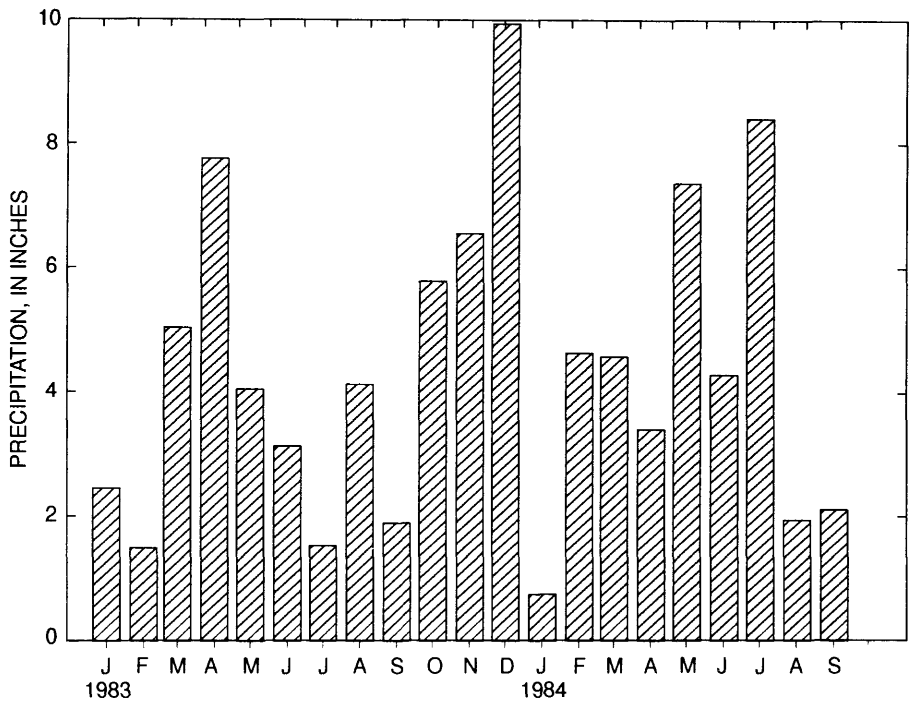


Figure 5. Total monthly precipitation at Field-Site 1.

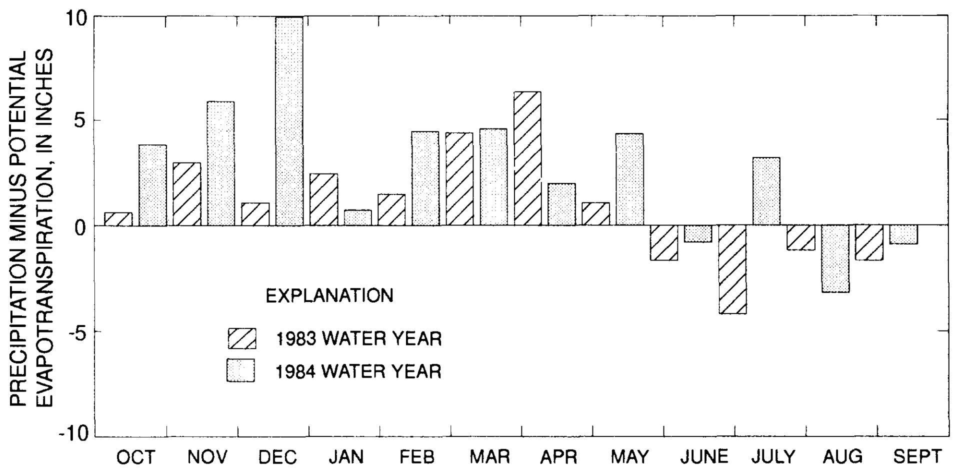


Figure 6. Monthly precipitation minus monthly potential evapotranspiration at Field-Site 1.

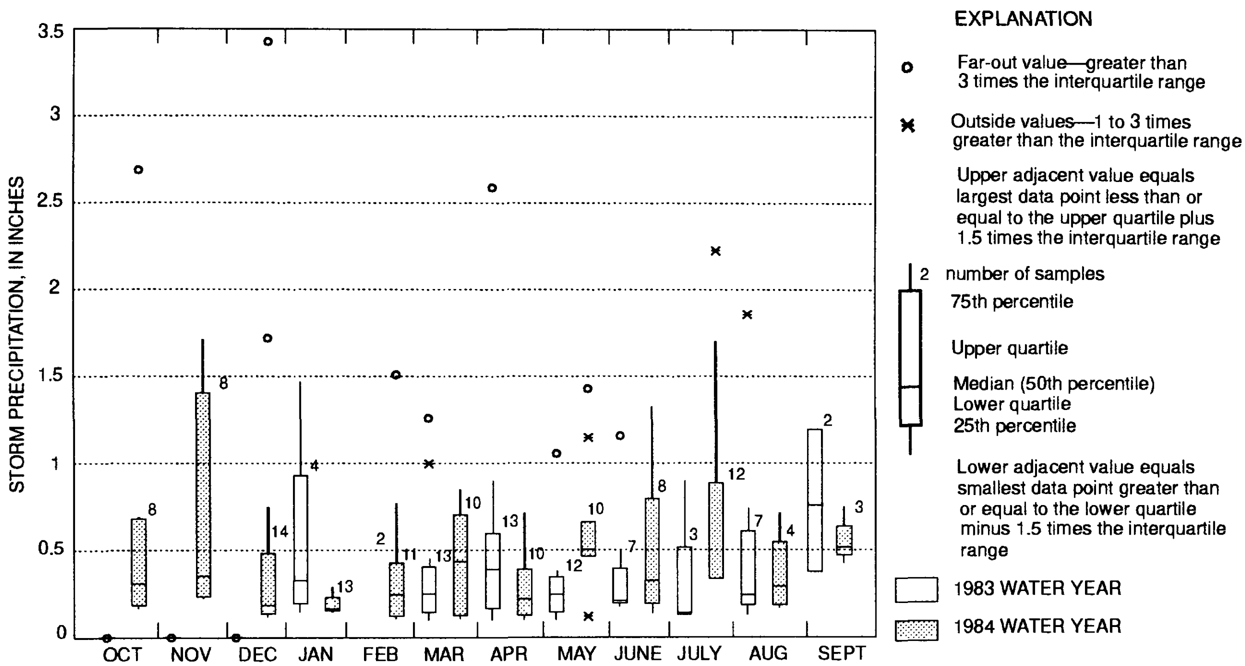


Figure 7. Distribution of storm precipitation at Field-Site 1 during January through September of the 1983 water year and the 1984 water year.

The median total storm precipitation for the study period was 0.29 in. The 20 storms with amounts of 1.0 in. or more of precipitation were scattered throughout the study period. Only four storms produced more than 2.0 in. of precipitation; the largest of these produced 3.4 in. of precipitation on December 12, 1983. Monthly median total storm precipitation ranged from 0.14 to 0.39 in., except for 4 months, February and September 1983 and May and September 1984, for which it ranged from 0.46 to 0.79 in. The season with the greatest median storm precipitation (0.43 in.) was the fall (September through November).

Intensities were measured for 125 storms during the study period. Thirty-minute intensities of as much as 1.5 in. of precipitation were recorded; the median 15- and 30-minute intensities were 0.08 and 0.13 in., respectively. The median 30-minute intensity was greatest in the fall, 0.20 in. Although the median 30-minute intensity for the summer (June through August) storms was less, 0.18 in., summer storms accounted for 16 of the 20 storms with the greatest 30-minute intensities, greater that 0.32 in. Fifteen-minute intensities also were greatest in the summer when 14 of the 17 storms with greater than 0.25-in. intensities occurred. Spring and winter (December, January and February) storms had relatively small median 30-minute intensities, 0.08 and 0.09 in., respectively.

Precipitation duration was measured for 123 storms; the median duration was 2.8 hours. Summer storms had the shortest duration; the median was 1.4 hours. Many short showers, as well as the long rains, occurred during the spring. The median length of spring and fall storms was 2.8 and 2.6 hours, respectively. The median precipitation duration for the winter storms, however, was much greater than for any other season, 4.3 hours. (Because the precipitation gage measured the amount of precipitation that entered a standpipe, and because snow sometimes collected in the funnel and slowly melted and dripped into the standpipe, the actual durations of precipitation possibly are less than recorded. However, snowstorms did not constitute most of the winter storms, and any elongation of the recorded duration of the storms also reflected the availability of the precipitation to runoff and recharge.) Spring storms accounted for 62 percent of the 13 storms lasting longer than 10 hours, and 44 percent of the 32 storms lasting longer than 5.0 hours; winter and fall storms accounted for about equal parts of the remainder.

Quality

Precipitation samples were collected during three storms. Nitrate concentrations in these samples ranged from 0.18 to 0.57 mg/L; the average was 0.4 mg/L; ammonium concentration ranged from 0.25 to 0.71 mg/L; the average was 0.4 mg/L (table 6). The average nitrate concentration in precipitation samples collected at the site compares well with values for the site location interpolated from published maps of 1983 and 1984 annual volume-weighted mean nitrate concentration determined from composite samples collected weekly at 13 locations in Pennsylvania (Lynch and others, 1984, 1985). Average ammonium concentration for precipitation samples collected at the field site was about twice the annual mean interpolated for the field site from the Pennsylvania study. These elevated concentrations probably were caused by volatilization of ammonium from large quantities of manure stored and spread on the field site and surrounding areas.

Table 6. Estimated daily deposition of nitrogen from precipitation at Field-Site 1

		Nitrate	Ammonium
Mean concentration for Field-Site 1 (milligram per liter as nitrogen)	1983-1984	0.4	0.4
Volume-weighted mean concentration [1]	1983 calendar year	[2] .4	[3] .2
(milligram per liter as nitrogen)	1984 calendar year	[2] .5	[3] .2
Estimated mean-daily deposition [4]	1983 water year	.01	.005
(pound of nitrogen per acre)	1984 water year	.02	.007

[1] Lynch and others, 1984; 1985.

[2] Concentration for Field-Site 1 interpolated from map for annual ion concentration for Pennsylvania.

[3] Concentration for Field-Site 1 interpolated from nearby Pennsylvania study-site locations.

[4] Calculated by use of measured rainfall from each water year for the field sites and volume-weighted mean concentration from this table for each corresponding calendar year.

Input loads of nitrate and ammonium to the site from precipitation were calculated from the precipitation-quantity data for the site during the study period and the mean annual constituent concentration from the Pennsylvania study (table 6). These input loads amounted to about 300 lb [7.8 (lb/acre)/yr] of nitrogen from precipitation during the study period.

Land Use and Agricultural Activities

Agriculture is the only land use at the site. The entire 22.1 acres was cropland during the study period. Corn and alfalfa were the major crops; tobacco, rye, and pumpkins also were cultivated. Crop locations and acreage are shown in figure 8 and table 7, respectively. Dairy cow and heifer manure (fig. 9), as well as commercial fertilizer, were applied to all fields except the one planted in alfalfa. Conventional tillage practices employing a moldboard plow were used.

Each spring when the field was plowed, soil was pushed into a long, deep gully (formed west to east in the center of the lower cornfield beginning at the alfalfa field and ending at the gage station) as well as small tributary gullies (fig. 9), so that only a depression in the topography remained. Beginning with the first heavy rains after plowing both years, soil washed from these gullies into the receiving stream. By the end of the summer, the gully was up to 3 ft deep and 2 ft wide and was lined by large boulders.

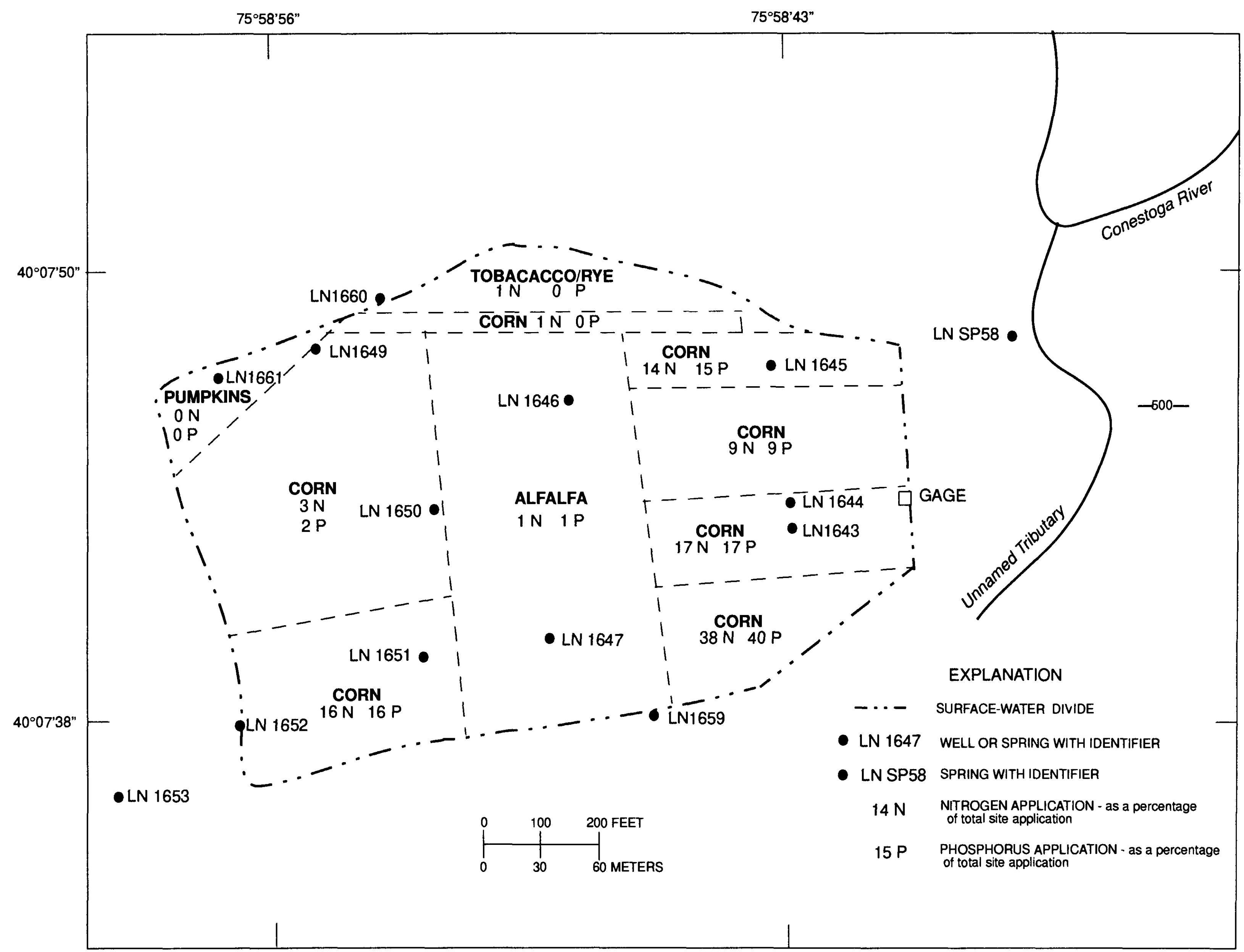


Figure 8. Distribution of corps and nitrogen and phosphorus applications at Field-Site 1, January 1983 through September 1984.

Table 7. Crops and acreage at Field-Site 1, 1983-84
[--, none planted]

Crop	Acres	
	1983	1984
Corn	14.4	14.4
Alfalfa	5.4	5.4
Rye	--	1.9
Tobacco	1.9	--
Pumpkins	.4	.4
Total	22.1	22.1

Fields were spread with manure and commercial fertilizer and plowed and disked in late April 1983 and early May 1984, when the fields were dry enough to work. Corn planting, followed by herbicide spraying was done as early as possible in May. Corn was harvested in late September both years, and manure was applied. After the 1982 and 1983 corn crops were harvested, rye was planted on the corn acreage as a winter cover crop and turned under with the spring plowing. Manure was spread on the cornfields 1 to 15 days of each month except January and February 1983 and months when the crop was planted or growing. Figure 10 shows the approximate crop canopy on the cornfields. The estimations were based on visual inspections and land-use data provided by the farmer. Alfalfa was cut as frequently as feasible during the spring and summer, approximately four times per year. Alfalfa fields remained undisturbed throughout the winter.

Corn yields at the site during the study period averaged about 140 bushels per acre; alfalfa yields were estimated to be about 5 ton/acre (Jeff Stoltzfus, Pennsylvania Extension Service, oral commun., 1990).

Nitrogen and phosphorus were distributed unevenly over the site (fig. 8). The largest applications were to cornfields; the field in the southeast corner (nearest the barn) received most of the manure. Monthly applications of nitrogen and phosphorus from manure and commercial fertilizer for the study period are shown in figure 11. No manure or commercial fertilizer applications were made from October through December 1982 (the remainder of the 1983 water year). Nutrient concentrations of 9.3 lb of nitrogen per ton of manure, and 2.5 lb of phosphorus per ton of manure (from laboratory analysis), along with a record of tons applied to the different areas of the site, were used to estimate the pounds of nitrogen and phosphorus applied. For the whole site for the 21-month study period, 12,100 lb of nitrogen and 3,070 lb of phosphorus were applied. Because no fertilizer was applied to the site from October through December 1982, the average annual application rate for the 1983 and 1984 water years was 270 lb/acre of nitrogen and 70 lb/acre of phosphorus. Ninety-five percent of the nitrogen and all of the phosphorus were from manure. Ninety-eight percent of the nitrogen and 99 percent of the phosphorus were applied to the cornfields. Almost three times as much nitrogen and phosphorus was applied to the cornfields during the 1984 water year as the 1983 water year. Each year, about 50 percent of the total nitrogen and phosphorus application was made during April. The average annual application rates for the corn crop only were about 410 lb/acre of nitrogen and 110 lb/acre of phosphorus. Much of the nitrogen can be lost by volatilization (the rate of this process is controlled by days between application and incorporation into the soil, as well as climatic factors). However, this nitrogen application rate is about three times the amount required for the site's average production of 140 bushels per acre of corn.

Herbicides were applied only to the 14.4 acres of corn. On May 13 and 14, 1983, 14 lb of atrazine and 22 lb of metolachlor were applied; on May 23, 1984, 26 lb of atrazine and 34 lb of metolachlor were applied to the site.

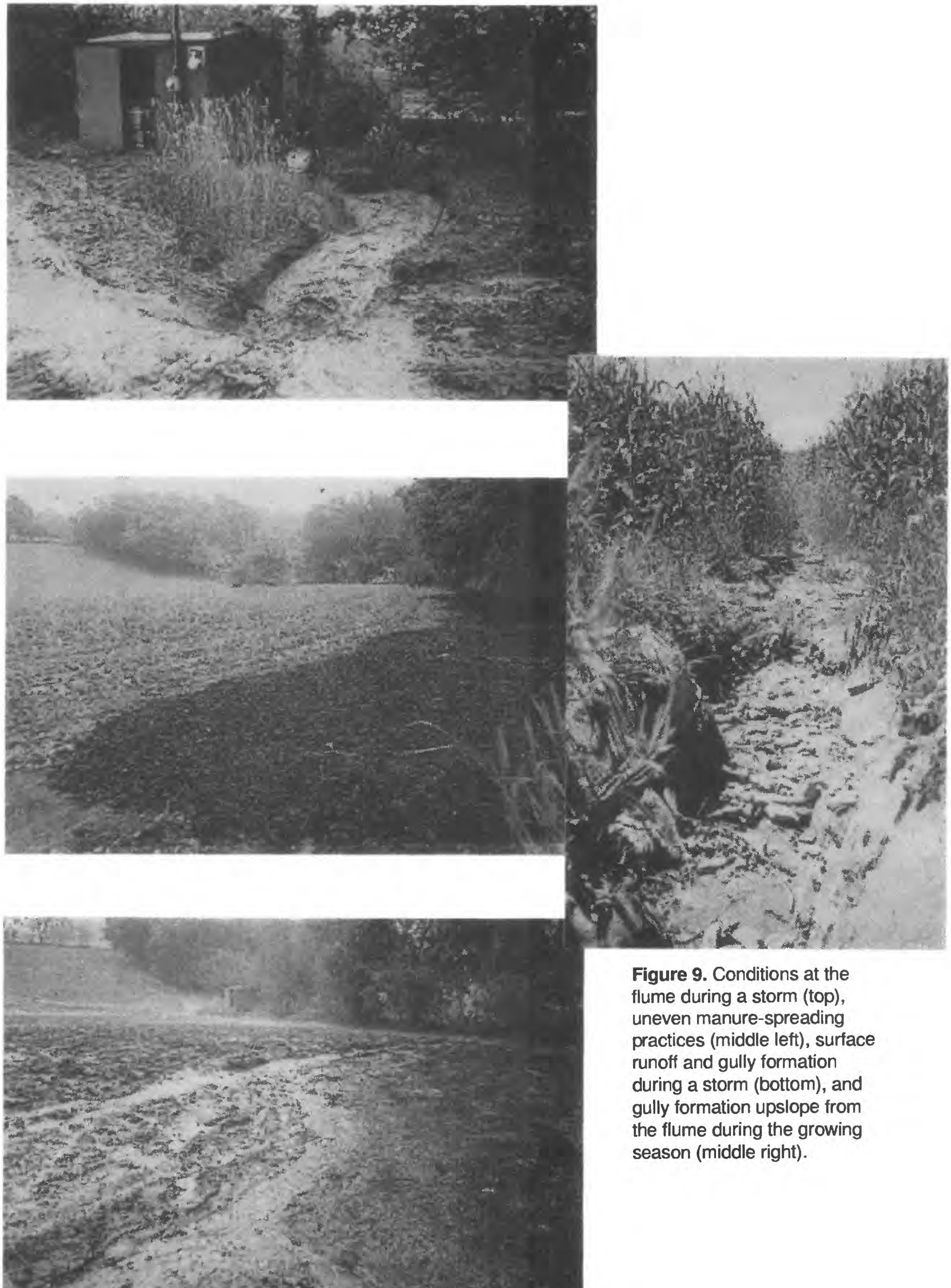


Figure 9. Conditions at the flume during a storm (top), uneven manure-spreading practices (middle left), surface runoff and gully formation during a storm (bottom), and gully formation upslope from the flume during the growing season (middle right).

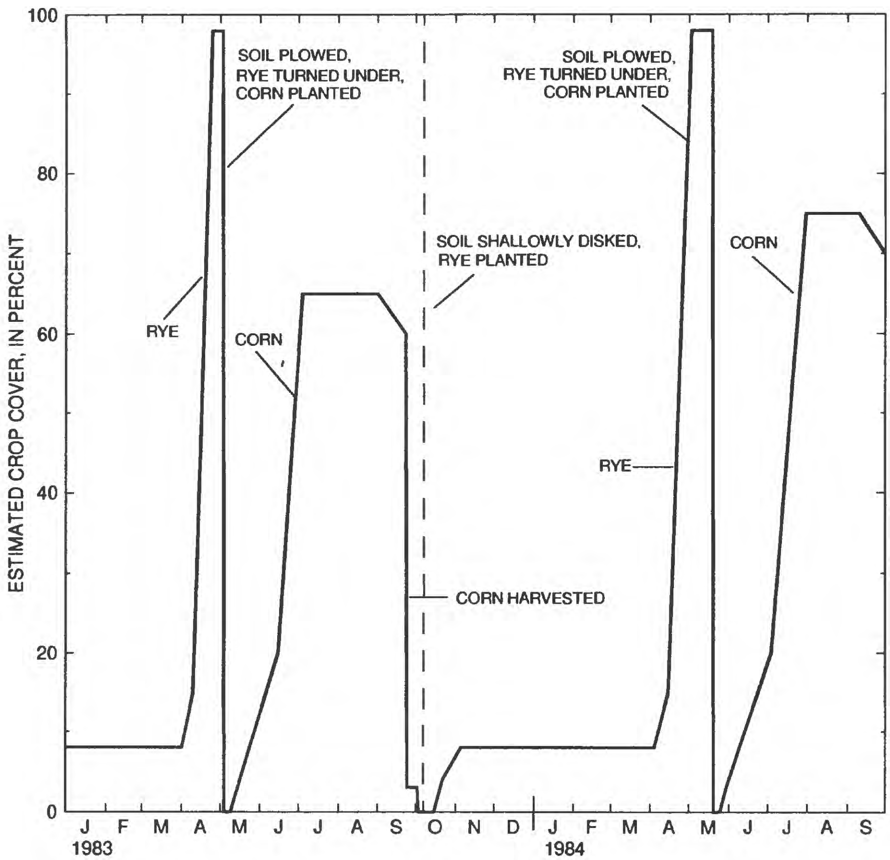


Figure 10. Estimated percent crop cover (canopy) on cornfields, and agricultural-activity information at Field-Site 1.

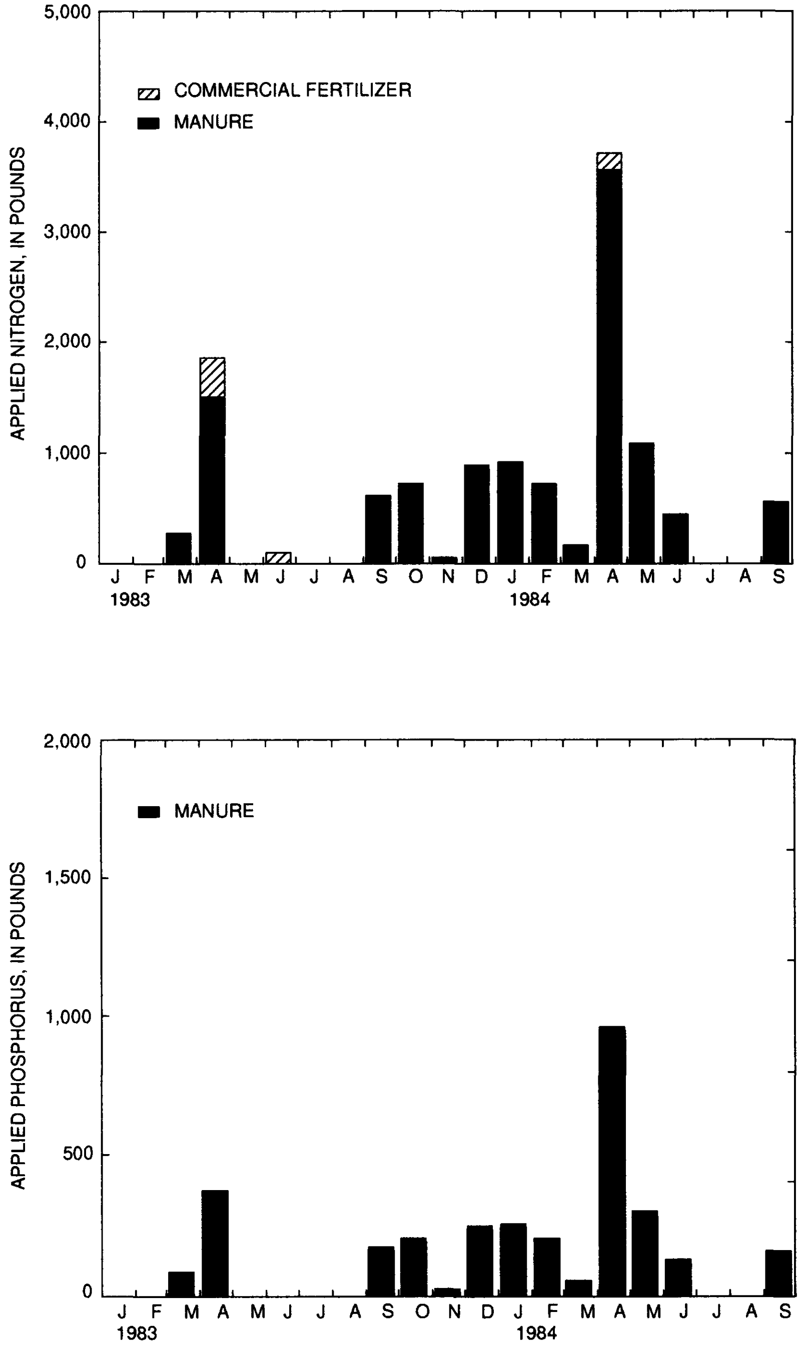


Figure 11. Nitrogen (top) and phosphorus (bottom) applications at Field-Site 1.

Soils

Soils in the study area are classified as Duffield and Hagerstown silt loams (U.S. Department of Agriculture, 1985). These soils are typically deep, well drained, and form in residuum of weathered carbonate rocks. Generally, clay content in the upper 6 in. ranges from 13 to 25 percent. Hagerstown soils, however, generally contain up to 50 percent clay at depths of 20 to 50 in. below land surface compared to 20 percent clay in the same depth interval of Duffield soils. The relatively high clay content in the Duffield and Hagerstown soils compared to other silt loams decreases the water available for plant growth. Soil pH is acidic, from 6 to 7 units at the surface to 5 to 6 units in subsoils. Cation-exchange capacity of the soils ranges from 10 to 20 mg per 100 grams, with the highest capacities near the surface (U.S. Department of Agriculture, 1985).

During the study period, three types of soil samples collected from various depths and locations within the site were analyzed for one or more of the following: particle size, pH, specific conductance, and concentrations of nutrients and herbicides. Selected soil data are summarized in table 8. The first type of soil samples were samples of the top 2 in. of soil composited from 13 locations across the site. In the three composite samples (collected May and July 1983 and early October 1984) analyzed for particle size, only a 2-percent variation was found among sample results. If particles larger than 2.0 mm were not considered (4 to 17 percent of the sample by weight), the topsoil contained an average of 17 percent sand (2.0 mm to 0.062 mm), 57 percent silt (0.004 to 0.062 mm), and 26 percent clay (less than 0.004 mm). Composite soil samples, collected March, May, July, and September 1983, had large variations in soil-moisture content, decreasing from 28 percent in March to 12 percent in July. Soluble nitrate concentration in the soil was lowest in March, 3.3 mg/kg, when the soil temperatures were coolest (nitrate conversion from other forms of nitrogen is slowed with cool temperatures), and greatest in July, 62 mg/kg. Total ammonium plus organic nitrogen varied dramatically, from 770 to 3,500 mg/kg; however, the large variability may be because of the difficulty in subsampling soil when only a very small weight can be used for analysis.

The second type of soil samples, 2-ft soil cores, was collected in the fall of 1983 after harvest (Dale Baker, Pennsylvania State University, written commun., 1984). Large variations in soluble nitrate concentrations were found between the 0- to 1-ft, and 1- to 2-ft soil sections, among triplicate samples (defined here as three samples collected within several feet of each other at a given location), and among the average value of triplicate samples for each soil section at the 13 collection locations spread across the field site. The magnitude of these differences were as great as 6-fold, 11-fold, and 26-fold, respectively. The average of triplicate concentrations at each of the 13 locations ranged from 2.0 to 24 mg/kg of soluble nitrate in the top 1 ft of soil, from 0.58 to 17 mg/kg in the 1- to 2-ft section, and from 1.3 to 21 mg/kg for the entire top 2-ft section. These concentrations were calculated from reported concentrations, in pounds per acre, and the relation of soil density to soil volume (a 6.67 in. depth of soil over 1 acre weighs about 2 million pound) (Dale Baker, Pennsylvania State University, oral commun., 1985). The median soluble nitrate concentration of all the 13 sampling locations at the site was 8.2 mg/kg in the top 2 ft of soil; median concentrations of nitrate were 8.4 and 6.2 mg/kg for the 0-1 ft and 1-2 ft soil sections, respectively. If the median nitrate concentration of 8.2 mg/kg was consistent throughout the top 4-ft soil profile (the corn root zone), then approximately 120 lb/acre of nitrate would have been left in this 4-ft zone after harvest, nearly enough to provide nutrients to an additional corn crop. [At 140 bushels per acre, each bushel removes about 1.1 lb of nitrogen (Robert Anderson, Pennsylvania State Extension Service, written commun., 1989)].

The third type of soil sample was collected in April 1984. The top 8 in. of soil (plow depth) was sampled at three locations: the upper cornfield just west of the alfalfa, the center of the alfalfa field, and the lower cornfield just east of the alfalfa. Concentrations of soluble nitrate were 10, 7.8, and 7.6 mg/kg and concentrations of soluble phosphorus were 0.15, 0.20, and 0.25 mg/kg. The average of these 8-in. soil-sample concentrations of nitrate, 8.4 mg/kg in April 1984, was the same as the average nitrate concentration in the top 8-in. of soil in the fall of 1983. Although manure was applied to the cornfields between the two sampling periods, little conversion of the applied organic nitrogen to nitrate was

Table 8. Summary of soil data at Field-Site 1
[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/kg, milligram per kilogram as nitrogen or phosphorus; Min, minimum; Max, maximum; --, no data]

Sampling period	Sampling depth	pH range, in units		Specific conductance range (µS/cm)		Nutrient concentration range (mg/kg)									
						Soluble nitrate		Soluble ammonium plus organic nitrogen		Total ammonium plus organic nitrogen		Soluble phosphorus		Total phosphorus	
		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Composite [1]	0-2 inches	6.7	6.9	120	353	3.3	62	3.0	5.8	770	3,500	0.18	1.4	300	1,800
Individual	0-1 foot	--	--	--	--	2.0	24	--	--	--	--	--	--	--	--
Fall 1983	1-2 feet	--	--	--	--	.58	17	--	--	--	--	--	--	--	--
	0-2 feet	--	--	--	--	1.3	21	--	--	--	--	--	--	--	--
Individual															
April 1984	0-8 inches	--	--	--	--	7.6	10	--	--	--	--	.15	.25	--	--

[1] March, May, July, September 1983.

expected to have taken place during the winter when soil temperatures were less than 50°F (Pennsylvania State University, 1987), so large variations in soil nitrate concentration between sampling periods were not expected. However, some loss of soluble nitrogen to ground water and runoff probably did occur. Although the soils contained large total concentrations of phosphorus, concentrations of soluble phosphorus measured in the soils in 1984 were very small.

Atrazine was the predominant triazine herbicide detected in analyses of six of the first type of soil samples, samples of the top 2 in. of soil, composited from 13 locations across the site (fig. 12). Soil samples were not analyzed for metolachlor, the other herbicide applied to the field. The maximum concentration of atrazine each year was detected in the first sample collected after application. The maximum concentration in 1984, 545 μg/kg, was about 1.5 times that of the maximum concentration in 1983, probably because application rates were about two times greater in 1984. No samples were collected in late summer of 1984. By the fall of both years, concentrations of atrazine had decreased to less than 50 μg/kg. The data also suggest that some small amount of residual atrazine remained in the soil throughout the winter and into the following spring.

Atratone and simazine were found at low concentrations (less than 15 mg/kg) in the first sample collected after application each year. These were probably impurities in the atrazine.

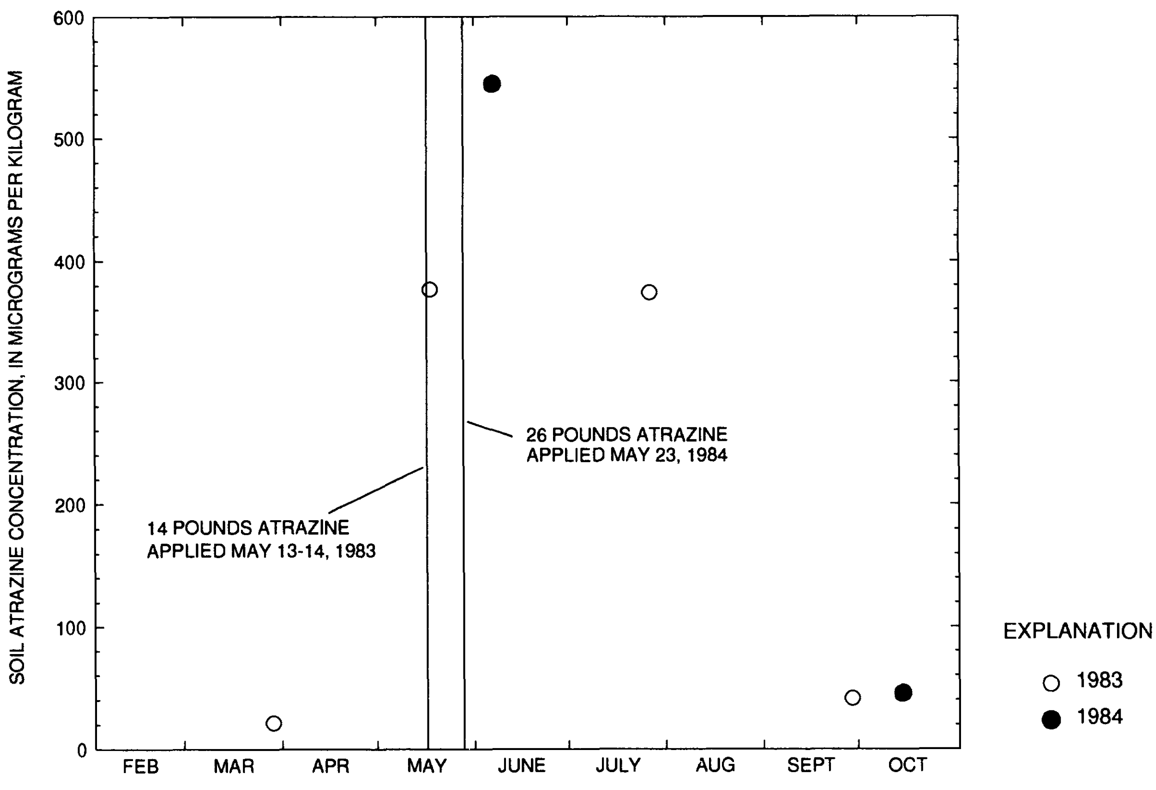


Figure 12. Atrazine concentrations in 2-inch-deep field-composite soil samples at Field-Site 1.

CHARACTERIZATION OF SURFACE RUNOFF

Characteristics of runoff and associated chemical quality at Field-Site 1 are discussed in this section. Relations between runoff quantity and chemical quality and between different chemical constituents are examined, as well as the effects of precipitation, soil conditions, and agricultural activities on runoff characteristics.

Quantity

Measurable runoff from the site occurred 97 times during the 21-month pre-BMP period. From April 29 to August 11, 1983, much of the 1983 growing season, only one storm produced measurable runoff. For storms that produced runoff, a median of 6.8 percent of precipitation was runoff (fig. 13). However, this ranged from 0.02 to 290 percent (rain on snow) and 72 storms did not produce measurable runoff. For the study period, 9.8 percent of the total precipitation left the site as runoff.

Median total runoff for storms that produced runoff during the study period was 2,130 ft^3, and the median of the mean event discharges was 0.11 ft^3/s (fig. 14). Total runoff was as great as 73,500 ft^3 during a 3.5-in. storm in December 1983. However, instantaneous maximum discharges were greatest during intense early summer thunderstorms in 1984 when there was little crop cover. For example, an instantaneous discharge of 26 ft^3/s was recorded during a 1.0 in. thunderstorm in May 1984. There are no consistent seasonal variabilities in the mean discharge or total runoff for storms (fig. 14).

Most runoff hydrographs contained numerous peaks and greatly varying discharges (fig. 15). The first peak, which generally occurred very soon after runoff began, appeared to be associated with runoff from the cornfields just upgradient of the gage house. The alfalfa strip in the center of the site slowed runoff velocities from the cornfields upgradient of the alfalfa. Numerous hydrograph peaks also reflect variability of precipitation intensity.

Relation of Surface Runoff to Precipitation, Soil Conditions, and Agricultural Activities

Surface runoff is controlled by a number of factors. Precipitation is the most obvious one. The amount of precipitation determines the occurrence, rate, and total amount of runoff. The intensity of precipitation also influences runoff because the soil can absorb water at a limited rate. Precipitation duration also can affect the amount of runoff; for example, a steady rain for a long period may first saturate the soils, but as the precipitation continues, runoff begins and infiltration declines. The frequency of precipitation helps determine soil-moisture conditions, and, therefore, affects runoff response as well.

During the study period, some storms with as little as 0.1 in. of precipitation produced measurable runoff, whereas some storms with up to 1.1 in. of precipitation produced no measurable runoff. A Mann-Whitney Rank-Sum test (SAS Institute, Inc., 1982b) used to determine statistically significant differences at the 95-percent confidence level showed that storms that produced measurable runoff had more total rainfall and higher 15- and 30-minute intensities than storms that produced no measurable runoff. However, no statistically significant difference was found between the duration of precipitation for storms that did or did not produce runoff.

In addition to precipitation factors, soil conditions affect runoff. When the soil is frozen, nearly all rainfall runs off. Snow on frozen ground slowly melts and produces slow runoff over long time periods. For runoff to occur on recently plowed ground, a large amount of rainfall is needed to saturate the soils, or high intensity rainfall is required to compact the soil and produce runoff.

Land-use factors and agricultural activities, such as the amount and type of crop cover, also can affect runoff by intercepting precipitation, thereby reducing the amount and energy of precipitation reaching the soil surface, and changing soil-moisture conditions through evapotranspiration.

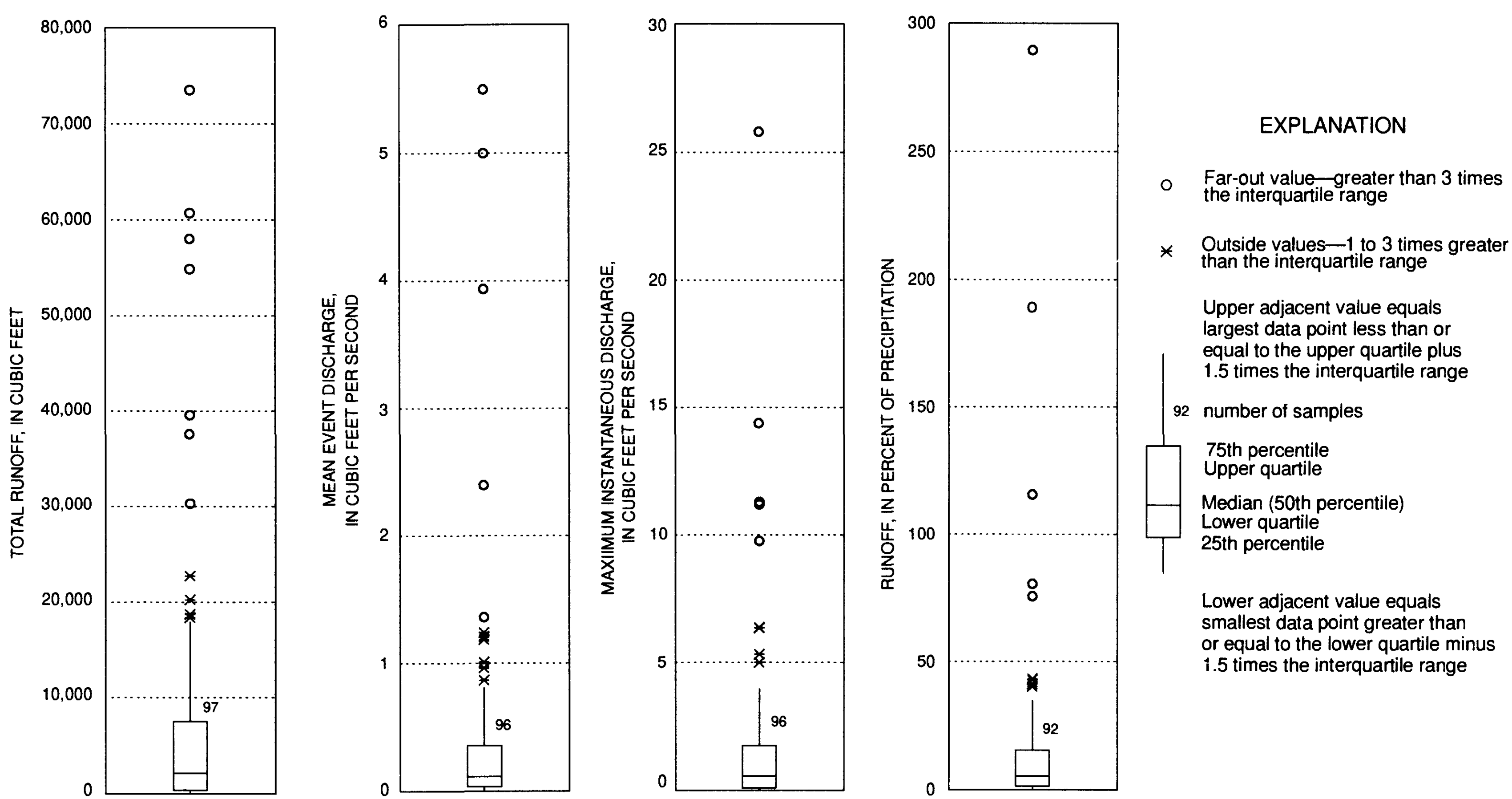


Figure 13. Distribution of total, mean, and maximum discharge and runoff as percentage of precipitation during storms producing measurable runoff at Field-Site 1, January 1983 through September 1984. (Storms with over 100 percent runoff represent rainfall on existing snow.)

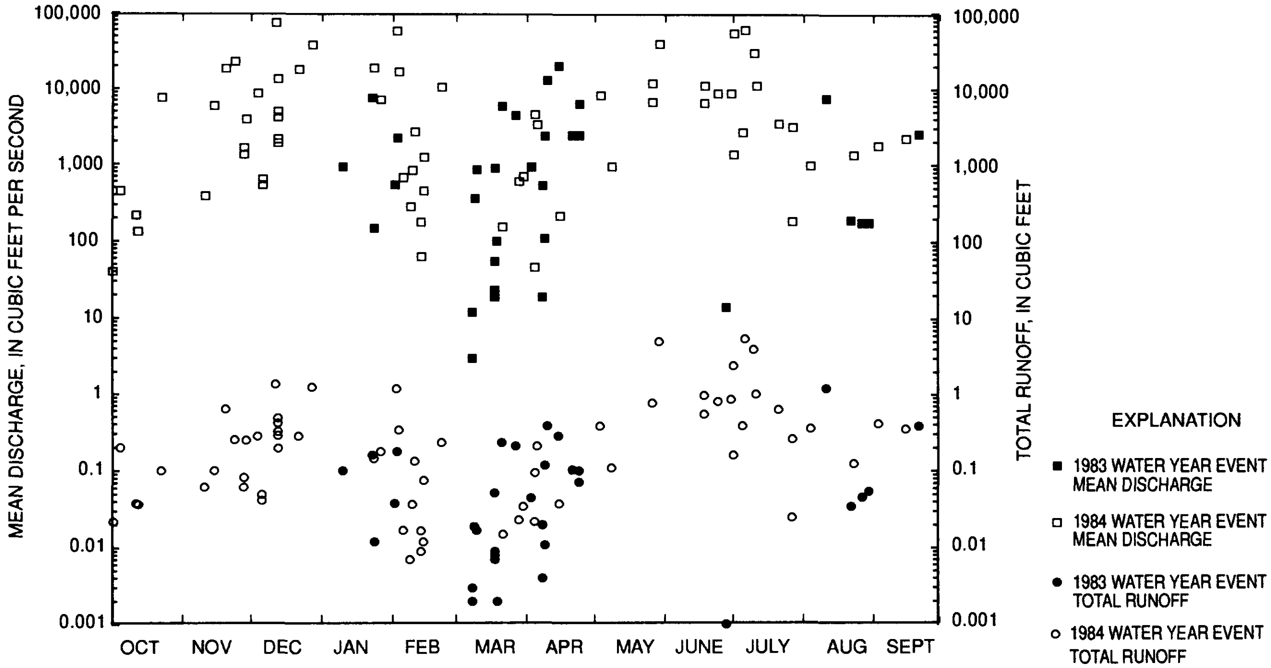


Figure 14. Mean discharge and total runoff for all storm events that produced runoff at Field-Site 1 during January through September of the 1983 water year and the 1984 water year.

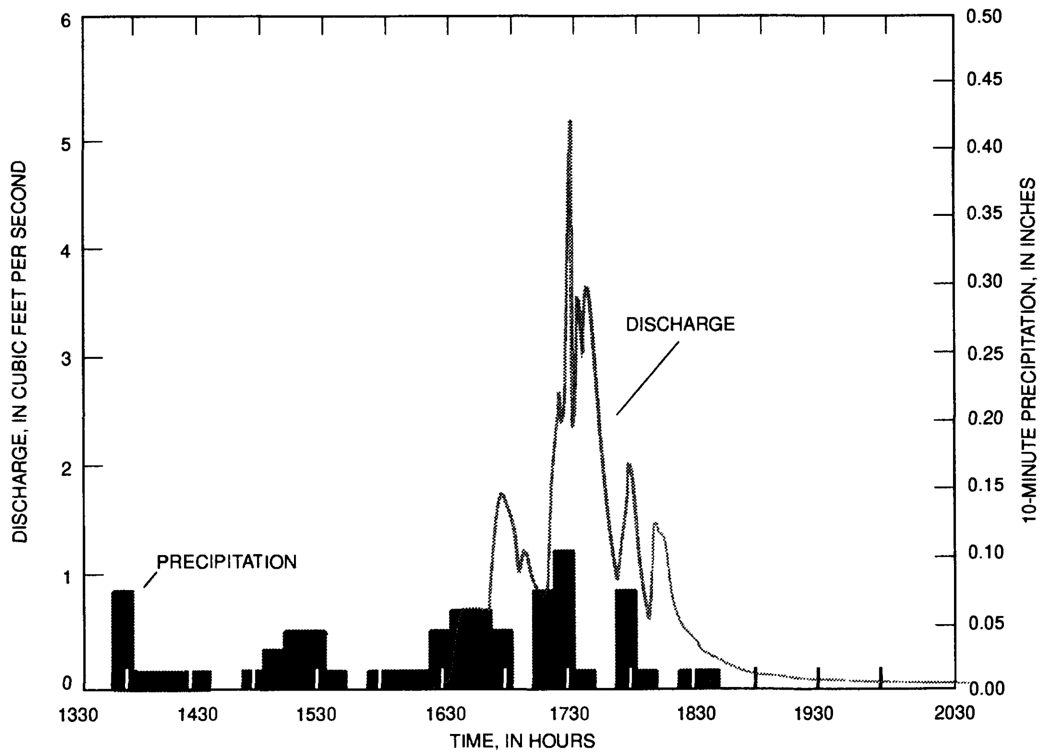


Figure 15. Discharge and precipitation for a runoff event at Field-Site 1 on June 24, 1984.

Regression analyses (P-STAT, Inc., 1986) were used to determine how these factors affected runoff and which factors had the greatest effect (table 9). Dependent variables included in the regressions are total runoff, mean event discharge, and maximum instantaneous storm discharge. Independent variables are total precipitation, 30-minute intensities, precipitation duration, total precipitation amounts occurring in the 30 days prior to runoff to reflect antecedent moisture conditions, and percentage of crop cover on cornfields estimated from visual observation and agricultural-activity data. All these variables are log-normally distributed and, therefore, transformed to log format before regression analyses. For the final regression analyses, 30-minute intensities (rather than 15-minute) and the amount of precipitation occurring in the 30 days prior to runoff (rather than the total amount of precipitation occurring 5, 10, 15, 20, 25, or 35 days prior to runoff) were used because they produced the highest adjusted coefficients of determination (adjusted R^2 values) for all runoff variables and data sets and minimized the standard errors of the models. Discrete variables used to separate the data set were crop cover, the presence of snow cover, whether or not the ground was frozen, and a factor representing the soil structure--that is, recent plowing.

The results of these regressions are shown on table 9. The R^2 values reported are all statistically significant at the 95-percent confidence level by use of the F-test and associated p-value. The regressions were checked graphically for normally distributed residuals, as shown in figure 16 for the total runoff models.

The 97-storm data set was reduced in various ways as described below. Data for some groupings, such as runoff events occurring when the ground was frozen, were insufficient for regression analysis.

The data set was first reduced to the 60 runoff events with measured precipitation data (table 9, data set A). The resulting regression models show that only 25 to 33 percent of the variability in runoff variables is accounted for by the precipitation variables.

When the four runoff events that occurred when the ground was frozen were removed from the data set (table 9, data set B), the regression models explained substantially more of the variability in runoff variables (60-71 percent), confirming that frozen ground has a large effect on runoff. Under frozen-ground conditions, virtually all the rainfall runs off.

The data set was further reduced by excluding the first runoff event producing measurable runoff after spring plowing (table 9, data set C), because, at this time, the soil structure was unusually loose and storage was greater than under other conditions. The resultant regression models explained slightly more of the runoff variability (74-78 percent). The improved model indicates that changes in water-storage capacity caused by changes in soil structure also can affect runoff.

Data set C on table 9, excluding events occurring when the ground was frozen or when the soil was unusually loose, represents runoff from storms occurring during the most general condition at the site. Table 10 shows that the precipitation data cover about the same range and have similar median values for runoff variables as observed for the data set with all the runoff events occurring during the study period. With the data set now reduced to 55 storms, all occurring when soil conditions were similar, regression analysis indicates that total runoff is controlled predominantly by the total amount of precipitation and, according to the first step in the regression, explains about 50 percent of the variability of the total runoff. The addition to these regressions of a variable reflecting the antecedent moisture content (the total precipitation occurring for the 30 days before the runoff event) explains 74 percent of the runoff variability. If the soil is moist at the beginning of the runoff event, soil saturation level is more quickly reached, increasing the total runoff. Precipitation-intensity is not statistically significant to the regression model. Because the coefficients of total precipitation and the 30-day antecedent moisture variables in the regression equation are similar (table 10), and the range of values for these variables are not substantially different, one of these variables does not appear to dominate the other in terms of its influence on runoff.

Graphical analysis of data set C (fig. 17) suggests that as little as an estimated 10-percent corn crop cover at the site affects total runoff, and that, as the percentage of crop cover increased, total runoff decreased. Increased crop cover on the corn acreage probably decreased total runoff by intercepting rainfall and increasing evapotranspiration and infiltration. This is additionally suggested by the data in figure 17. No storms were recorded with low runoff rates when crop cover above 10 percent existed. The estimated percentage of crop cover on the corn acreage is a significant variable in the regression model for storms when crop cover exceeds 10 percent (table 9; data set E).

Similar analysis was performed by use of the instantaneous maximum and, separately, the mean discharge for each runoff event (table 9). Storms on frozen ground and extremely loose soil structure also had a large effect on the maximum- and mean-event discharge. After reducing the data sets to runoff events with similar soil conditions (table 9; data set C), regression models indicate that the 30-minute precipitation intensity explains about 50 percent of the variation in the maximum and mean discharge. Antecedent moisture also is a major factor, and when added into the regression model with intensity, explains 78 and 74 percent, respectively, of the variation in maximum and mean discharge. Addition of total precipitation data did not substantially improve the regression model for either runoff variable. The coefficients of the independent variables and the range of values are not substantially different (table 10), so that neither of these variables appears to dominate control of the predicted discharge values.

Graphs of crop cover as a function of the log of mean and maximum event discharge showed a similar trend as crop cover as a function of the log of total runoff (fig. 17). The percentage of crop cover on corn acreage was statistically significant in the regression models, indicating that crop cover also plays a role in controlling maximum and mean discharge, as it does with total runoff.

In summary, multiple-regression analyses suggest that total runoff primarily is controlled by total precipitation and antecedent soil moisture, whereas the maximum instantaneous discharge and mean storm discharge are controlled primarily by precipitation intensity and antecedent soil moisture. A small amount of crop cover on corn acreage (estimated at as little as 10 percent) reduces total runoff and mean and maximum discharges by intercepting rainfall and increasing evapotranspiration rates.

Table 9. Multiple-regression statistics for log of runoff as a function of log of precipitation and agricultural-activity variables
[ft^3, cubic feet; ft^3/s, cubic feet per second; DV, dependent variable used for the regression; NS, independent variable was entered as possible independent variable in stepwise regression, but did not contribute significantly to the regression equation; <, less than; --, not entered in regression]

Data set	Degrees of freedom [1]	Log of dependent variables: Total runoff (ft^3)	Log of dependent variables: Mean event discharge (ft^3/s)	Log of dependent variables: Maximum discharge (ft^3/s)	Coefficients and associated statistics for logs of independent variables: Total precipitation (inches)	t-statistic	p-value	30-minute intensity (inches)	t-statistic	p-value	Total precipitation for 30 days prior to runoff (inches)	t-statistic	p-value
A	(ALL RUNOFF EVENTS WITH MEASURED PRECIPITATION DATA												
	59	DV	--	--	1.115	4.107	<0.001	NS	--	--	0.743	2.139	0.04
	59	--	DV	--	.455	3.026	.004	NS	--	--	.079	2.080	.05
	59	--	--	DV	NS	--	--	.801	3.526	<0.001	.972	3.259	.002
B	(DATA SET A WITHOUT RUNOFF EVENTS OCCURRING ON FROZEN GROUND)												
	55	DV	--	--	1.535	8.035	<.001	NS	--	--	1.725	6.618	<.001
	55	--	DV	--	1.494	7.219	<.001	1.409	6.094	<.001	NS	--	--
	55	--	--	DV	NS	--	--	1.508	8.448	<.001	1.685	7.619	<.001
C	(DATA SET B WITHOUT FIRST RUNOFF EVENT AFTER SPRING PLOWING)												
	54	DV	--	--	1.630	9.938	<.001	NS	--	--	1.606	7.184	<.001
	54	--	DV	--	.375	2.468	.02	1.254	7.410	<.001	1.188	6.898	<.001
	54	--	--	DV	NS	--	--	1.650	10.609	<.001	1.581	8.311	<.001
D	(DATA SET C WITH RUNOFF EVENTS OCCURRING WHEN THERE WAS LESS THAN 10 PERCENT CROP COVER)												
	31	DV	--	--	1.518	7.128	<.001	NS	--	--	1.858	5.924	<.001
	31	--	DV	--	1.380	6.474	<.001	NS	--	--	1.380	7.058	<.001
	31	--	--	DV	NS	--	--	1.484	5.123	<.001	1.641	5.677	<.001
E	(DATA SET C WITH RUNOFF EVENTS OCCURRING WHEN THERE WAS 10 TO 100 PERCENT CROP COVER)												
	22	DV	--	--	1.676	5.708	<.001	NS	--	--	1.204	3.505	.002
	22	DV	--	--	1.522	5.907	<.001	NS	--	--	.938	3.035	.007
	22	--	DV	--	NS	--	--	1.701	4.638	<.001	1.248	3.160	.005
	22	--	DV	--	NS	--	--	1.400	3.893	.001	.879	2.224	.04
	22	--	--	DV	NS	--	--	1.385	4.978	<.001	1.290	4.305	<.001
	22	--	--	DV	NS	--	--	1.135	4.275	<.001	.984	3.371	.004

[1] Degrees of freedom equal to number of storms minus one.
[2] R^2 adjusted for degrees of freedom and number of independent variables to allow comparison of regression models on the basis of different sets of data.
[3] G.D. Tasker, U.S. Geological Survey, written commun., 1978.

Table 9. Multiple-regression statistics for log of runoff as a function of log of precipitation and agricultural-activity variables—Continued

[ft^3, cubic feet; ft^3/s, cubic feet per second; DV, dependent variable used for the regression; NS, independent variable was entered as possible independent variable in stepwise regression, but did not contribute significantly to the regression equation; <, less than; --, not entered in regression]

Coefficients and associated statistics for logs of independent variables								Standard error		
									Percent	
Precipitation duration (hours)	t-statistic	p-value	Estimated crop cover on corn acreage (percent)	t-statistic	p-value	Intercept	Coefficient of determination (adjusted R^2) [2]	Log units	Plus	Minus[3]
A (ALL RUNOFF EVENTS WITH MEASURED PRECIPITATION DATA)										
NS	--	--	--	--	--	3.122	0.28	0.812	548	85
NS	--	--	--	--	--	-.255	.17	.806	540	84
NS	--	--	--	--	--	-.224	.33	.682	381	79
B (DATA SET A WITHOUT RUNOFF EVENTS OCCURRING ON FROZEN GROUND)										
NS	--	--	--	--	--	2.540	.66	.546	252	72
-0.748	4.938	<0.001	--	--	--	-1.041	.61	.484	205	67
NS	--	--	--	--	--	-.235	.71	.463	190	66
C (DATA SET B WITHOUT FIRST RUNOFF EVENT AFTER SPRING PLOWING)										
NS	--	--	--	--	--	2.675	.74	.465	192	66
NS	--	--	--	--	--	-.625	.76	.358	128	56
NS	--	--	--	--	--	-.042	.78	.395	148	60
D (DATA SET C WITH RUNOFF EVENTS OCCURRING WHEN THERE WAS LESS THAN 10 PERCENT CROP COVER)										
NS	--	--	NS	--	--	2.465	.75	.484	205	67
-.669	4.031	<.001	NS	--	--	-.854	.73	.329	113	53
NS	--	--	NS	--	--	-.267	.71	.435	172	63
E (DATA SET C WITH RUNOFF EVENTS OCCURRING WHEN THERE WAS 10 TO 100 PERCENT CROP COVER)										
NS	--	--	--	--	--	2.996	.62	.440	175	64
NS	--	--	-.844	2.858	0.01	4.531	.72	.377	137	58
NS	--	--	--	--	--	-.485	.48	.444	178	64
NS	--	--	-.752	2.256	.04	.850	.57	.405	154	60
NS	--	--	--	--	--	.088	.55	.337	117	54
NS	--	--	-.624	2.536	.02	1.195	.65	.299	99	50

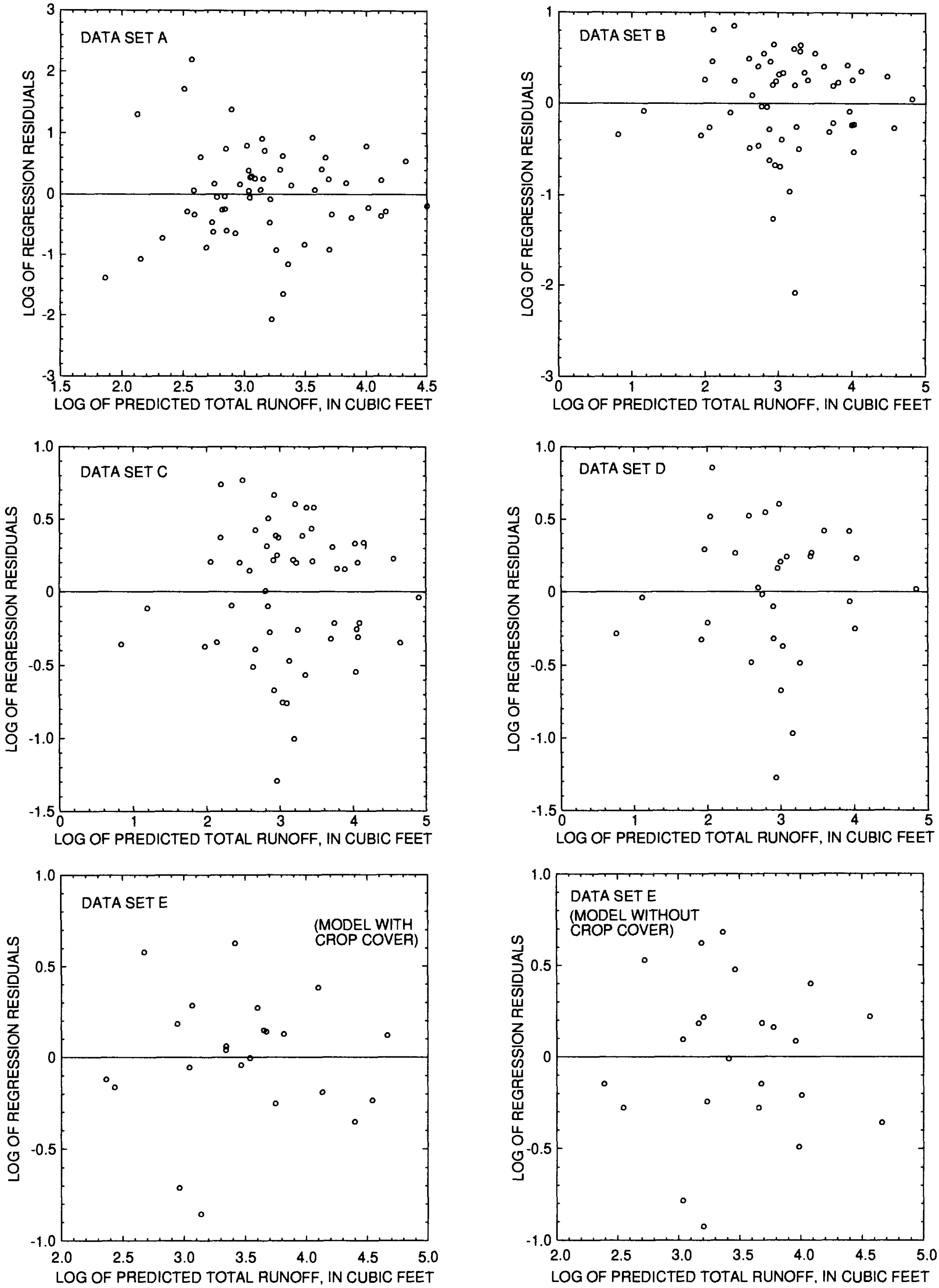


Figure 16. Relation of residual to predicted values of total runoff for regression models of runoff events at Field-Site 1 described in table 9, data sets A-E.

Table 10. Summary statistics for runoff variables for all 97 events and for runoff and precipitation variables for 55 events used in regression analyses
[ft^3, cubic feet; ft^3/s, cubic feet per second; <, less than]

Variable	Data set	Unit	Mean	Minimum	Maximum	Median
Total runoff	All runoff events	ft^3	7,359	3.00	73,500	2,127
	Runoff events in regression [1]	ft^3	6,630	3.00	73,500	1,960
Mean event discharge	All runoff events	ft^3/s	.40	<.01	5.50	.11
	Runoff events in regression [1]	ft^3/s	.42	<.01	5.50	.10
Maximum event discharge	All runoff events	ft^3/s	1.89	<.01	25.8	.58
	Runoff events in regression [1]	ft^3/s	1.92	<.01	14.4	.60
Total precipitation	Runoff events in regression [1]	inches	.75	.07	3.43	.50
30-minute precipitation intensity	Runoff events in regression [1]	inches	.27	.04	1.53	.17
Total precipitation 30 days prior to runoff events	Runoff events in regression [1]	inches	4.65	1.06	10.78	3.94

[1] Includes runoff events in table 9, data set C.

Monthly and Annual Runoff

Total monthly surface runoff varied from 0.0 in. in May 1983 to 2.1 in. (168,000 ft^3) in July 1984; the median was 0.10 in. (fig. 18). In January 1984, runoff was as much as 44 percent of the total monthly precipitation or 111 percent (rain on melting snow) if only precipitation from storms that produced runoff is considered. Storms that produced no runoff comprised 13 percent (April 1983) to 100 percent (May 1983) of the total monthly precipitation. For months when precipitation from storms that produced runoff was less than 50 percent of the total monthly precipitation, runoff was less than 0.4 percent of the total monthly precipitation.

Over the 21-month study period, a total of 714,000 ft^3 (8.9 in.) of water ran off the 22.1-acre site. Runoff during the 1984 water year alone was 631,000 ft^3 (7.9 in.). Runoff was 9.8 percent of the total precipitation recorded for the study period. The percentage of precipitation that became runoff varied greatly for the 2 years; only 3.3 percent of the total precipitation ran off during the 9 months of the 1983 water year, whereas 13 percent ran off during the 1984 water year.

Quality

Runoff was measured for the 97 storms that produced runoff during the period of study. Samples of runoff from 77 of these storms were analyzed for suspended sediment; samples from 54 storms were analyzed for nutrients; and samples from all or part of 16 storms were analyzed for herbicides. Mean flow-weighted concentrations and total loads in runoff for each event were calculated from graphs of constituent concentrations on the basis of instantaneous data.

A total of 424 instantaneous samples were analyzed during the study period for phosphorus and four species of nitrogen. Of the 424 samples analyzed for nutrient concentrations, 417 were analyzed for the total phase, 120 for total and dissolved, and 7 for only the dissolved phase. The suspended concentration for a constituent is the difference between the total and dissolved concentrations. The individual species, as well as combinations of some nitrogen species, are discussed because the mean nutrient concentrations and loads for each event will only be presented in terms of the combined species.

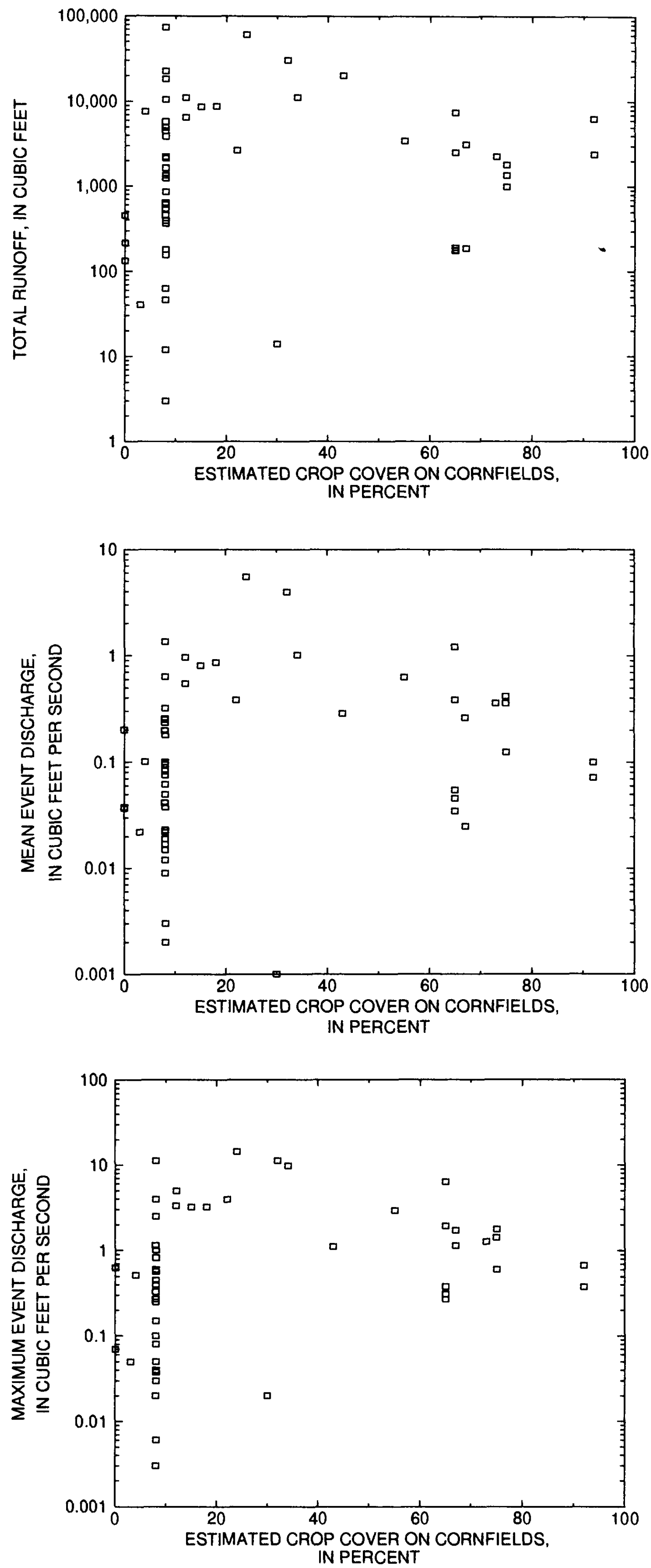


Figure 17. Relation of total runoff (top), mean event discharge (middle), and maximum event discharge (bottom) to estimate crop cover on cornfields for runoff events at Field-Site 1, occurring January 1983 through September 1984, and described in table 9, data set C.

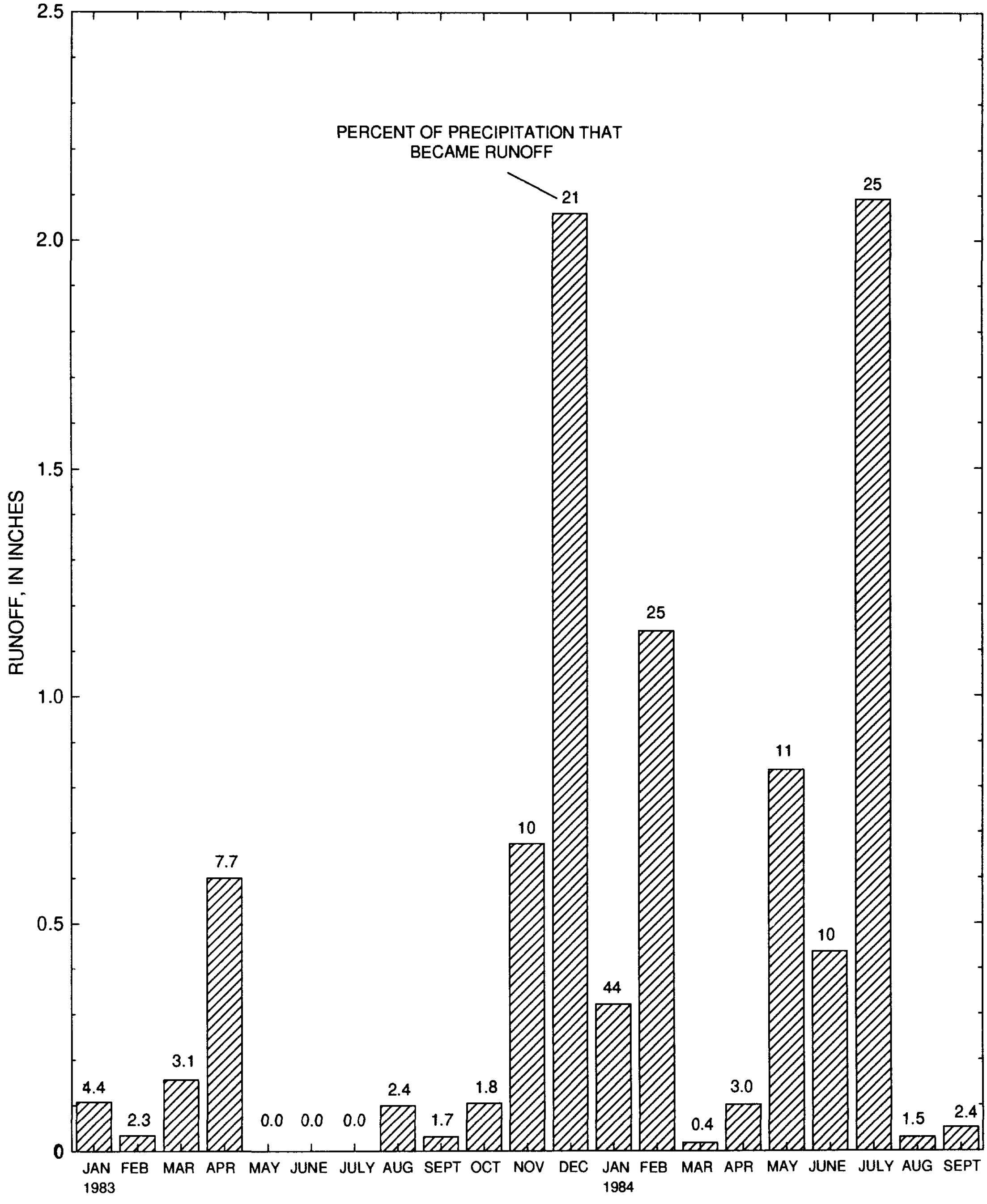


Figure 18. Total monthly surface runoff and percent of precipitation that became runoff, Field-Site 1.

Total Nitrogen Speciation

Concentration ranges and medians for the 417 instantaneous samples analyzed for total nitrogen species, associated with instantaneous discharges of 0.01 to 15 ft^3/s, are shown in table 11. A median of 87 percent of the total nitrogen concentration in the samples was ammonium plus organic nitrogen and 14 percent was nitrate plus nitrite (fig. 19).

Total organic nitrogen comprised a median of 72 percent of the concentration of total nitrogen and a median of 88 percent of the concentration of ammonium plus organic nitrogen.

Table 11. Discharge and concentration ranges and medians for total nitrogen species in 417 instantaneous runoff samples collected from January 1983 through September 1984
[ft^3/s, cubic feet per second; mg/L as N, milligrams per liter as nitrogen]

	Instantaneous discharge (ft^3/s)	Total nitrogen (mg/L as N)	Total organic nitrogen (mg/L as N)	Total ammonium (mg/L as N)	Total nitrate (mg/L as N)	Total nitrite (mg/L as N)
Range	0.0 - 15	0.19 -79	0.00 - 63	0.06 - 33	0.00 - 7.8	0.01 - 1.5
Median	.50	3.9	2.8	.50	.38	.06

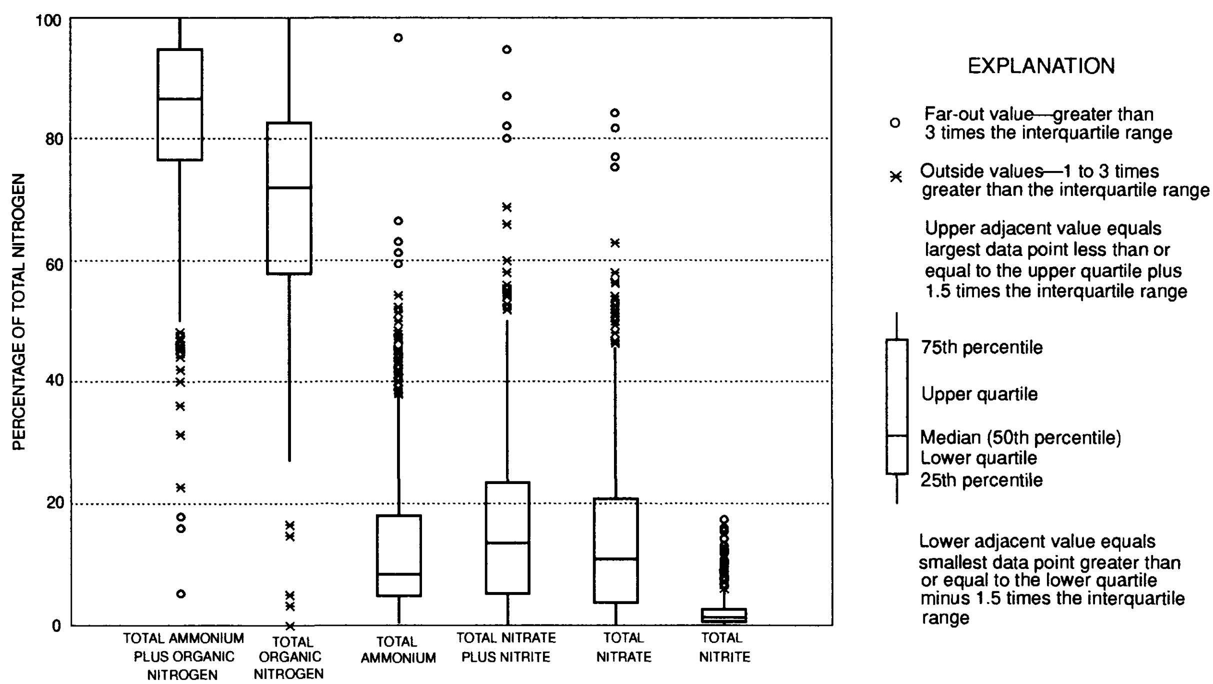


Figure 19. Distribution of percentage of total nitrogen represented by each species or combination of species in 417 instantaneous runoff samples from Field-Site 1, January 1983 through September 1984.

Total ammonium and total nitrate comprised 8.4 and 11 percent (median percentages) of the total nitrogen, respectively. However, the percentage of ammonium and nitrate that contributed to total nitrogen varied greatly both by season and during the course of a runoff event. Most of the samples where ammonium comprised a large percentage of the total nitrogen (up to 97 percent) were collected during the nongrowing season [November through April when most of the manure was applied (fig. 9)], and many of the greater percentages (greater than 40 percent of total nitrogen) were in samples of runoff from snowmelt or snowmelt plus rainfall. Ammonium concentrations during snowmelt ranged from 1.9 to 15 mg/L. Snowmelt runoff generally was slow moving and had little energy to carry suspended material. However, slow runoff from snowmelt had sufficient contact time with surface spread manure and nutrient rich surface soil to dissolve highly soluble nutrients. Ammonium is readily available for dissolution during the winter months, inasmuch as low temperatures do not favor the conversion of ammonium and organic nitrogen in surface-spread manure to highly soluble nitrate. Less ammonia volatilizes at low temperatures, and ammonia solubility increases with decreasing temperature. Nearly all of the runoff samples in which nitrate comprised a large percentage of the total nitrogen (greater than 50 percent) were collected during summer storms (June through August). In about 55 percent of the runoff events throughout the year, the maximum nitrate concentrations were in the last samples collected at the end of the event. Generally, increases in nitrate concentration in runoff during a storm appear to occur regardless of season. However, in 22 percent of the runoff events, the maximum nitrate concentration was found in the first runoff sample collected at the beginning of the storm. In these cases, rains that produced measurable runoff had occurred 0 to 6 days earlier. Thus, wet antecedent conditions may have already dissolved nitrate in soil water, so that nitrate was readily available for solution in runoff.

Total nitrite comprised only 1.4 percent (median percentage) of the total nitrogen. Nitrite is a short-lived intermediate product in the nitrification of ammonium and organic nitrogen to nitrate. The greatest nitrite concentrations generally were found in storms that occurred shortly after manure application.

Nutrient-Phase Distribution

Total and dissolved nutrients were analyzed in 120 samples collected during 23 storms distributed throughout the study period. These samples represent instantaneous discharges of 0.01 to 15 ft^3/s. A comparison of this subgroup of samples to the 417 samples analyzed for only the total-nitrogen species shows similar distributions and no statistically significant differences (by use of the Mann-Whitney Rank Sum test) among the total-nitrogen species in both groups (table 12). Therefore, the relative distribution of dissolved and suspended constituents described in this section probably represents the distribution in phases found in runoff from the entire study period.

Total nitrogen was equally distributed between the dissolved and suspended phases (fig. 20). On the basis of median percentages, 64 percent of the organic nitrogen and 91 percent of the total phosphorus were found in the suspended phase. The other species of nitrogen were found primarily in the dissolved phase; 78 percent of the ammonium, 95 percent of the nitrate, and 60 percent of the nitrite were dissolved.

Table 12. Median percentage of nitrogen each nitrogen species represents for two instantaneous sample subgroups representing 98 and 28 percent of the 424 nutrient samples collected at Field-Site 1 from January 1983 through September 1984

	Samples analyzed for total nitrogen species	Samples analyzed for total and dissolved nitrogen species
Number of samples	417	120
Percentage of total nitrogen:		
Total organic nitrogen	72	73
Total ammonium	8.4	8.1
Total nitrate	11	9.6
Total nitrite	1.4	1.3

The phase distribution of all the nutrient species varies greatly (fig. 20), largely because of climatic conditions, agricultural activities, and nutrient concentrations. The greatest concentrations of dissolved nitrogen are in runoff produced from slow rain on snow-covered, frozen ground where manure had been recently surface spread. Greater than 50 percent of the organic nitrogen was dissolved in this type of sample. Most of the samples in which the suspended phase comprised greater than 50 percent of the concentrations of total ammonium were collected during heavy rains in November 1983. Particles of manure, which had been applied to the cornfields after the fall harvest, probably were carried from the field by runoff during these November storms. Care needs to be taken when reviewing data for suspended and dissolved nitrate and nitrite, because only 7 percent of the concentrations of total nitrate and total nitrite exceeded 1.0 and 0.20 mg/L, respectively. Large variations in dissolved and suspended phases exist within a small range of concentrations. Nitrate and nitrite are generally assumed to be all dissolved because they are so highly soluble. For samples in which less than 80 percent of the nitrate was dissolved, concentrations generally were less than 0.15 mg/L. Dissolved phosphorus comprised more than 50 percent of the concentration of total phosphorus in runoff during storms shortly after fertilizer applications, such as occurred in May 1984.

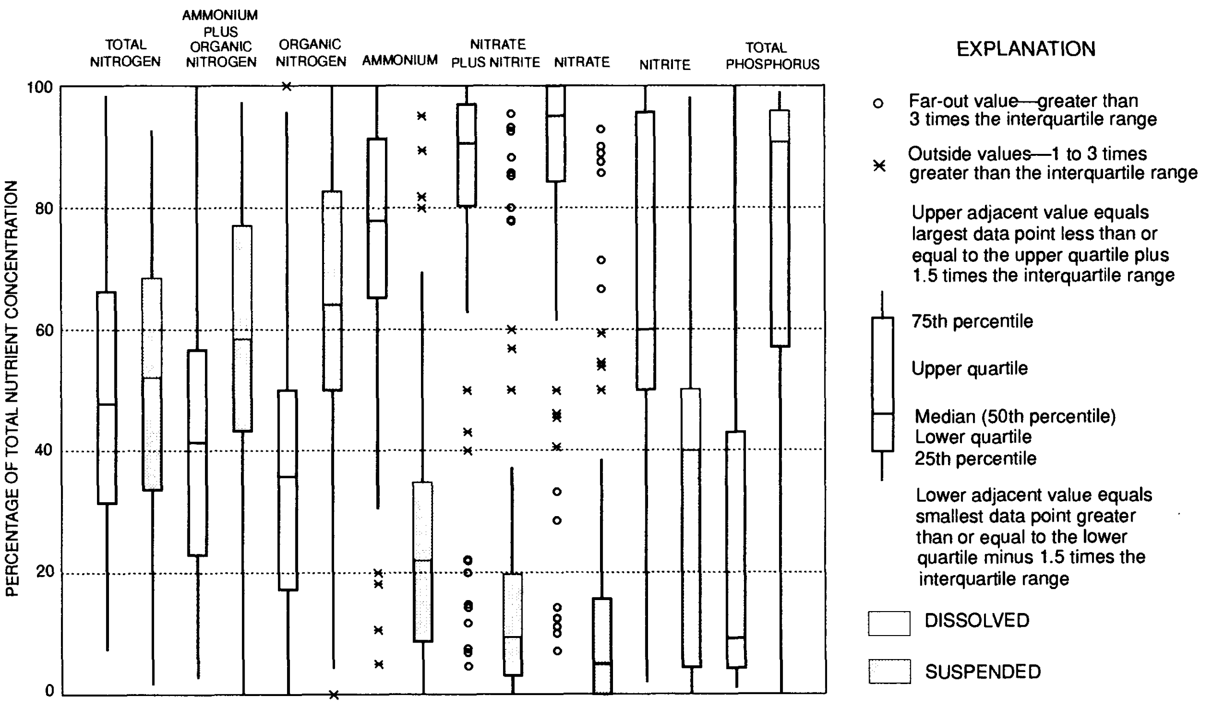


Figure 20. Distribution of nutrients in the dissolved or suspended phase for 120 instantaneous runoff samples from Field-Site 1, January 1983 through September 1984.

The median percentages of dissolved and suspended nitrogen species comprising the concentrations of total-nitrogen in runoff are shown on table 13. Suspended organic nitrogen in runoff samples comprised almost 50 percent of the total nitrogen, because most of the nutrients transported with runoff from the site were from solid dairy manure, in which about 80 percent of the nitrogen was in the form of suspended organic nitrogen (according to analysis of manure from the site). The soil nitrogen transported with runoff (mostly from the top 2 in.) was nearly all organic nitrogen. In the 120 runoff samples, the dissolved nitrogen was comprised of a median of 50 percent organic nitrogen, 13 percent ammonium, 24 percent nitrate, and 1.6 percent nitrite. The suspended nitrogen consisted of a median of 93 percent organic nitrogen, 3.8 percent ammonium, 1.2 percent nitrate, and 0.72 percent nitrite.

Table 13. Median percentage composition of total nitrogen of each dissolved and suspended nitrogen species on the basis of 120 instantaneous runoff samples collected from Field-Site 1, January 1983 through September 1984
[Total will not necessarily add up to 100 percent; medians were used because of nonnormal distribution of data]

TOTAL NITROGEN (100 percent):		
Dissolved	48	
Suspended	52	
DISSOLVED NITROGEN (48 percent):		
Ammonium plus organic nitrogen		32
Organic nitrogen		22
Ammonium		5.2
Nitrate plus nitrite		9.8
Nitrate		9.0
Nitrite		.61
SUSPENDED NITROGEN (52 percent):		
Ammonium plus organic nitrogen		50
Organic nitrogen		47
Ammonium		1.7
Nitrate plus nitrite		1.2
Nitrate		.62
Nitrite		.43

Variation During Runoff Events

Constituent concentrations in runoff, without the moderating effects of base flow, vary greatly not only among storms but during storms. Factors such as precipitation quantity, intensity, and duration as well as soil cover, condition, and structure, and land-surface applications of agricultural chemicals all can have direct and intense effects on constituent concentrations in runoff. Although some factors change slowly over time, such as soil cover, others can differ greatly from storm to storm, such as soil structure and permeability before compaction and immediately following plowing; some factors such as precipitation intensity change during a storm.

Variations in discharge and constituent concentrations in runoff during runoff events are shown for (1) a long, slow rainfall, typical of spring and fall storms (fig. 21); (2) an intense thunderstorm, typical of summer storms (fig. 22); and (3) rain on snow-covered frozen ground, typical of winter conditions (fig. 23). In addition, the figures show the changes in total and dissolved nitrogen species throughout the three storms. The continuous total constituent concentrations were estimated on the basis of the analyzed samples denoted on the graphs. Periods of the runoff events that were not well defined by sample analysis concentrations were estimated on the basis of the general shapes and proportional sizes of peaks and from data from runoff events that occurred under similar climatic, soil, and agricultural-activity conditions.

The first runoff event (fig. 21) to be discussed occurred after corn harvest on November 15-16, 1983.

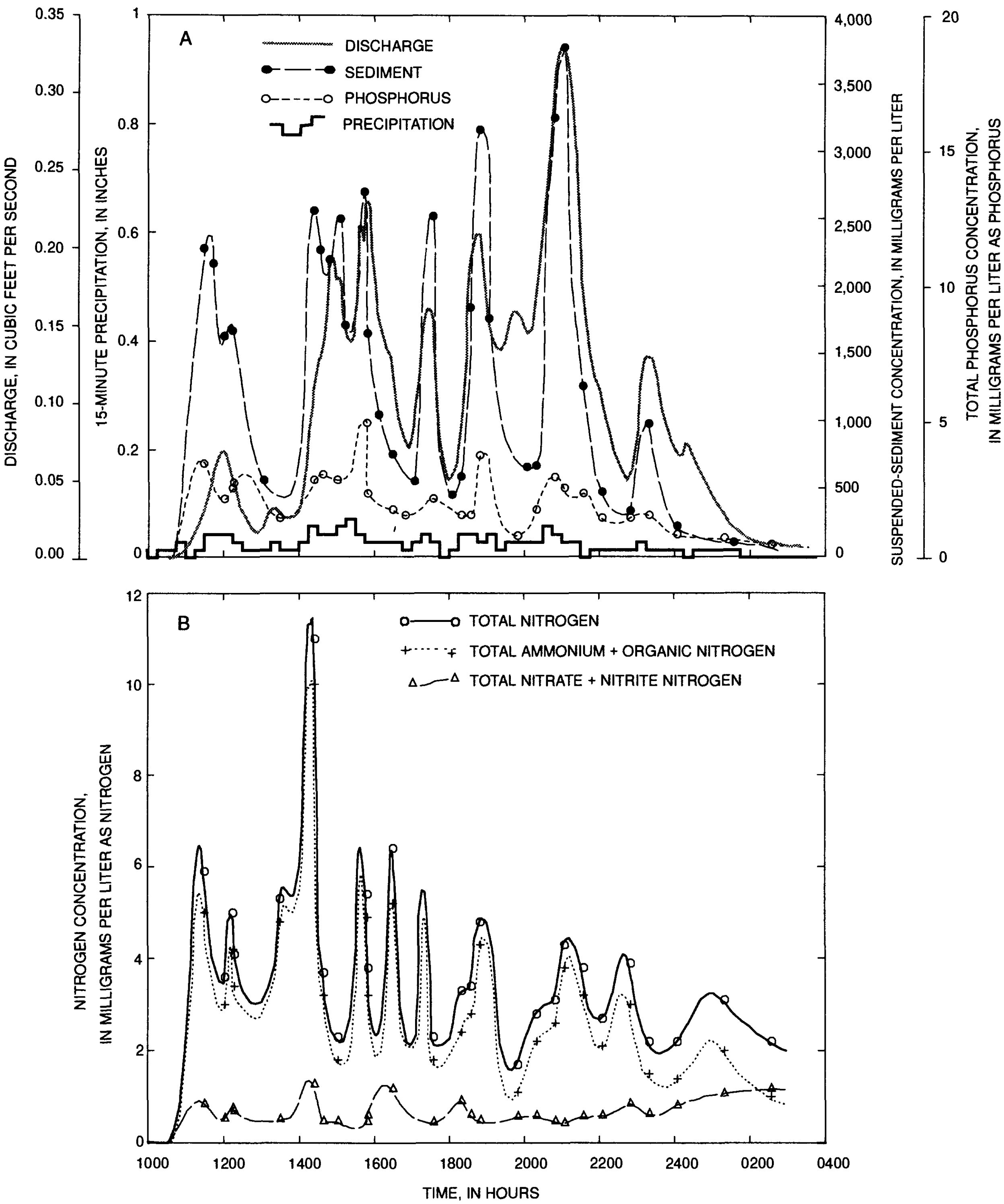


Figure 21. Discharge, constituent concentrations, and nitrogen speciation and phases in runoff for a steady-fall storm at Field-Site 1 on November 15-16, 1983.

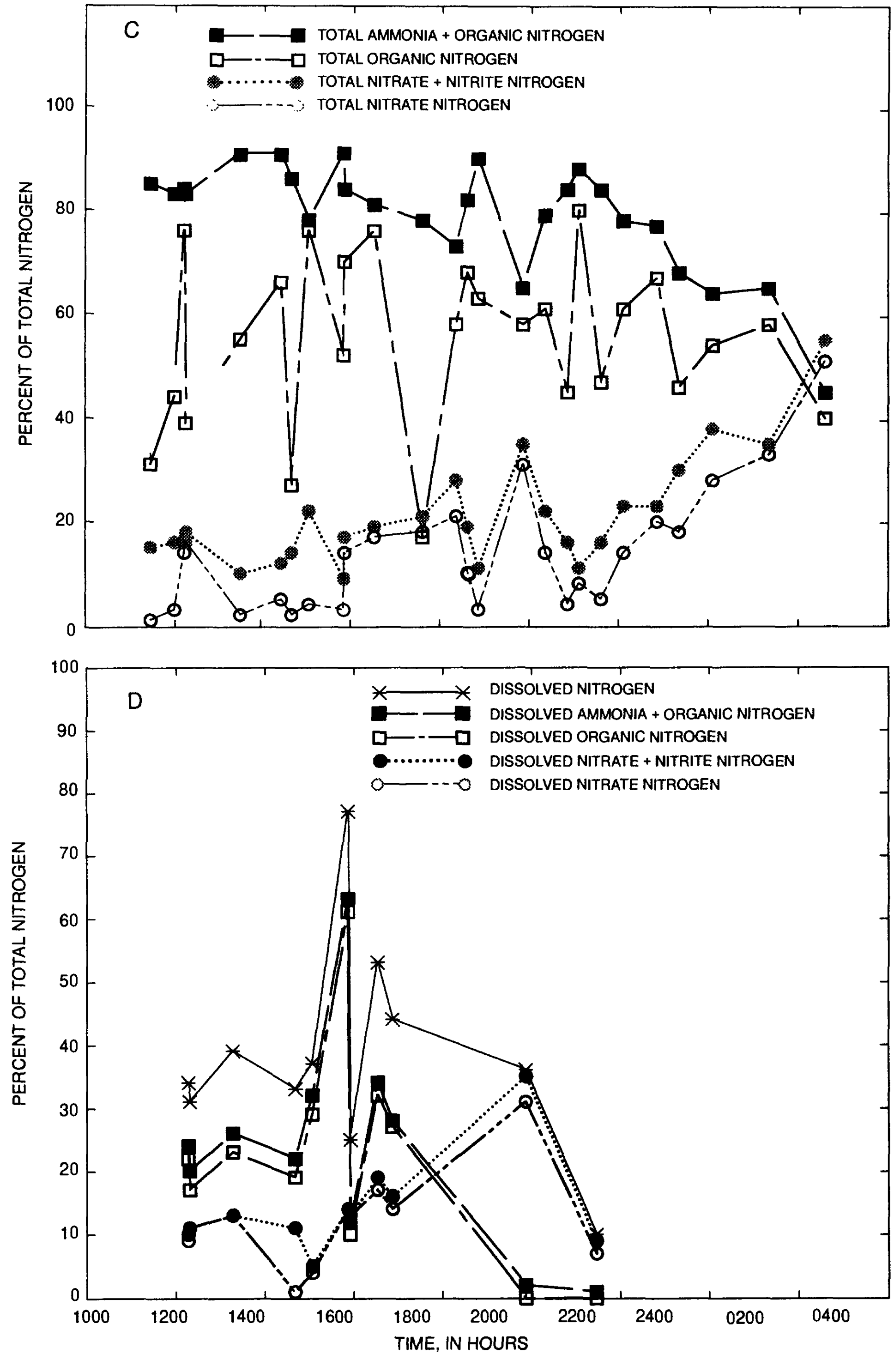


Figure 21. Discharge, constituent concentrations, and nitrogen speciation and phases in runoff for a steady-fall storm at Field-Site 1 on November 15-16, 1983—Continued.

Rye, planted in early October as a cover crop was less than 1 ft high, and corn stubble remained on the cornfields [crop cover was estimated to be less than 10 percent (fig. 8)]. A total of 1.54 in. of rain fell during 15 hours. The maximum 15-minute intensity was 0.07 in. and the maximum 30-minute intensity was 0.13 in. Measurable runoff duration was 16.2 hours. The maximum temperature for the day was 47°F. The soil, which was of about average compaction, was still moist from a 1.75-in. rainfall 4 days earlier. Manure containing about 400 lb of nitrogen and 100 lb of phosphorus had been applied in the 30 days preceding the storm, including about 50 lb of nitrogen and 15 lb of phosphorus applied the morning before the storm began.

The maximum instantaneous discharge during this storm was 0.33 ft^3/s (fig. 21A). This peak discharge occurred well into the storm when soil became saturated and high rainfall intensities occurred. Throughout the storm, numerous runoff peaks were produced by variable rainfall intensities and by runoff from various parts of the field that reached the flume at different times. Runoff velocities from the upper cornfield were temporarily slowed as runoff passed through the alfalfa strip separating the upper and lower cornfields. This caused a delay in traveltime to the flume. However, runoff then channelized into a deep erosion ditch in the lower cornfield, resulting in increased velocities.

The maximum concentration of suspended sediment was 3,770 mg/L and occurred at the same time as the maximum discharge peak (fig. 21A). Throughout the storm, suspended-sediment concentrations generally peaked about the same time as runoff. However, the initial sediment-concentration peak was larger relative to the runoff peak than were subsequent peaks.

The maximum concentration of total phosphorus was 5.2 mg/L (fig. 21A). The timing of peaks in total-phosphorus concentration was similar to that of suspended sediment. This was expected because total phosphorus is generally tightly bound to soil particles. However, the magnitude of the peaks did not vary proportionally with those of suspended sediment. Most of the transported phosphorus (72-97 percent in the samples analyzed for total and dissolved phosphorus) was in the suspended phase. The dissolved-phosphorus concentration ranged from 0.09 to 0.25 mg/L.

The maximum concentration of total nitrogen in runoff during the storm was 11 mg/L (fig. 21B). Total ammonium plus organic nitrogen constituted 91 percent of the total nitrogen in runoff samples collected near the beginning of the storm, and decreased to 45 percent in the last sample collected (fig. 21C). The concentrations of total ammonium plus organic nitrogen, up to 10 mg/L, peaked numerous times, generally when discharge peaked. Subsequent peaks generally were less than the initial peak concentration (fig. 21B). In the beginning of the storm, peak concentrations of total ammonium plus organic nitrogen generally corresponded to peak concentrations of suspended sediment, suggesting similar transport mechanisms. This was expected because a large percentage of the total ammonium plus organic nitrogen was in the suspended phase (fig. 21D).

Concentrations of total nitrate plus nitrite in the runoff were less than 1.0 mg/L and generally not much greater than the concentration in precipitation (0.20 mg/L) (fig. 21B). However, total nitrate plus nitrite constituted 15 percent of the total nitrogen near the beginning of the storm, and 55 percent near the end of the storm as concentrations of ammonia plus organic nitrogen decreased (fig. 21C). The total nitrate plus nitrite measured was predominantly dissolved nitrate (fig. 21D), except at the beginning of the storm when suspended nitrite constituted up to 97 percent of the total nitrate plus nitrite. The large percentage of nitrite may reflect the recent manure applications. The conversion of ammonium to nitrate, in which nitrite is a short-lived intermediate product, may have been slowed by the cool temperatures in November.

The second storm (fig. 22) was a thunderstorm on June 18, 1984. A total of 1.3 in. of rain fell in 5.6 hours. The maximum 15-minute intensity was 0.33 in., and the maximum 30-minute intensity was 0.48 in. Measurable runoff duration was 5.6 hours. The corn, planted on May 21 and 22, was less than 1 ft high (about 15 percent crop cover). Several large thunderstorms had occurred in late May, compacting the soil after plowing. No storms had occurred between the end of May and the June 18 storm, so the soil surface was dry. The maximum temperature was 65°F, but had been preceded by 2 weeks of maximum temperatures in the 80 and 90°F range. Manure containing about 800 lb of nitrogen and 200 lb of phosphorus was spread on the lower cornfield (mostly along the borders) during the 30 days preceding the storm. The last application before the storm was made on June 11.

Peak discharge from this storm was 3.3 ft^3/s (fig. 22A)—a rate that was an order of magnitude greater than during the November storm because of greater rainfall intensities. Similar to the November 1983 storm, a number of discharge peaks occurred throughout the storm caused by varying precipitation intensities and travel times of runoff through different fields.

The initial suspended-sediment peak, 35,000 mg/L (fig. 22A), was an order of magnitude greater than the maximum suspended-sediment peak resulting from the November storm (fig. 21A). The suspended-sediment concentrations overall were greater than concentrations resulting from the November storm because rainfall intensities were greater, more sediment was available, and drier antecedent moisture conditions and a slightly looser soil structure existed on June 18 than in the fall. Peak suspended-sediment concentrations generally occurred simultaneously with peak flows. However, as during many runoff events at this site, the maximum suspended-sediment peak concentration corresponded to the first flush of runoff, not necessarily the maximum discharge peak. Despite the greater rainfall intensities as the storm progressed, peaks in suspended-sediment concentrations decreased as the storm progressed. This probably occurred because most of the loose soil particles were transported with the initial runoff.

The maximum concentration of total phosphorus in runoff was 8.7 mg/L (fig. 22A)—slightly higher than during the November storm. The multiple phosphorus peaks occurred about the same time as the discharge and suspended-sediment peaks and decreased after the initial peak, although concentrations did not vary proportionally with suspended sediment. Dissolved-phosphorus concentrations ranged from 0.18 to 1.0 mg/L and varied throughout the storm; the total phosphorus that was dissolved increased gradually from 7.1 percent near the beginning of the storm to 47 percent near the end of the storm.

The maximum concentration of ammonium plus organic nitrogen in runoff was 9.5 mg/L (fig. 22B) —about the same as during the November storm (fig. 21B). Only the initial ammonium plus organic nitrogen peak occurred at the same time as the discharge or suspended-sediment peaks. Total ammonium plus organic nitrogen comprised 94 percent (median percentage) of the total nitrogen in runoff at the beginning of the storm when nitrogen concentrations were at a maximum (fig. 22C) and was predominantly suspended organic nitrogen (fig. 19D). However, total ammonium plus organic nitrogen comprised only 44 percent of the total nitrogen during small discharges at the end of the storm (fig. 22C) and was predominantly dissolved organic nitrogen (fig. 22D).

Concentration of total nitrate plus nitrite ranged from 0.57 mg/L at the beginning of the storm during relatively large discharges, to 3.3 mg/L near the end in the storm during small discharges. The mean concentration of total nitrate plus nitrite, predominantly dissolved nitrate throughout the storm, exceeded the ammonium plus organic nitrogen concentration in the last analyzed sample (figs. 22C and 22D).

The third storm (fig. 23) occurred on snow covered, frozen ground on February 3-4, 1984. Snow cover of approximately 2 to 4 in. began to melt, causing about 1.5 hours of runoff before 0.25 in. of rain fell on the snow cover during 6.7 hours. The total duration of runoff was 16.7 hours. The maximum 15-minute intensity of the rainfall was 0.03 in. and the maximum 30-minute intensity was 0.04 in. Manure had been surface spread on the cornfield below the alfalfa strip; and total manure applications for the 30 days preceding this storm amounted to about 1,050 lb of nitrogen and about 300 lb of phosphorus. This included about 140 lb of nitrogen and 40 lb of phosphorus applied the day of the storm. The maximum

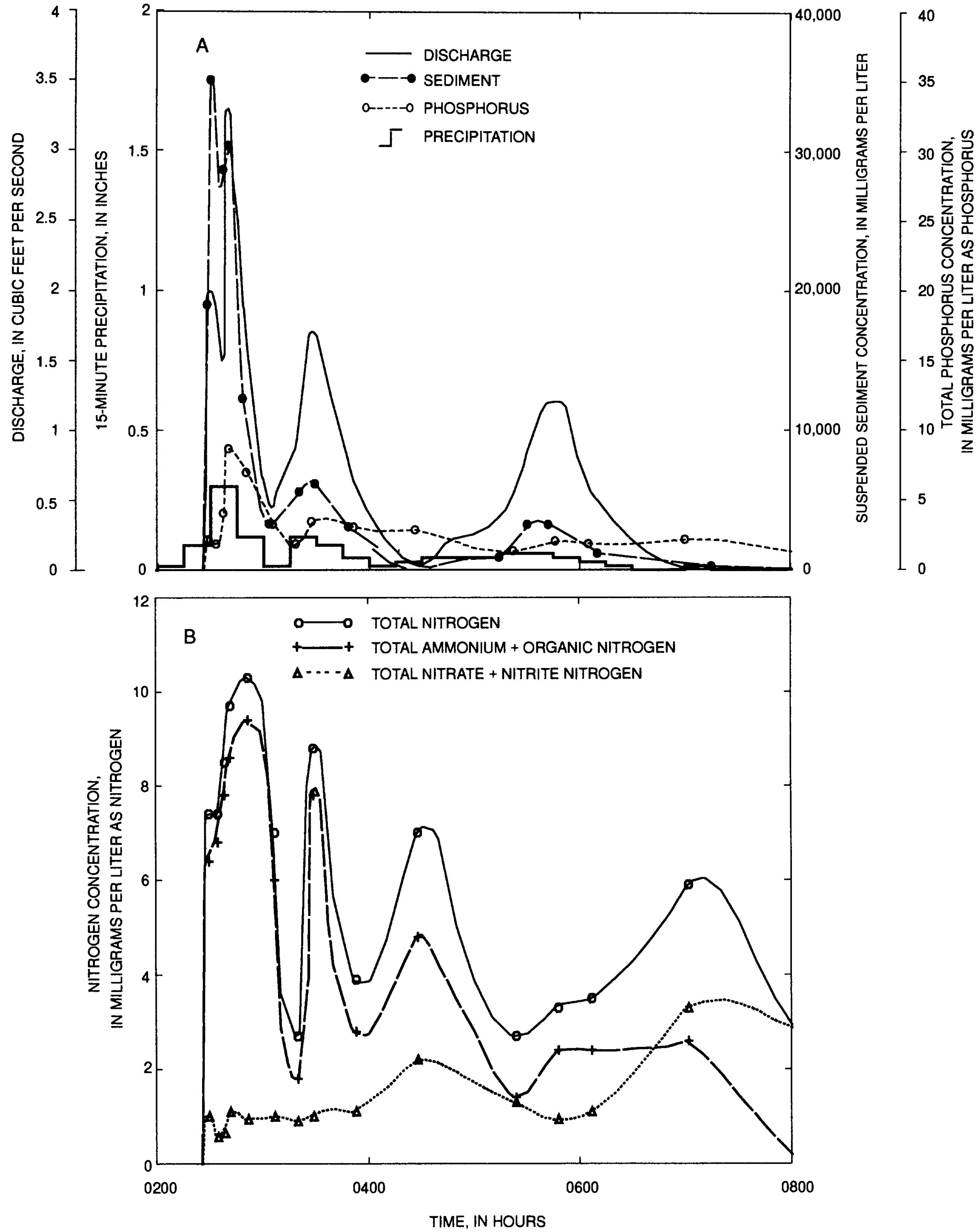


Figure 22. Discharge, constituent concentrations, and nitrogen speciation and phases in runoff for a thunderstorm at Field-Site 1 on June 18, 1984.

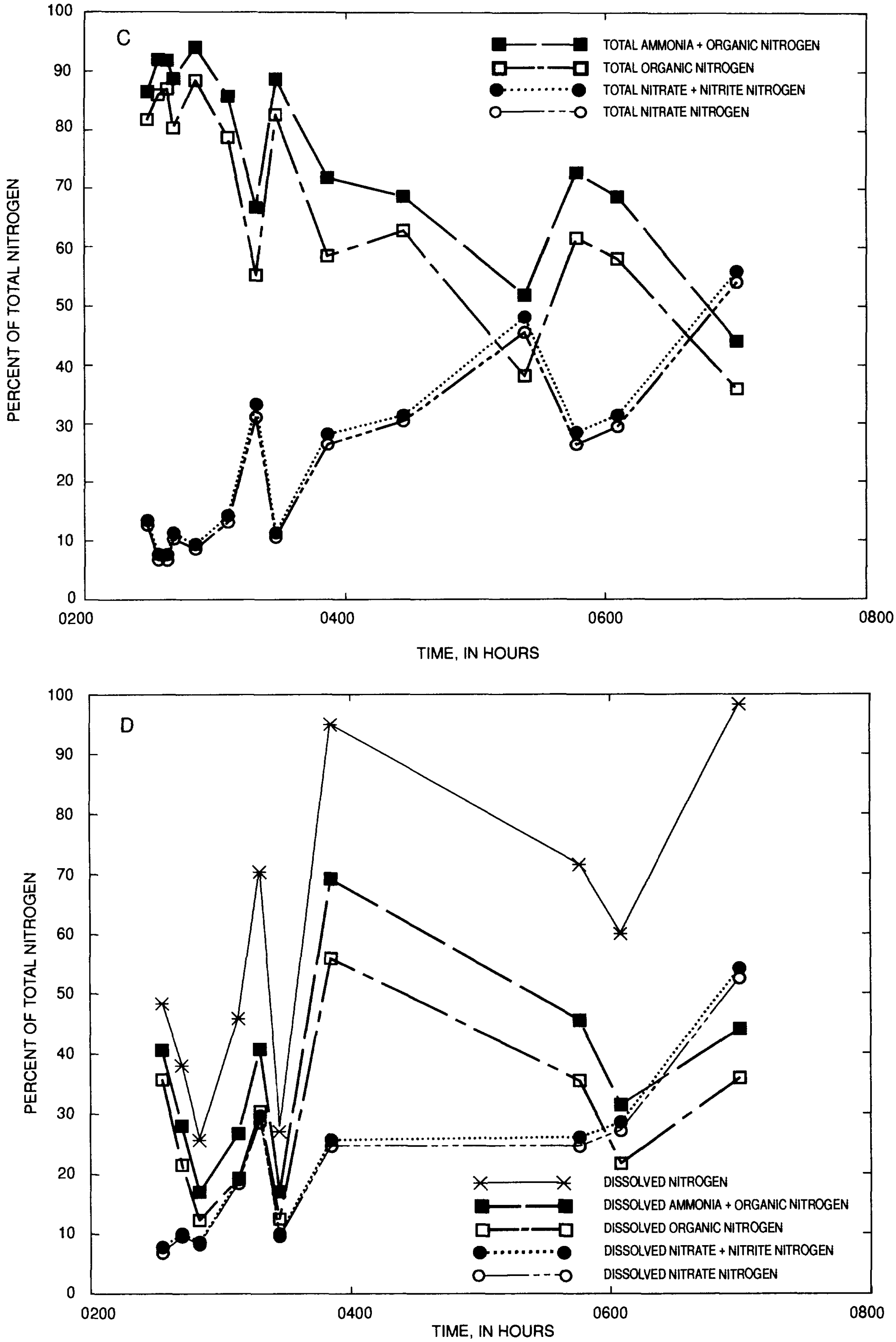


Figure 22. Discharge, constituent concentrations, and nitrogen speciation and phases in runoff for a thunderstorm at Field-Site 1 on June 18, 1984—Continued.

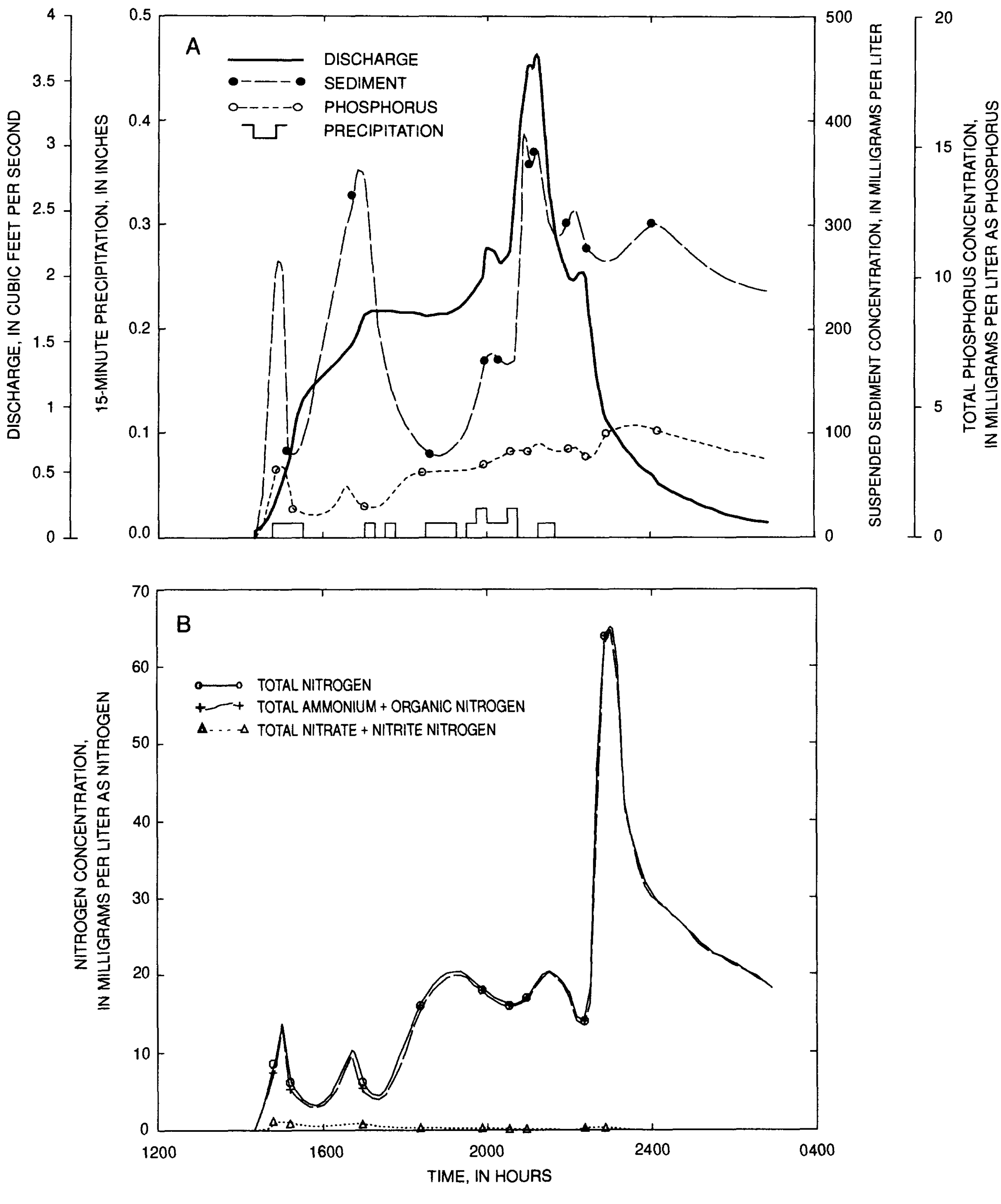


Figure 23. Discharge, constituent concentrations, and nitrogen speciation and phases in runoff for a rainstorm on melting snow at Field-Site 1 on February 3-4, 1984.

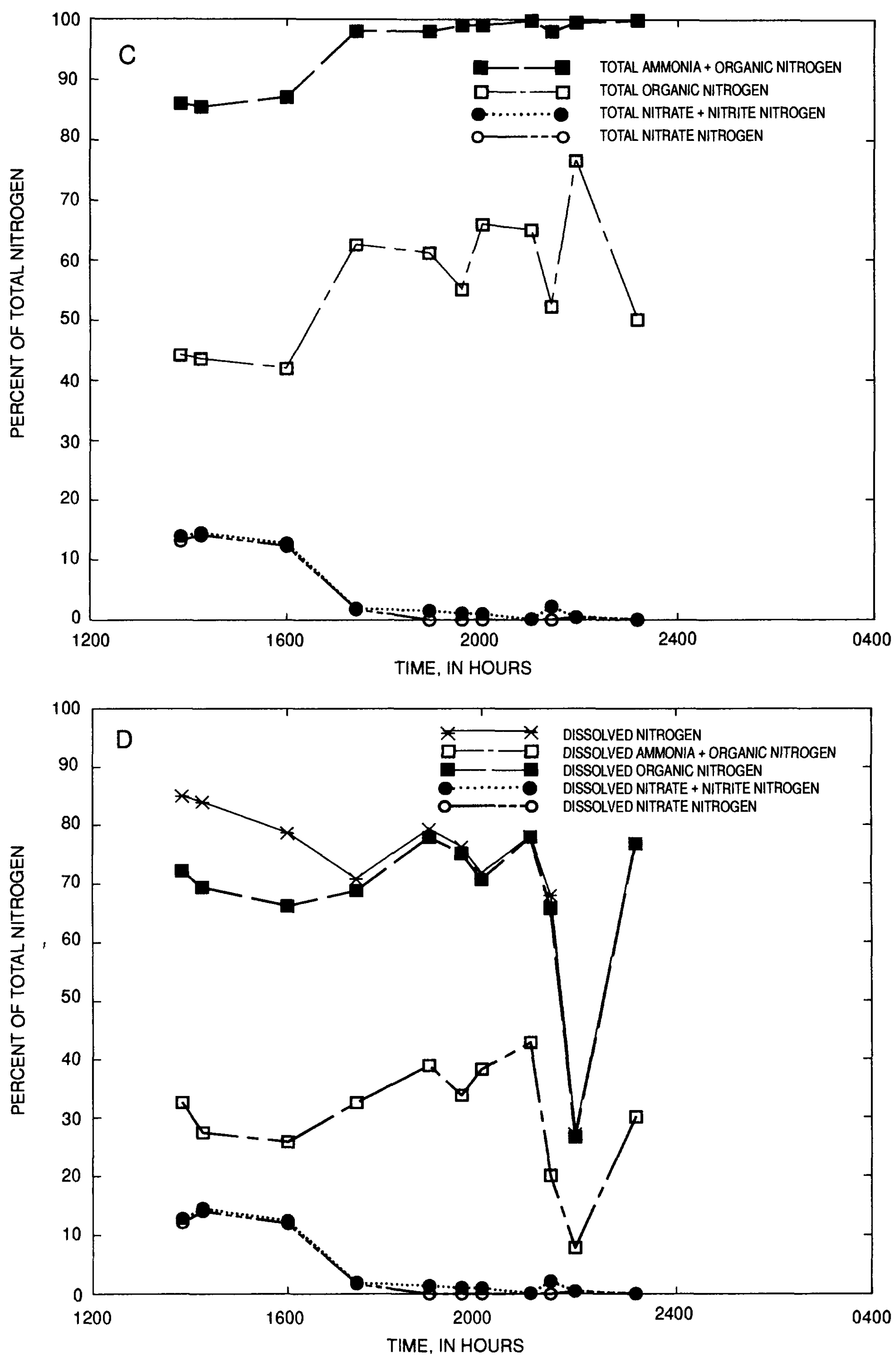


Figure 23. Discharge, constituent concentrations, and nitrogen speciation and phases in runoff for a rainstorm on melting snow at Field-Site 1 on February 3-4, 1984—Continued.

temperature the day of the storm was 38°F. Snow cover had been continuous since January 11. Rain on snow produced runoff on January 24, and temperatures were warm enough to cause measurable runoff from snowmelt on January 27.

The maximum discharge during the February 3 storm was 3.7 ft^3/s (fig. 23A)—about the same as during the June thunderstorm (fig. 22A). Although rainfall intensities for the February storm were very small, the frozen ground prevented infiltration of the runoff water.

A maximum concentration of suspended sediment in runoff of only 370 mg/L (about one-tenth and one-one hundredth of that during the November and June storms, respectively) occurred well into the storm, during the peak discharge (fig. 23A). Little soil was available for erosion because of the snow cover and frozen condition of the soil.

The maximum concentration of total phosphorus was 4.3 mg/L during the February storm (fig. 23A). Concentrations of total phosphorus were about the same as they were during the November and June storms, although suspended-sediment concentrations were much lower. Concentrations of dissolved phosphorus ranged from 0.75 to 3.2 mg/L, and comprised a large percentage (48 to 78 percent) of the total phosphorus, in contrast to the 3.2 to 47 percent range for dissolved-phosphorus concentrations in the November and June storms. The major source of the phosphorus was probably soluble phosphorus in the freshly surface-spread manure because the frozen ground probably reduced the ability of soluble phosphorus to interact with soil particles.

The maximum concentration of total ammonium plus organic nitrogen in runoff was 64 mg/L (fig. 23B), far exceeding the maximum concentration of about 10 mg/L in runoff from the November and June storms (figs. 21B and 22B). The total nitrogen was nearly all ammonium plus organic nitrogen (fig. 23C); the organic nitrogen comprised slightly more of the total nitrogen than ammonia throughout the storm. For the analyzed samples, an average of about 70 percent of the total nitrogen was dissolved nitrogen (fig. 23D) of which an average of 30 percent was organic nitrogen and 37 percent was ammonium.

The concentration of total nitrate plus nitrite only reached 1.2 mg/L (fig. 23B), and declined to less than 0.30 mg/L [less than 3 percent of the total nitrogen (fig. 23C)], one-third of the way into the storm. Initially, some nitrate may have been available from the fresh barn manure spread the day of the storm. However, conversion of the manure's ammonium and organic nitrogen to nitrate was greatly slowed by the cold temperatures, so little nitrate probably was available to runoff.

The total loads in runoff from the three storms discussed are—

	November 15-16, 1983	June 18, 1984	February 3-4, 1984
Total runoff, in cubic feet	5,800	11,100	58,100
Suspended sediment, in tons	.27	3.2	.40
Total nitrogen, in pounds as nitrogen	1.4	4.2	61
Total phosphorus, in pounds as phosphorus	.81	2.5	9.8

The data for the three storms are presented to demonstrate the wide variability in runoff and constituent concentrations and loads that can occur under different seasons, largely as a function of precipitation characteristics, temperature, and agricultural activities. The data for runoff from these storms are not necessarily representative of any group of storms, for example, the maximum instantaneous discharge for runoff from the June thunderstorm was 3.3 ft^3/s, whereas maximum discharges for runoff from all summer thunderstorms ranged from 0.77 to 26 ft^3/s.

However, many of the observations made regarding runoff from these storms were consistently observed in runoff throughout the study period. These similarities, as well as general relations among different constituents that are consistently observed in most runoff, are discussed below. Generally, the runoff data suggest the existence of relations between discharge and suspended-sediment concentrations, and among suspended-sediment concentrations and concentrations of total phosphorus and total organic nitrogen.

Regression analysis shows that about 50 to 60 percent of the variation in suspended-sediment concentrations is explained by discharge for runoff from all storms except those on snow-covered or frozen ground (snowmelt carries substantially smaller suspended-sediment concentrations in comparison to runoff over exposed soil) (table 14, data sets B and D). High instantaneous suspended-sediment concentrations were associated with high instantaneous discharges; this is expected because high velocities have the energy to erode and transport more material (fig. 24, table 14). There was a different relation between discharge and suspended-sediment concentrations for runoff from April through December than January through March, as shown graphically (fig. 24) and by regression analysis. The difference was probably because of variable soil conditions; in the winter months, large suspended-sediment concentrations relative to discharge may have been caused by freezing and thawing of the surface soils that disrupts them and made them readily available to removal by runoff.

The first sample collected during a storm generally contained greater suspended-sediment concentration per unit of discharge than did other samples (fig. 24), primarily because of the availability of fine, loose surface-soil particles to removal by initial runoff, especially under dry conditions, and the great potential for raindrop erosion before substantial overland flow began (Statham, 1979).

There was little relation between instantaneous concentrations of total phosphorus and associated instantaneous discharges. However, graphical and regression analyses show that total-phosphorus concentrations generally increased as suspended-sediment concentrations increased (fig. 25, table 14). The ratio of concentrations of phosphorus to suspended sediment are generally larger for the January to March samples (fig. 25, table 14, data sets B and C), probably because of the practice of spreading manure close to the barn during the colder months, thereby concentrating the manure closer to the runoff sampling site. The variability in the suspended-sediment concentrations only explains about 30 percent of the variability in the total-phosphorus concentrations. Although sediment transports some of the phosphorus, manure organic matter (the form of nearly all phosphorus applications) can also transport much. Therefore, concentration of total organic nitrogen was entered into the regression analyses as a rough estimate of organic material present in runoff. In the resultant April to December regression model, concentration of total organic nitrogen is a significant explanatory variable and, in combination with suspended-sediment concentration, explained about 45 percent of the variability in total-phosphorus concentrations. The addition of total organic nitrogen did not improve the regression for January through March data.

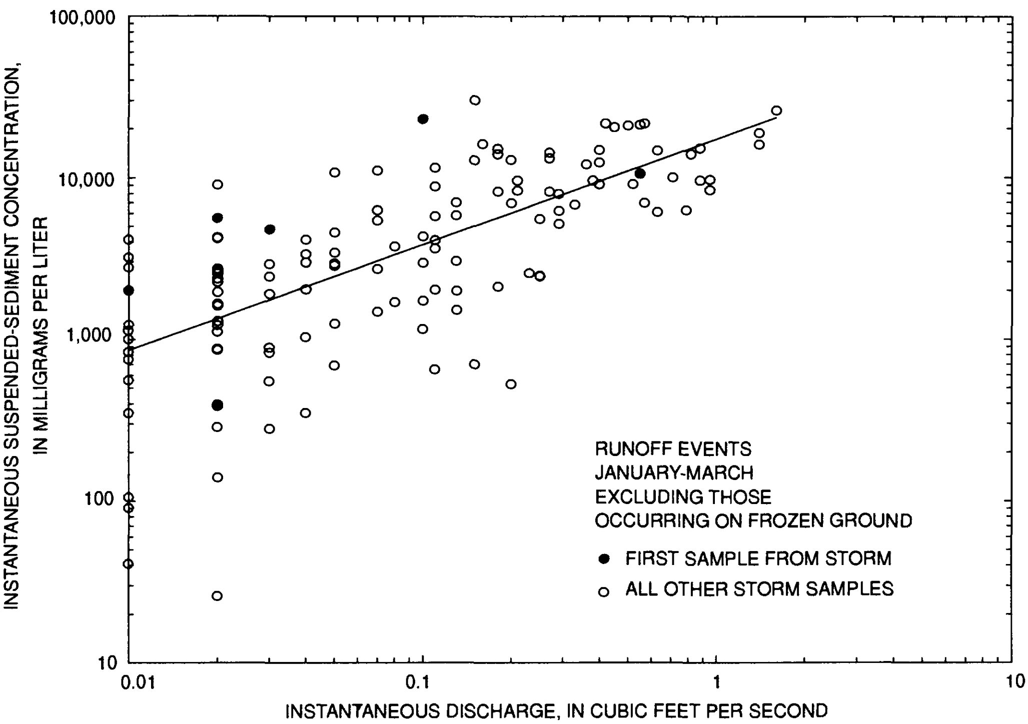
Graphical and regression analyses showed no significant relation among any of the instantaneous total-nitrogen species concentrations and discharge or suspended sediment or total-phosphorus concentrations. Nitrogen concentration in soils and, therefore, its availability for dissolution in runoff is highly variable, because many bacterially-mediated transformations of nitrogen probably occurred. Nitrogen is lost in variable degrees by volatilization of ammonia, releases of nitrogen gas, leaching of nitrate, and uptake of ammonium and nitrate by crops. In contrast, the soils accumulate phosphorus because it binds strongly to soil particles, creating a source that was always available for removal along with suspended sediment by runoff.

Table 14. Regression statistics for the log of instantaneous discharge and suspended-sediment, total-phosphorus, and total organic-nitrogen concentrations in runoff from Field-Site 1

[mg/L, milligrams per liter; ft^3, cubic feet; ft^3/s, cubic feet per second; DV, dependent variable used for the regression analysis; <, less than; --, not entered into regression as independent variable]

Data set	Degrees of freedom [1]	Log of dependent variables: Suspended sediment (mg/L)[2]	Log of dependent variables: Total phosphorus (mg/L as phosphorus)	Coefficients and associated statistics for logs of independent variables: Discharge (ft^3/s)	t-statistic	p-value	Suspended sediment (mg/L)	t-statistic	p-value	Total organic nitrogen (mg/L as nitrogen)	t-statistic	p-value	Intercept	Coefficient of determination (adjusted R^2) [2]	Standard error: (log units)	Standard error: Percent (plus	/ minus)[3]
A	(ALL SAMPLES FROM ALL RUNOFF EVENTS)																
	707	DV	--	0.537	19.791	<0.001	--	--	--	--	--	--	3.69	0.36	0.544	250	71
	210	--	DV	--	--	--	0.281	8.960	<0.001	--	--	--	-.481	.27	.284	92	48
	210	--	DV	--	--	--	.266	8.929	<.001	0.218	5.236	<0.001	-.527	.36	.268	85	46
B	(ALL SAMPLES FROM RUNOFF EVENTS, APRIL THROUGH DECEMBER)																
	509	DV	--	.697	26.635	<.001	--	--	--	--	--	--	3.70	.58	.425	166	62
	153	--	DV	--	--	--	.263	8.288	<.001	--	--	--	-.456	.31	.233	71	42
	153	--	DV	--	--	--	.231	8.067	<.001	.237	6.389	<.001	-.453	.45	.208	61	38
C	(ALL SAMPLES FROM RUNOFF EVENTS, JANUARY THROUGH MARCH)																
	197	DV	--	.220	2.845	.005	--	--	--	--	--	--	3.51	.03	.705	407	80
	56	--	DV	--	--	--	.428	5.646	<.001	--	--	--	-.844	.36	.359	129	56
	56	--	DV	--	--	--	.441	5.900	<.001	.208	1.782	.084	-.982	.38	.352	125	56
D	(DATA SET C WITHOUT SAMPLES FROM RUNOFF EVENTS ON SNOW COVERED OR SURFACE-FROZEN GROUND)																
	151	DV	--	.651	11.972	<.001	--	--	--	--	--	--	4.24	.48	.408	156	61
	44	--	DV	--	--	--	.382	5.051	<.001	--	--	--	-.635	.36	.331	114	53

[1] Degrees of freedom equal to number of storms minus one.
[2] R^2 adjusted for degrees of freedom and number of independent variables to allow comparison of regression models on the basis of different sets of data.
[3] G.D. Tasker, U.S. Geological Survey, written commun., 1978.



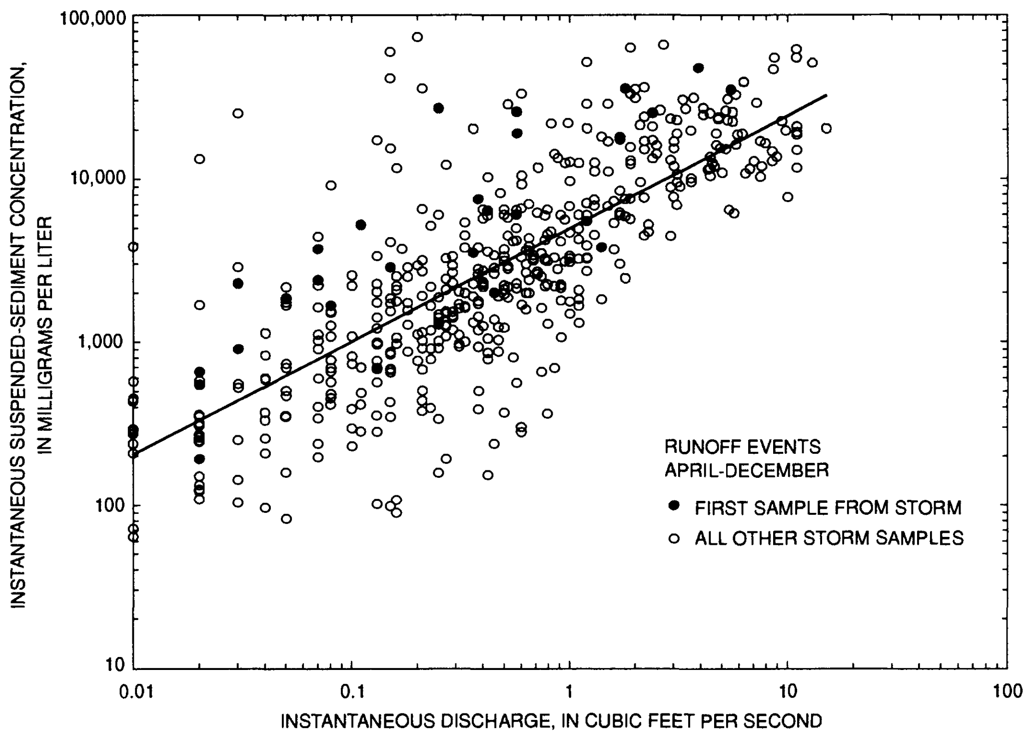


Figure 24. Relation of suspended-sediment concentrations to discharge for instantaneous samples for runoff events occurring January through March at Field-Site 1, except those storms when the ground was frozen, and runoff events occurring April through December, January 1983 through September 1984. (Regression line statistics are shown in table 14, data sets D and B.)

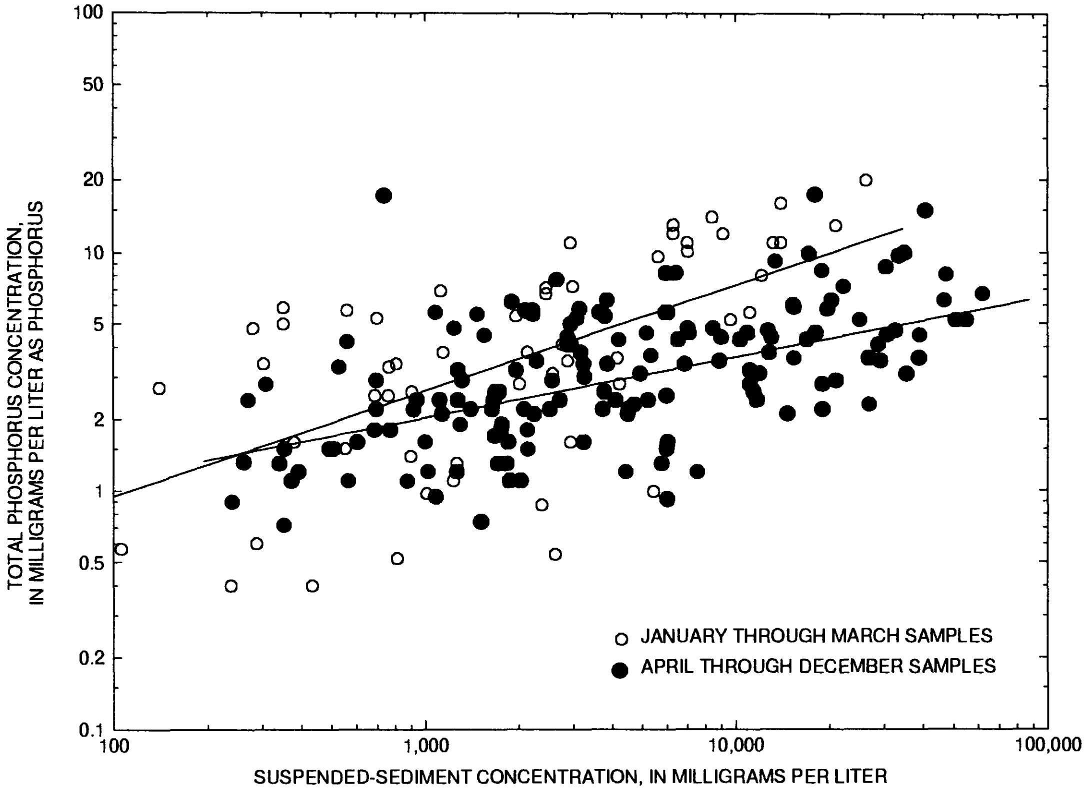


Figure 25. Relation of total phosphorus to suspended-sediment concentrations for instantaneous runoff samples from Field-Site 1, January 1983 through September 1984. (Regression line statistics are shown in table 14, data sets B and C.)

Mean Constituent Concentrations and Loads in Runoff

Procedures for calculating mean concentrations and loads for runoff events and total annual and study period loads are discussed in the section *Sampling Network and Data Analysis*. Mean concentrations of suspended sediment in runoff events at the site ranged from 24 to 73,000 mg/L; the median was 2,900 mg/L (fig. 26). Loads of suspended sediment in runoff ranged from less than 0.01 to 50 tons; the median was 0.20 tons (fig. 26). The greatest mean concentrations and loads occurred during the first intense thunderstorms following spring plowing. At this time, soil loosened from plowing, and soil plowed into previously formed deep gullies provided a large source of suspended sediment in runoff. Two sampled runoff events of this type accounted for about 30 percent of the total estimated load leaving the site during the 1984 water year. One other runoff event, occurring between these two events and not sampled, may have carried suspended-sediment loads that could account for about another 5 percent of the 1984 total estimated load. Suspended-sediment loads from only 5 storms (10 percent of the sampled runoff events, including runoff from the two sampled storms just discussed, two thunderstorms in July 1984, and a 3.4-in. storm in December 1983) make up nearly 60 percent of the estimated total suspended-sediment load for the 1984 water year.

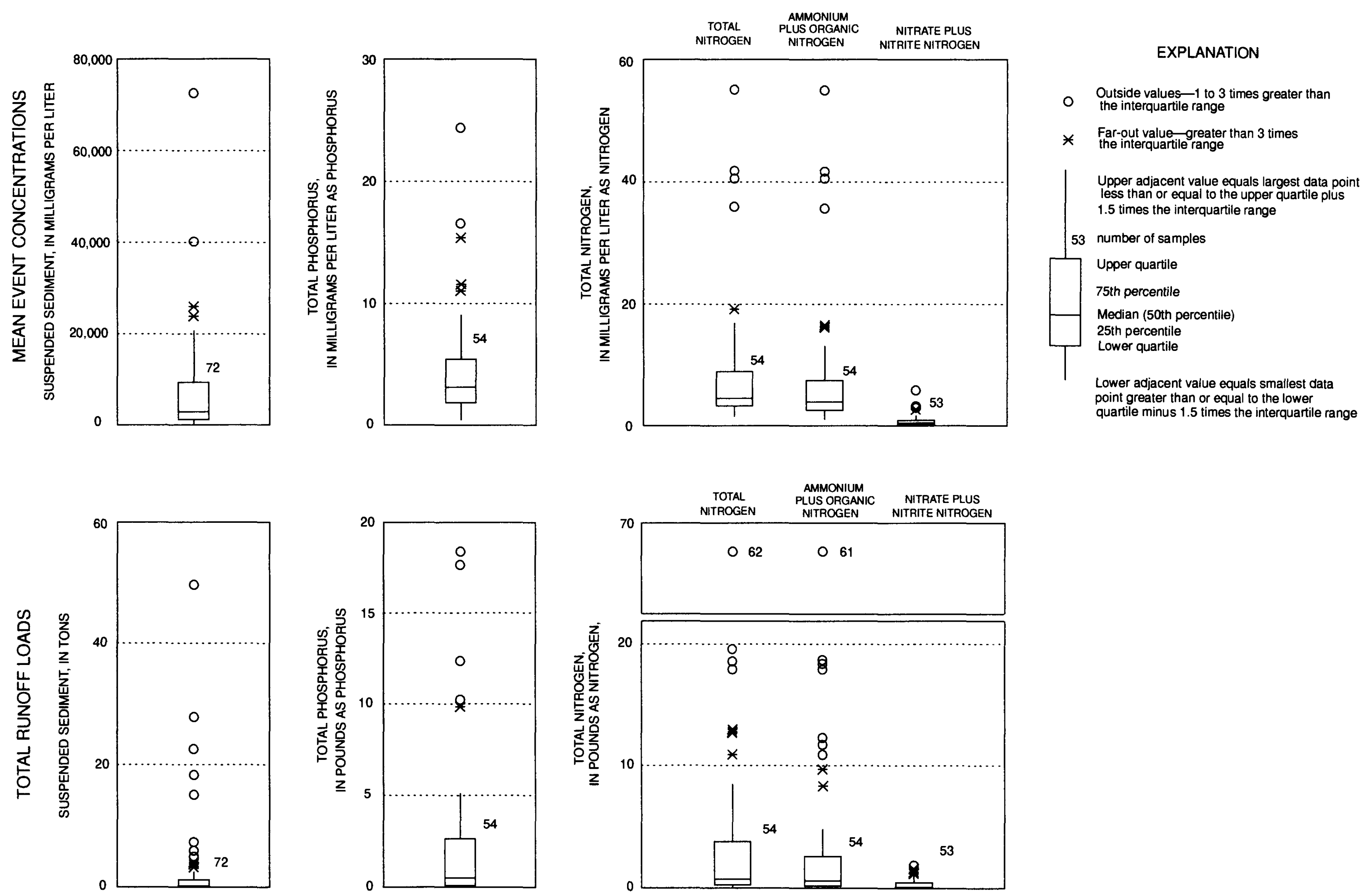


Figure 26. Distribution of mean flow-weighted event concentrations and loads of suspended sediment, total phosphorus, and total nitrogen in runoff from Field-Site 1, January 1983 through September 1984.

Mean concentrations of total phosphorus for runoff events ranged from 0.45 to 24 mg/L; the median was 3.1 mg/L (fig. 26). Loads of total phosphorus in runoff ranged from 0.002 to 18 lb; the median was 0.50 lb (fig. 26). Mean concentrations and loads of phosphorus differed greatly among runoff events, but no seasonal trends were apparent. Total-phosphorus loads from five sampled runoff events in 1984 accounted for about 45 percent of the estimated total-phosphorus load for the 1984 water year. Four of these are the same as four of the five runoff events contributing 60 percent of the 1984 estimated suspended-sediment load (the other runoff event contributing to the suspended-sediment load was not measured for total phosphorus). The fifth runoff event with a large total-phosphorus load was a winter snowmelt storm on February 3, 1984, which was discussed in detail earlier.

Mean concentrations of total nitrogen for runoff events ranged from 1.5 to 55 mg/L; the median was 4.5 mg/L (fig. 26). Loads of total nitrogen in runoff ranged from 0.005 to 62 lb; the median was 0.72 lb (fig. 26). On the average, about 85 percent of the mean event concentrations and loads of total nitrogen were ammonium plus organic nitrogen. The remaining 15 percent was nitrate plus nitrite. No seasonal trends in the data were apparent.

Data for runoff events on snow and frozen ground are discussed separately below (table 15). Because data from these runoff events differed greatly from the data from the other runoff events, and masked the cause-effect relations for the other runoff events, the events during snow and frozen-ground conditions were eliminated from the statistical analysis. However, the small number of this type of runoff event does not provide sufficient data for separate statistical analysis.

Rain fell on snow-covered, frozen ground six times during the study period. In addition, snowmelt alone caused measurable runoff five times. Flows were determined as accurately as possible for each of these 11 runoff events. Runoff samples from six events were analyzed for suspended sediment; samples from four events were analyzed for nutrients.

Mean concentrations and loads of suspended sediment were low for five of the six sampled storms—less than 700 mg/L and less than 0.40 ton, respectively. For the other sampled event (on February 11, 1984), the mean suspended-sediment concentration and load were 6,800 mg/L and 0.56 ton, respectively. A surface thaw probably increased the availability of suspended sediment to runoff during this storm.

With respect to total phosphorus, the February 3 load in runoff accounted for 5.8 percent of the total estimated phosphorus load for the study period.

Of all the runoff events sampled during the study period, three of the five events with the largest total nitrogen loads, 13 to 61 lb, were rain-on-snow or snowmelt events (table 15). The February 3, 1983, event transported 20 percent of the total estimated nitrogen load from the site during the study period. The nitrogen in runoff for this event was predominantly dissolved ammonium plus organic nitrogen.

The six rain-on-snow or snowmelt runoff events sampled and analyzed for suspended sediment (table 15) accounted for 13 percent of the total estimated runoff for the study period, but only 0.5 percent of the total estimated suspended-sediment load. The combination of the four rain-on-snow or snowmelt events sampled and analyzed for total phosphorus and nitrogen, which accounted for 12 percent of the total estimated runoff for the study period, accounted for 9.5 percent of the estimated total-phosphorus load, and 31 percent of the estimated total nitrogen load for the study period. Seven additional runoff events that occurred under similar conditions (rain-on-snow or snowmelt), but were not sampled for suspended sediment or nutrients, accounted for about 64,000 ft^3 of runoff and probably a substantially larger percentage of the load than discussed above. Total suspended-sediment, nitrogen, and phosphorus loads were estimated on the basis of the same regression equations used for all other runoff events during the nongrowing season, because there was insufficient data to estimate these values separately. Therefore, projections for nitrogen loads for these seven events and for the study period are probably too small, and projections for suspended-sediment loads are probably too large.

Atrazine, metolachlor, and alachlor were the only herbicides detected in runoff. Except for an atrazine concentration of 0.2 μg/L in one sample, no herbicides were detected in runoff samples collected during the nongrowing seasons of 1983 and 1984. No samples were collected during the 1983 growing

Table 15. Precipitation, runoff, and suspended-sediment and nutrient concentration and load data for runoff from six rainstorms occurring on snow-covered frozen ground, and comparison data from other sampled runoff events, January 1983 through September 1984, Field-Site 1

[ft^3, cubic foot; mg/L, milligram per liter; lb, pound; <, less than; --, no data; NA, not applicable]

Date	Precipitation (inches)	Runoff (inches)	Runoff (ft^3)	Total nitrogen, as nitrogen: Mean event concentration (mg/L)	Total nitrogen, as nitrogen: Maximum event concentration (mg/L)	Total nitrogen, as nitrogen: Load (lb)	Total phosphorus, as phosphorus: Mean event concentration (mg/L)	Total phosphorus, as phosphorus: Maximum event concentration (mg/L)	Total phosphorus, as phosphorus: Load (lb)	Suspended sediment: Mean event concentration (mg/L)	Suspended sediment: Maximum event concentration (mg/L)	Suspended sediment: Load (lb)
January 23, 1983	1.47	0.09	7,542	--	--	--	--	--	--	151	1,190	0.036
January 24, 1983	.00	.00	149	--	--	--	--	--	--	316	872	.002
January 24, 1984	.29	.23	18,700	11	22	13	0.80	1.2	0.93	24	77	.014
January 27 1984	.00	.09	7,060	41	52	18	2.7	6.7	1.2	658	770	.14
February 3, 1984	.25	.72	58,100	17	65	61	2.7	4.3	9.8	222	380	.40
February 11, 1984	.11	.03	2,660	3.7	5.6	.64	24	41	4.1	6,760	13,000	.56
ALL 50 OTHER RUNOFF EVENTS SAMPLED FOR NUTRIENTS												
Minimum	.06	<.01	19	1.5	2.2	.005	.45	.55	.002	NA	NA	NA
Maximum	3.43	.92	73,500	55	81	20	17	23	18	NA	NA	NA
Median	.48	.03	2,200	4.4	8.1	.70	3.2	5.6	.46	NA	NA	NA
ALL 66 OTHER RUNOFF EVENTS SAMPLED FOR SUSPENDED SEDIMENT												
Minimum	.06	<.01	19	NA	NA	NA	NA	NA	NA	230	550	<.00
Maximum	3.43	.92	73,500	NA	NA	NA	NA	NA	NA	72,600	137,000	49.7
Median	.50	.03	2,300	NA	NA	NA	NA	NA	NA	3,000	6,440	.23

season, because there was very little runoff. During the 1984 growing season, when 26 lb of atrazine and 34 lb of metolachlor were applied to the cornfields, instantaneous concentrations in runoff ranged from 1.4 to 73 μg/L for atrazine, and 0.4 to 85 μg/L for metolachlor. Alachlor, which had not been applied to the site since 1982, was found in two samples at concentrations of 0.8 and 0.6 μg/L.

Maximum instantaneous and mean water-weighted concentrations of atrazine and metolachlor in sampled runoff events during the 1984 growing season are shown on table 16. The first two runoff events after application, which both occurred on May 26, 1984, were not sampled. For sampled runoff events, the maximum mean concentrations, 56 μg/L for atrazine and 71 μg/L for metolachlor, occurred during the next storm on May 29, 1984. Mean event concentrations of the herbicides decreased dramatically by the next runoff event, and a general decrease continued throughout the remainder of the growing season. The atrazine concentrations in soil samples also decreased during this time period, from 540 μg/kg on June 7, 1984, to 46 μg/kg on October 15, 1984 (fig. 12).

Table 16. Maximum instantaneous measured concentrations and mean water-weighted concentrations of atrazine and metolachlor in runoff from storms during the 1984 growing season at Field-Site 1
[ft^3, cubic foot; μg/L, microgram per liter; --, no data]

Date	Total runoff (ft^3)	Runoff duration (hours)	Atrazine		Metolachlor	
			Maximum (μg/L)	Mean (μg/L)	Maximum (μg/L)	Mean (μg/L)
May 26	6,650	2.38	--	--	--	--
May 26	11,800	--	--	--	--	--
May 29	39,600	2.20	73	56	84	71
June 18	11,100	5.65	13	6.1	9.9	4.6
June 18-19	6,480	1.88	12	9.7	11	8.3
June 24	8,720	3.00	8.4	7.4	5.3	5.0
June 30	8,780	2.83	9.6	7.5	4.7	4.2
July 1	1,370	2.33	--	--	--	--
July 1	54,900	6.33	--	--	--	--
July 5	2,660	1.92	--	--	--	--
July 6	60,700	3.08	5.6	3.9	2.4	1.8
July 10	30,300	2.15	5.4	4.3	2.5	2.0
July 11	11,100	3.07	3.6	3.1	2.0	2.0
July 21	3,420	1.52	--	--	--	--
July 27	3,110	3.25	1.4	--	.4	--

The maximum loads in runoff, 0.14 lb of atrazine and 0.18 lb of metolachlor, occurred during the May 29, 1984, storm. These represent 64 and 88 percent of the total atrazine and metolachlor loads in runoff from sampled storms, respectively. Loads in runoff for each of the other sampled storms were less than or equal to 0.015 lb for each herbicide.

Relation of Suspended Sediment and Nutrients in Runoff to Agricultural Activities and Precipitation

As previously discussed, instantaneous suspended-sediment concentrations are related to discharge, and discharge depends on various factors related to precipitation. Therefore, a relation would be expected to exist between mean concentrations of suspended sediment and precipitation variables (total amount, duration, intensity, and antecedent moisture conditions) associated with the storm producing the runoff. Multiple regression, by use of data from storms producing runoff for which suspended-sediment concentration and precipitation were measured, indicates that mean suspended-sediment concentrations depend primarily on precipitation intensity (table 17). Suspended-sediment concentrations increased with increasing precipitation intensity. When the data set was limited by excluding all runoff events in January through March, more of the variability in mean suspended-sediment concentration could be explained. In addition to precipitation intensity, the addition of precipitation duration to the regression equation was statistically significant. The negative sign of the coefficient for precipitation duration in the regression equation indicates that suspended-sediment concentrations decreased with increases in precipitation duration. Sediment available for transport by runoff varied widely during winter storms because of variable soil conditions associated with small maximum 30-minute intensities (less than 0.15 in.). No precipitation intensities were measured for the several storms during the study period that immediately followed plowing. Runoff from these storms, not included in the regression analyses, may have transported sediment differently than most storms in relation to precipitation factors because of the extremely loose soil conditions.

If nutrient-management BMP's are to improve runoff water quality, a strong relation has to exist between nutrient applications and nutrient concentrations in surface runoff. The nutrient application variables that were considered to have a significant influence on nutrient concentrations in runoff were amounts of nutrients applied to the site and time between application and runoff. The amount of nitrogen available to runoff from nutrient applications would be expected to decrease with time because of losses through volatilization, leaching, and previous runoff. Runoff events occurring within 1 hour of each other were composited because nutrient variables for each event were the same. However, the movement of nutrients in runoff from the field also depends on factors affecting the amounts and velocities of runoff, specifically the precipitation factors and soil conditions, as discussed in the surface-runoff section.

Multiple regressions were used in an attempt to determine the principal agricultural activity and precipitation factors influencing nutrients in runoff (table 18). The data set was reduced to the runoff events for which nutrient concentrations and precipitation were measured, and then further reduced by excluding runoff events that occurred when the ground was frozen and immediately following plowing.

Graphical and regression analyses indicate that a general increase in mean concentration of total nitrogen occurred with increasing nitrogen applications during the 15, 30 (producing the best correlations; fig. 27, table 18), or 45 days before the runoff event.

Four runoff events occurred during late July through September 1984, when no nutrient applications had been made to the field for 45-113 days before the storms because of the crop cover. These runoff events were excluded from the data set because they occurred under different conditions than prevailed during the other events. Also, the independent variable used in regression analysis, nitrogen application in the last 15 to 45 days before the storms, is equal to zero for these storms. One runoff event had a large effect on the regression analysis (table 18). This December 4, 1983, runoff event produced a high mean nitrogen concentration in the runoff, 36 mg/L (see fig. 27), following a period when very little nitrogen had been applied to the site. Although data for this event was questioned on the initial laboratory report, insufficient sample was available for laboratory reanalysis.

Precipitation factors considered in the data analyses included total inches of precipitation, hours of precipitation duration, and inches of precipitation that occurred in the 30 days preceding the runoff event (an indicator of antecedent moisture conditions). The addition of precipitation intensity did not appear to improve the regression, although intensity data were missing for 6 of the 36 storms. Of the remaining variables, only the addition of precipitation was statistically significant in the regression (table 18, data set B). The relations of residual to predicted values for the regression models with nitrogen application and

Table 17. Regression statistics for the log of mean suspended-sediment concentrations in runoff from Field-Site 1, as a function of the log of precipitation variables
[<, less than; --, not entered into regression as independent variable]

Data set	Degrees of freedom [1]	Coefficients and associated statistics for logs of independent variables: Maximum 30-minute intensities (inches)	t-statistic	p-value	Precipitation duration (hours)	t-statistic	p-value	Intercept	Coefficient of determination (adjusted R^2) [2]	Standard error (log units)	Standard error, Percent (plus	/ minus) [3]
A	(ALL RUNOFF EVENTS WITH MEASURED SUSPENDED-SEDIMENT CONCENTRATIONS AND PRECIPITATION DATA)											
	44	1.232	6.730	<0.001	--	--	--	4.453	0.50	0.450	182	64
	44	1.124	5.903	<.001	-0.235	1.680	0.10	4.479	.52	.441	176	64
B	(DATA SET A WITHOUT RUNOFF EVENTS OCCURRING JANUARY THROUGH MARCH)											
	33	1.139	7.185	<.001	-.213	2.130	.042	4.446	.66	.300	100	50

[1] Degrees of freedom equal to number of storms minus one.
[2] R^2 adjusted for degrees of freedom to permit comparison of regression models on the basis of different sets of data.
[3] G.D. Tasker, U.S. Geological Survey, written commun., 1978.

Table 18. Regression statistics for the log of mean event total-nitrogen concentrations in runoff from Field-Site 1, in milligrams per liter as nitrogen, as a function of the log of nitrogen application and precipitation-duration variables
[lb, pound; <, less than; --, not entered into regression]

Data set	Degrees of freedom [1]	Coefficients and associated statistics for logs of independent variables: Nitrogen application [2] (lb as nitrogen)	t-statistic	p-value	Precipitation duration (hours)	t-statistic	p-value	Intercept	Coefficient of determination (adjusted R^2) [3]	Standard error (log units)	Standard error, Percent (plus	/ minus) [4]
A	ALL RUNOFF EVENTS WITH MEASURED NITROGEN CONCENTRATIONS AND PRECIPITATION DATA, WITHOUT RUNOFF EVENTS WHERE NO NUTRIENT APPLICATIONS HAD BEEN MADE FOR 45-113 DAYS PREVIOUSLY AND RUNOFF EVENTS OCCURRING ON FROZEN GROUND											
	36	0.514	5.279	<0.001	--	--	--	-0.565	0.43	0.265	84	46
	36	.500	5.267	<.001	-0.138	1.785	0.086	-.464	.46	.257	81	45
B	DATA SET A WITHOUT RUNOFF EVENT ON DECEMBER 4, 1983											
	35	.550	6.881	<.001	--	--	--	-.685	.57	.216	64	39
	35	.535	7.144	<.001	-.149	2.451	.020	-.578	.62	.202	59	37

[1] Degrees of freedom equal to number of storms minus one.
[2] Pounds of nitrogen as manure or commercial fertilizer applied to the field in the 30 days preceding the runoff event.
[3] R^2 adjusted for degrees of freedom to permit comparison of regression models on the basis of different sets of data.
[4] G.D. Tasker, U.S. Geological Survey, written commun., 1978.

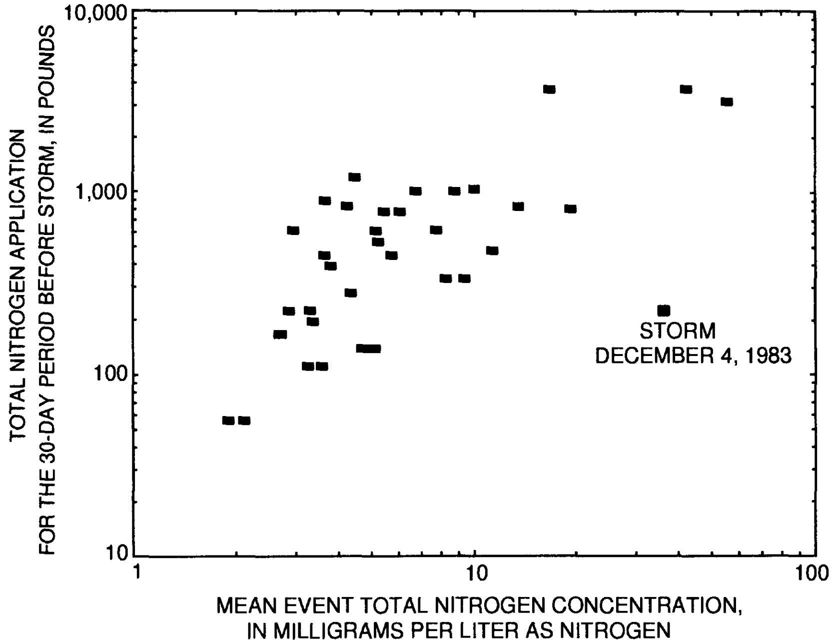


Figure 27. Relation of total amount nitrogen applied to Field-Site 1 in the 30-day period prior to a runoff event to mean total nitrogen concentration for runoff events indicated on table 18, data set A, January 1983 through September 1984.

precipitation duration are shown in figure 28. The negative sign of the coefficient for precipitation duration indicates nitrogen concentration decreases with increasing duration, implying that concentrations are diluted by continuing rainfall.

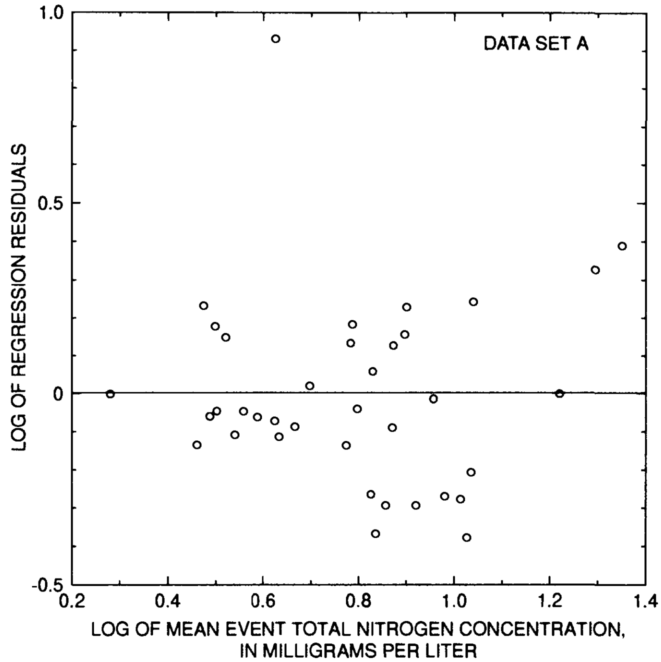
Regression coefficients and values of the independent variables in the equation indicate that for most runoff events, the nitrogen application plays a much larger role in controlling the concentration of total nitrogen than does precipitation duration. [For the data set B (table 18) of 36 storms (excluding the December 4, 1983, event), nitrogen applications ranged from 56 to 3,700 lb; the median was 460 lb. Precipitation duration ranged from 0.33 to 31 hours; the median was 3.6 hours.] This same type of data analysis was performed with phosphorus data but did not result in any significant relations between variables.

Another factor that probably affects the mean nitrogen concentration during a runoff event is the amount of nitrogen bound to the soil. Total nitrogen accounts for an average of about 0.25 percent (by weight) of the soil, on the basis of soil analyses of the top 2 in. This nitrogen probably contributes to the base nitrogen concentration in runoff that, by examination of the runoff data, appears to have occurred regardless of fertilizer use. A quantification of this contribution to runoff, however, was not possible with the existing data.

Possible Effects of Best-Management Practices on Runoff Quality

Nutrient management and terracing BMP's will be implemented at the site in the 1985 water year. Some projections on how these BMP's can effect runoff quality are discussed below. The projections are based on data analyses previously presented in this report.

One key factor in the nutrient-management BMP to be implemented is the timing of fertilizer applications with crop uptake. A manure-storage facility, constructed in 1984, allows for manure to be stored for 6 months and spread twice a year over the farm rather than "daily" as practiced during this study period. This facility may greatly reduce the amount of nutrients available to runoff during the winter and, therefore, the elevated nitrogen concentrations in runoff from rain-on-snow or snowmelt. One



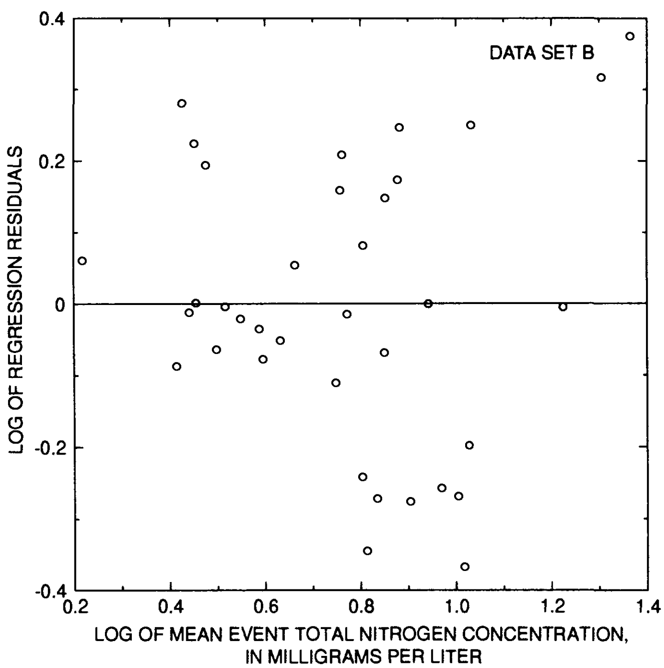


Figure 28. Relation of residual to predicted mean concentration of total nitrogen for regression models of runoff events described on table 18, with nitrogen applications and precipitation duration as the independent variables.

reason for the elevated dissolved-nitrogen concentrations, such as found in runoff from the February 3, 1984, storm, is increased contact time of runoff with the manure and soil nutrients. After terrace construction at this site (another planned BMP), runoff may pool in areas behind each terrace before entering drain pipes. This may increase contact time between runoff water (water leaving the field through the pipe outlet of the terraces) and surface-available nutrients and could elevate dissolved-nutrient concentrations in runoff regardless of season.

Regressions for total nitrogen mean concentrations in runoff indicate that any reduction in the amount of nitrogen applied to the field should result in a reduction in the mean concentrations, assuming similar field conditions. Also, assuming similar precipitation conditions, a reduction in nitrogen loads leaving the site in runoff would be expected. Nutrient-management BMP's recommend applying only the nutrients required by the crop, taking into account the residual soil nutrients and available manure nutrients and the fact that nutrients are applied to the site at a time as close as possible to the time when the crops can use them. Therefore, under similar field conditions, nutrient management would be expected to be effective in reducing the nitrogen leaving the site in surface runoff. The other BMP to be implemented on this site is terracing. Terracing would not affect the nitrogen-application and precipitation-duration variables in the regression equation. But the equation only explains about 50 percent of the factors affecting the concentrations of total-nitrogen in storm runoff. Terracing will, at a minimum, alter the topography and soil tilth and, therefore, the runoff conditions that now exist at the site. Therefore, the relations described by the regression equations are likely to change after terraces are installed.

Monthly and Annual Nutrient Loads

The large temporal variation in precipitation amounts and characteristics makes comparisons of monthly loads from year to year difficult. No runoff occurred during May through July 1983.

Monthly suspended-sediment loads (fig. 29) were as large as 109 ton in July 1984; median monthly load was 0.90 ton. Generally, the monthly loads of suspended sediment varied proportionally with runoff (fig. 18). However, the large monthly suspended-sediment loads occurred during the same months in which the large ratios of runoff to total monthly precipitation occurred. Also, runoff in January of 1983 and 1984, when the ground was frozen, produced the smallest suspended-sediment loads relative to the amount of runoff. Intense thunderstorms from May through July 1984 caused proportionally large suspended-sediment loads in relation to the amount of runoff.

Monthly total-phosphorus loads (fig. 30) were as large as 55 lb in July 1984; median monthly load was 2.1 lb. Monthly phosphorus loads were somewhat proportional to the amount of runoff. However, because phosphorus generally is tightly bound to soil particles, large loads were more directly related to large suspended-sediment loads that occurred during intense thunderstorms from May through July 1984.

Monthly total-nitrogen loads (fig. 31) reached 76 lb in February 1984; the median monthly load was 3.4 lb. A median monthly load of ammonium plus organic nitrogen was 2.7 lb and of nitrate plus nitrite was 0.19 lb. Months in which total-nitrogen loads exceeded 25 lb generally corresponded to the months when runoff was greater than or equal to 20 percent of precipitation. Runoff during December 1983 through February 1984 carried the largest ammonium plus organic nitrogen loads (30 to 71 lb). About 100 ton per month (900 lb of nitrogen per month) of dairy manure were surface-applied to the site during these 3 months. Runoff during December 1983 and from May through July 1984 carried the largest nitrate plus nitrite loads (more than 2.0 lb). Generally, more nitrate was available in warmer months because temperature conditions favored conversion of manure nitrogen to this form.

Because data were not collected for 2 complete years, the average annual constituent loads were calculated by multiplying an average monthly load for the 21-month study period by 12. Over the 21-month period, an estimated 258 ton of sediment left the field site in runoff. The annual suspended-sediment load for the pre-BMP period was 147 ton, or 6.7 (ton/acre)/yr. This exceeds the erosion factor, T, of 4 (ton/acre)/yr recommended for the site by the U.S. Soil Conservation Service according to soil types. ["The erosion factor T is an estimate of the maximum average annual rate of soil erosion by wind or water that can occur without affecting crop productivity over a sustained period" (U.S. Department of Agriculture, 1985). The contribution of wind to erosion is considered to be negligible for the site.] Because the delivery ratio of sediment to the edge of field is generally less than 1, the actual erosion rate is usually greater than the sediment yield.

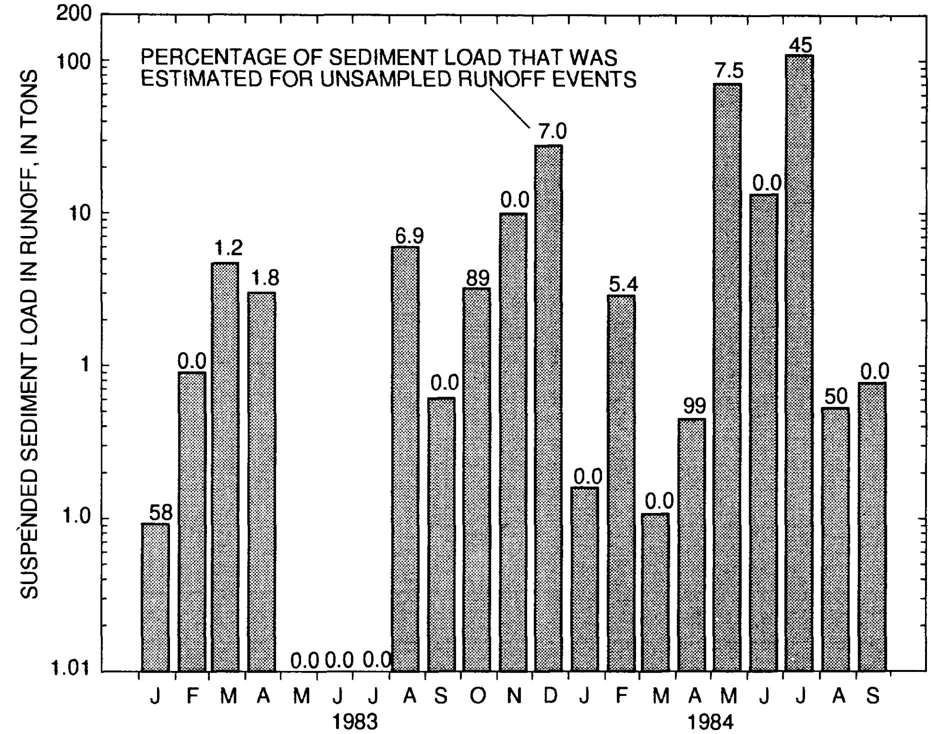


Figure 29. Total monthly suspended-sediment load in runoff from Field-Site 1.

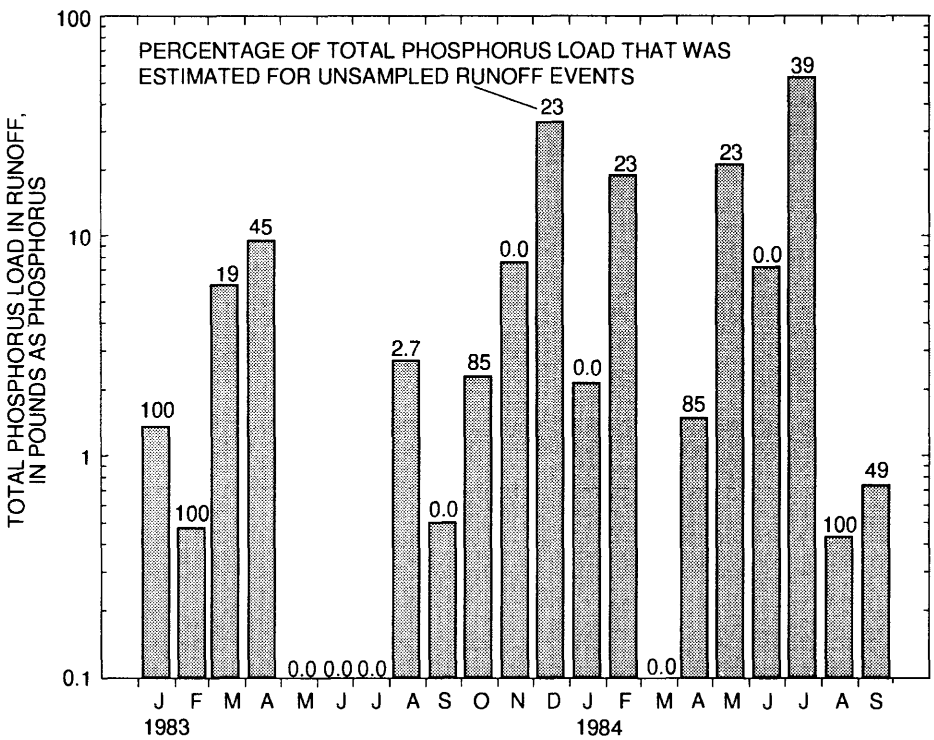


Figure 30. Total monthly phosphorus load in runoff from Field-Site 1.

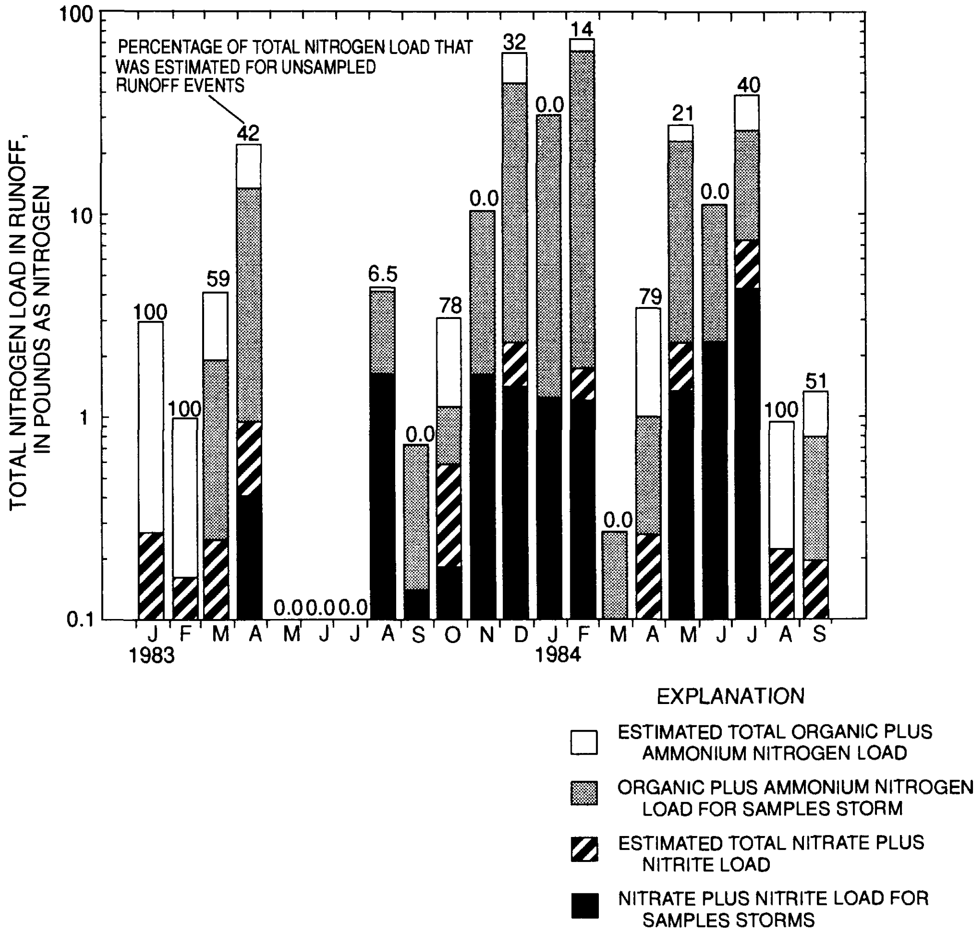


Figure 31. Total monthly nitrogen load in runoff from Field-Site 1.

During the study period, an estimated 176 lb, or 4.6 (lb/acre)/yr, of phosphorus and 314 lb, or 8.1 (lb/acre)/yr, of nitrogen were transported in runoff from the site. Of the nutrients applied to the site as manure and commercial fertilizer during the study period, 5.5 percent of the total phosphorus and 2.5 percent of the total nitrogen left the site in runoff.

The annual loads presented above are a combination of loads during the relatively dry 1983 water year and wet 1984 water year, so they can be considered to represent a runoff load for the site during an average year. However, runoff during the 2 years differed dramatically. Of the total runoff and nutrient loads for the 21-month study period, 88 percent of the runoff occurred during the wet 1984 water year (57 percent of the study period), and transported 94 percent (230 ton) of the suspended-sediment load and 88 percent of the load of total phosphorus (150 lb) and total nitrogen (265 lb). The suspended-sediment load for the 1984 water year exceeded the erosion factor T by 2.5 times. The dramatic differences between wet and dry years have been documented in previously published streamflow studies. One such study was conducted in the Pequea Creek Basin (148 mi^2), which is adjacent to the Conestoga River Basin, and has similar geology, soils, and land use (Lietman and others, 1983). In that study, if streamflow data from the wet 1979 calendar year are combined with data from the dry 1980 calendar year, the wet 1979 calendar year accounted for 90 percent of the streamflow, 97 percent of the suspended-sediment load, and 94 percent of the load of total phosphorus and total ammonium plus organic nitrogen (the form of nitrogen which generally makes up 80 to 90 percent of the nitrogen in runoff at Field-Site 1).

Deposition of nitrate and ammonium from precipitation at the site was calculated to be 60 and 30 lb, respectively, for January through September 1983, and 150 and 60 lb, respectively, for the 1984 water year. However, 3.3 percent of the precipitation became runoff during the 9-month study period in 1983, and 13 percent of the precipitation became runoff during 1984. If all of the nutrients input by the precipitation remained associated with the precipitation that ran off, about 10 percent of the total-nitrogen load in runoff during the study period could have been nitrate and ammonium from precipitation, and 85 percent of the nitrate load in runoff could have originated from precipitation. Assuming 50 percent of the total nitrogen was dissolved and about 50 percent of the dissolved nitrogen was ammonium and nitrate (estimated by use of instantaneous data), then about 40 percent of the dissolved-nitrogen load could have been from precipitation. However, some of the nitrogen from precipitation could have remained on the site from processes such as soil absorption of ammonia. A study in Iowa by Schuman and Burwell (1984) indicated that 53 percent of the dissolved ammonium plus nitrate that left a 12-acre cornfield in runoff, fertilized at a rate of 400 lb/acre, could be attributed to precipitation input. However, they also noted that hydrologic and chemical processes reduce the amount of nitrogen input by precipitation that is carried off in runoff.

CHARACTERIZATION OF GROUND WATER

Site hydrogeology, chemical quality of the ground water, and ground-water hydrologic and nitrogen budgets are discussed in this section. The three-dimensional configuration of the ground-water-flow system was determined by geologic interpretation of outcrops and well logs. Water-level data from six primary observation wells with continuous water-level recorders were used to help determine the water-table configuration and flow direction. Agricultural-activity, precipitation, and recharge data were used to determine the relation of agricultural activities to ground-water quality.

Quantity

Physical Setting

The water table in carbonate-rock areas of Lancaster County is generally a subdued replica of the land surface (Gerhart, 1984). Boundaries for the ground-water basin were estimated from observed water levels, geology, and topographic features. The ground-water basin at the site is slightly larger than the surface-water basin. Ground water from the flow system discharges along the eastern boundary at the Conestoga River and its unnamed tributary. The northern, western, and southern boundaries of the ground-water-flow system are at ground-water divides, which are approximately in the same position as surface-water divides (fig. 32). Near coincidence between the surface-water and ground-water divides on northwestern and southern boundaries is a reasonable assumption on the basis of topographic relief (fig. 2) and observed ground-water levels (fig. 32). The southwestern boundary of the ground-water-flow system was also estimated on the basis of observed water levels and topographic relief; however, it was more difficult to locate because topographic relief is low and the water table is nearly flat.

The aquifer in the study area is the Zooks Corner Formation, a dolomitic-rock aquifer under water-table conditions. The diabase dike in the north-central part of the site impedes the flow of ground water and contributes to an elevated water table in this part of the site.

Unsaturated-zone materials at the site are 5 to 70 ft thick and are very permeable. Secondary porosity in the soils and regolith of the unsaturated zone caused by root channels, worm holes, and subsurface erosion facilitate rapid movement of water and dissolved materials from the land surface to the water table. A small sinkhole developed near well LN 1646 (fig. 32) from 1983 to 1984, possibly providing a direct path for recharge water and surface materials to travel to the water table. In the carbonate bedrock, solutionally developed passages along bedding planes, fractures, joints, and cleavage are the dominant pathways for ground-water flow. Lithologic logs indicate that in some areas these passages are filled with silt, clay, or rock fragments (fig. 33).

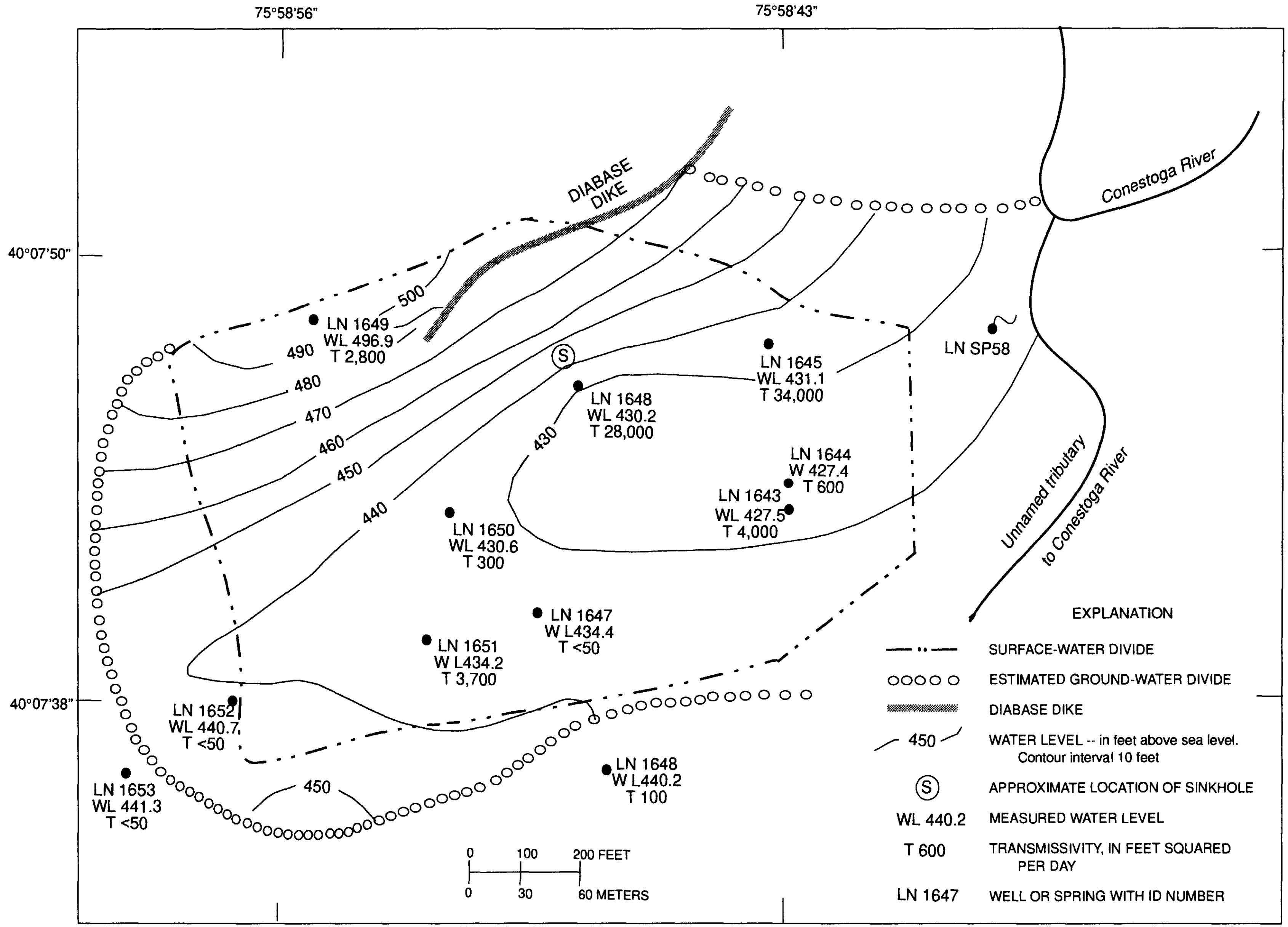


Figure 32. Estimated water-table configuration on November 2, 1982, and transmissivity of the Zooks Corner Formation at Field-Site 1.

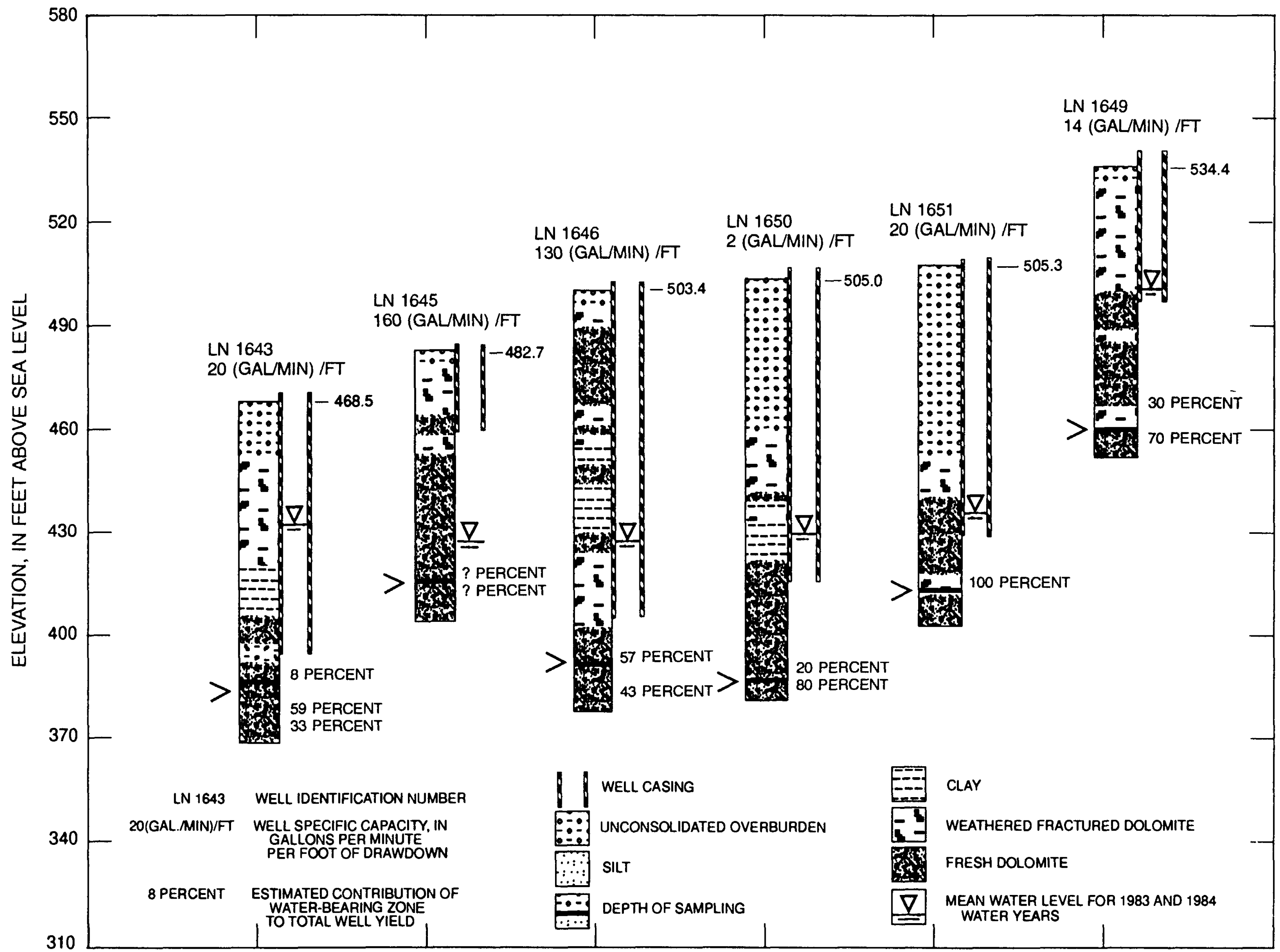


Figure 33. Lithology, mean water levels, and water-bearing zones of wells measured continuously for water level and sampled for water quality at Field-Site 1. (Modified from Gerhart, 1986, fig. 4.) (Site locations are shown on fig. 2.)

Hydrologic System

The specific yield of an aquifer is the volume of water it will yield by gravity drainage divided by its total volume (Lohman and others, 1972). At Field-Site 1, the specific yield of the saturated ground-water-flow system was estimated from water-level rises measured in well LN 1643 during recharge events under conditions of high antecedent soil-water saturation and negligible evapotranspiration (as described by Gerhart, 1986)(table 19). The water-level hydrograph from well LN 1643 was selected to calculate the specific yield at the site because it is nearly complete for the study period and because it is similar in range and shape to hydrographs from the other wells. Water-level rises resulting from rain on frozen ground, rain on a snowpack, or snowstorms were not used because infiltration rates were low and caused lags in response time of the water table. Of the recharge events that met the above conditions, nine occurred from January to April 1983 and six from December 1983 through April 1984, when most vegetation was dormant and soil moisture was at or near field capacity. Under these conditions, it was assumed that all precipitation became either runoff or ground-water recharge. Precipitation, runoff, and water-level rise, measured for each recharge event, were used to calculate specific yield (tables 19 and 20) according to the following equation:

$$\text{Specific yield} = (P-R)/WLR, \qquad (1)$$

where P is precipitation, in inches;
R is runoff, in inches;
WLR is water-level rise in an observation well, in inches.

Table 19. Precipitation, runoff, water-level rise, and calculated specific yield for well LN 1643, January 1983 through September 1984
[Calculations are based on methods of Gerhart, 1986]

Date	Precipi-tation (inches)	Runoff (inches)	Water-level rise in well LN 1643 (inches)	Specific yield
Jan. 23, 1983	1.5	0.10	7.7	0.18
Feb. 2-4, 1983	1.1	.04	15.0	.03
March 10, 1983	.35	.01	3.7	.09
March 18-19, 1983	.60	.01	4.3	.13
March 21, 1983	1.0	.07	5.5	.16
April 3, 1983	.60	.01	5.4	.11
April 8, 1983	.50	.02	2.6	.18
April 9-10, 1983	1.3	.19	13.0	.09
April 15-16, 1983	2.6	.26	17.8	.14
Dec. 12-13, 1984	4.6	1.2	38.4	.09
Feb. 15, 1984	1.3	.02	9.1	.13
March 23-24, 1984	1.5	.13	8.0	.17
March 28, 1984	.85	.01	6.4	.13
April 4, 1984	.71	.06	4.8	.14
April 5, 1984	.56	.04	4.5	.12
		AVERAGE SPECIFIC YIELD =		.13

Table 20. Water-level rise and calculated specific yields of seven wells at Field-Site 1 for a storm on March 21, 1983, with 1.0 inch of rain and 0.07 inch of runoff, and a storm on April 9-10, 1983, with 1.3 inches of rain and 0.19 inch of runoff

Well	Date	Water-level rise (inches)	Specific yield
LN 1645	03/21/83	7.1	0.13
	04/09-10/83	8.5	.13
LN 1646	03/21/89	6.8	.13
	04/09-10/83	7.9	.14
LN 1647	03/21/83	9.6	.09
	04/09-10/83	13.8	.08
LN 1650	03/21/83	8.4	.11
	04/09-10/83	10.0	.11
LN 1651	03/21/83	8.7	.10
	04/09-10/83	13.8	.08
LN 1652	03/21/83	9.1	.10
	04/09-10/83	11.0	.10
LN 1653	03/21/83	12.1	.08
	04/09-10/83	13.7	.08

The median estimated specific yield at well LN 1643 was 0.13. Estimates of median specific yield at seven other wells at the site ranged from 0.08 to 0.14 (table 20). An unquantified error in the estimation of specific yield by the preceding technique can occur when horizontal flow through the aquifer during periods of recharge to ground water influences the altitude of the water table. The specific yields at the site are somewhat elevated relative to those in other hydrogeologic settings in southeastern Pennsylvania (Gerhart and Lazorchick, 1984) and are attributed to the highly developed secondary porosity. Spatial variation in estimated specific yield is caused by the presence or absence of fractures, joints, faults, voids, and bedding planes that can differentially store water in different parts of the site (Parizek and others, 1971). Temporal variation in the specific-yield estimates probably occurs because of differences in soil moisture between recharge events, and because of the position of the water level in different parts of the aquifer at different times.

The specific capacity of a well is the rate of discharge of water from the well divided by the drawdown of the water level in the well (Lohman and others, 1972). Specific capacities of the wells at the site (table 4) were calculated on the basis of estimates made by the driller and by aquifer tests at the finished wells. Estimated specific capacities range from less than 1 (gal/min)/ft to 160 (gal/min)/ft (median of 9 (gal/min)/ft) (table 4). The two wells with the greatest specific capacity (LN 1645 and LN 1646) are in the northeastern part of the site. Large variations in specific capacity are characteristic of wells in carbonate aquifers because of the relative presence or absence of fractures, joints, faults, and voids that may differentially transmit water in different parts of the aquifer (Parizek and others, 1971).

Transmissivity is the rate at which water passes through a unit width of aquifer under a unit hydraulic gradient (Lohman and others, 1972). Transmissivity was calculated from estimates of specific capacity by rearrangement of the Jacob equation (Driscoll 1986)

$$Q/s = (T/264)\log(0.3(T)(t)/(r^2)(S)), \qquad (2)$$

where s is drawdown in the well, in feet;
Q is yield of the well, in gallons per minute;
T is transmissivity of the well, in feet squared per day;
t is time of pumping, in days;
r is radius of the well, in feet; and
S is storage coefficient of the aquifer.

The values used for t and Q were from actual aquifer tests, r is 0.25 ft, and S was assumed to be equal to specific yield, calculated from equation (1).

Transmissivity values differ by about three orders of magnitude at this small study area--from less than 50 ft^2/d at wells LN 1647, LN 1652, and LN 1653, to 34,000 ft^2/d at well LN 1645 (fig. 32).

Large local variations in transmissivity are common in carbonate aquifers with highly irregular dissolution occurring along joints, faults, fractures, and bedding planes (Freeze and Cherry, 1979). Because of a small primary porosity and variable secondary porosity, carbonate aquifers are poorly productive to extremely productive; flow velocities of up to 350 ft per hour have been recorded in the Ordovician limestone near Tussey and Nittany Mountains in central Pennsylvania (Parizek and others, 1971).

The aquifer in parts of the site where the hydraulic gradient of the water table is low has a large transmissivity. Accordingly, the 70-ft relief of the water table between wells LN 1649 and LN 1650 suggests that the transmissivity between these two wells is small. In the area between the wells, the impermeable diabase dike forces ground water to flow across rather than along bedding. The large clay content of materials in the unsaturated zone in the vicinity of well LN 1649 also may limit ground-water flow.

Occurrence and Flow

Although the depth of the shallow ground-water-flow system has not been determined, most flow probably occurs near the water table, primarily along solution-enhanced fractures in the bedrock (Davis and DeWiest, 1966). Most ground water discharges from the site as base flow to the Conestoga River and its unnamed tributary, although some small amount of water discharges from the spring. Because the water table is generally more than 30 ft below the land surface, evapotranspiration from the water table is probably not a significant mechanism of ground-water discharge.

The highly fractured bedrock contains evidence of a preferred flow direction parallel to strike. Major solutional passages commonly develop along planes of bedding in carbonate aquifers (Fetter, 1980). The strike of the dolomite at the site ranges from about N. 60° E. to N. 70° E.; dip ranges from about 40° NW. to 70° NW. (fig. 4). Water samples from well LN 1651, drilled along strike from spring LN SP58, have similar concentrations of dissolved nitrate (correlation coefficient, $R = 0.88$), suggesting that ground water is rapidly moving along strike from the well site to the spring (fig. 4).

Water-Level Fluctuations

A water-table map (fig. 32), constructed on the basis of elevations of streams and measured ground-water levels, approximates low water-table conditions at the site on November 2, 1982. Depth from the land surface to the water table ranges from 35 to 75 ft, and flow generally is toward the Conestoga River and its unnamed tributary. Water-table contours bend as shown because of the steep slope of the land just outside the site.

At five of the primary observation wells, the maximum difference in water-level altitude is about 10 ft. The water-level altitude at well LN 1649 is 60 to 75 ft higher than it is at the other wells because of the presence of the diabase dike that controls flow in that part of the site.

Water-level fluctuations at the six primary observation wells ranged from 3.5 ft at well LN 1645 to 8.6 ft at wells LN 1649 and LN 1651 (fig. 32). Temporal variations in water levels measured at these wells were similar throughout the study period (fig. 34). Major recharge periods occurred during the spring and winter of 1983, and during the spring of 1984. Water levels in each well (except well LN 1649) responded quickly to recharge, and water levels peaked several hours to 1 day following precipitation (figs. 35 and 36). Rapid response occurred because of the presence of permeable soils that overlie a carbonate aquifer containing solution-enhanced fractures in the unsaturated and saturated zones. These conditions permit rapid movement of water and, in some instances, permit precipitation to reach the water table directly. Recharge of this type may be enhanced by sinkholes and an intersecting set of vertical joints found at the site.

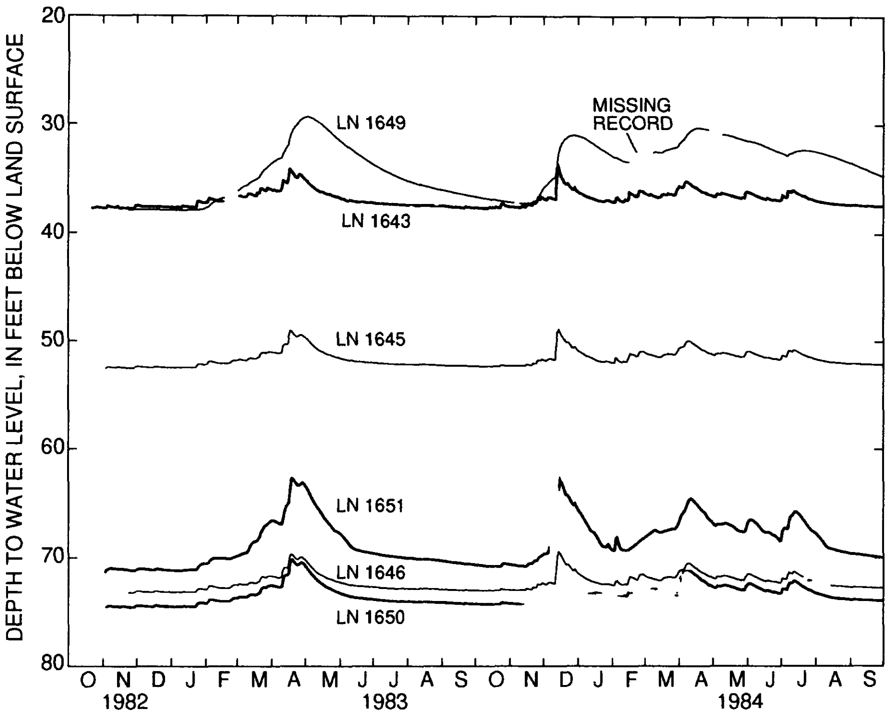


Figure 34. Variations in ground-water level at six wells, Field-Site 1.

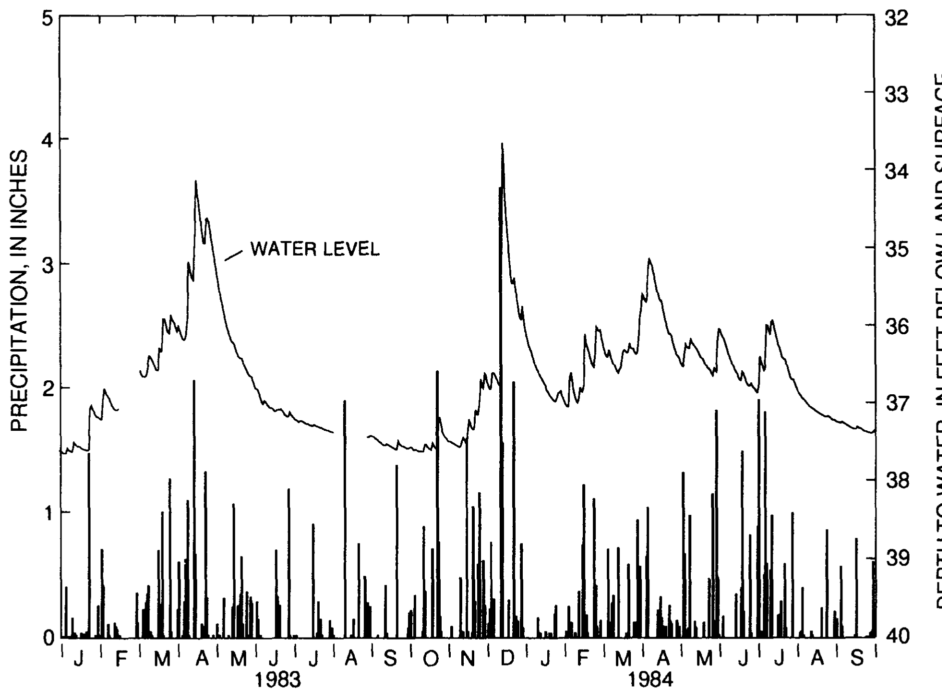


Figure 35. Water-level response to precipitation at well LN 1643.

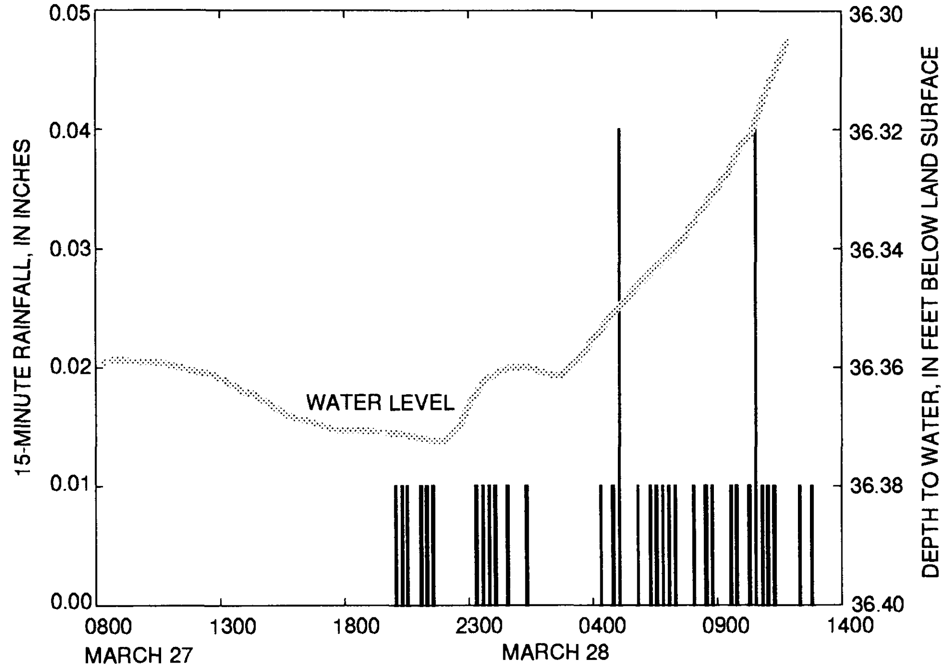


Figure 36. Water-level response to precipitation at well LN 1643 for a storm on March 27-28, 1984. (Modified from Gerhart, 1986.)

Water levels in well LN 1649 peaked 7 to 10 days following recharge. The water-level hydrograph for well LN 1649 was smoother than the other five observation wells because of the slow response of water levels to recharge (fig. 34). A relatively slower water-level response to recharge in well LN 1649 probably is caused by the presence of clay upgradient of the well. Lithologic logs (fig. 31) made during installation of well LN 1649 indicate the presence of clay to a depth of 34 ft. Clay also was found adjacent to this well site when holes were augured for lysimeters.

Recharge and Discharge

The ground-water-flow system was assumed to be closed to inputs except recharge from precipitation. The amount of ground-water recharge at the site was estimated from data collected at well LN 1643. This well was chosen because a continuous record of water-level data is available. Because precipitation infiltrates quickly to the water table at well LN 1643, water-level rise multiplied by the specific yield (0.13) gives a reasonable estimate of ground-water recharge for any storm. Hence, monthly recharge can be estimated by summing water-level rises occurring during each month and multiplying the sum by the median specific yield of 0.13. These calculations are summarized in figure 37.

For the study period (January 1983 through September 1984), ground-water recharge was 39.7 in. or 43 percent of total precipitation. For the 9 months of the 1983 water year, total recharge was 14.7 in., or 45 percent of precipitation. For the relatively wet 1984 water year, recharge was 25.0 in. or 41 percent of precipitation. If recharge had been evenly distributed throughout the study period, the ground-water-flow system would have been recharged by 1.86 in. monthly. However, as shown in figure 33, most recharge occurred in winter or early spring when evapotranspiration was negligible and vegetation was dormant. Fifty-nine percent of the recharge in the last 9 months of the 1983 water year was in March and April, whereas 42 percent of recharge in the 1984 water year was in December and February. The 3.23 in. of recharge in July 1984 demonstrates that significant recharge can occur in any month depending on the amount, duration, intensity, and frequency of precipitation.

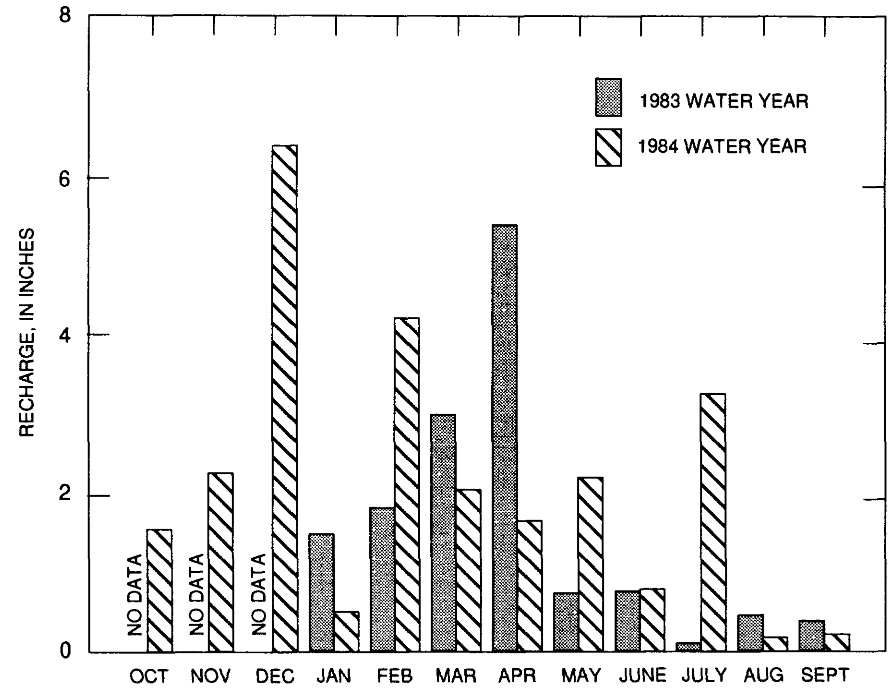


Figure 37. Estimated ground-water recharge at well LN 1643.

Ground-water discharge from the site was estimated by multiplying the annual inches of recharge from precipitation times the drainage area and assumes that annual recharge entering the site approximates annual discharge leaving the site. Supporting this assumption are ground-water levels that are consistently near the same altitude across the field site for October or November of 1983 and 1984. Total monthly discharge computed for the site (table 21) also are based on data from well LN 1643 because this well is closest to the discharge area of the basin (water-table contours in figure 28 indicate that most of the discharge occurs near this well), and the water-level record for 1983 and 1984 water years is nearly complete. Annual discharge was prorated, by month, by use of Darcy's Law (Freeze and Cherry, 1979)

$$D = (K)\,(A)\frac{\Delta h}{\Delta l}, \qquad (3)$$

where D is discharge, in cubic feet per minute;

K is hydraulic conductivity, in feet per minute;

A is cross-sectional area, in square feet; and

$\frac{\Delta h}{\Delta l}$ is hydraulic gradient, dimensionless.

Because K and A are essentially constant throughout the year, the hydraulic gradients control the discharge. Monthly change in water level at well LN 1643 was determined by subtracting the stream elevation immediately downgradient of well LN 1643 from the monthly mean water levels recorded at the well. Proportional monthly changes in water level were then multiplied by annual recharge to estimate monthly discharge.

For the study period approximately 3,187,000 ft^3 of ground water discharged from the site. The average monthly discharge was 152,000 ft^3, the average daily discharge was 5,000 ft^3.

Table 21. Summary of estimated monthly ground-water discharge at Field-Site 1, January 1983 through September 1984
[--, no data]

Month	Monthly ground-water discharge (cubic feet)	Month	Monthly ground-water discharge (cubic feet)
1983 WATER YEAR		1984 WATER YEAR	
October	--	October	70,000
November	--	November	93,000
December	--	December	267,000
January	59,000	January	162,000
February	118,000	February	174,000
March	189,000	March	197,000
April	283,000	April	267,000
May	200,000	May	197,000
June	118,000	June	174,000
July	83,000	July	197,000
August	71,000	August	116,000
September	59,000	September	93,000
Total	1,180,000	Total	2,007,000
TOTAL DISCHARGE FOR STUDY PERIOD		3,187,000 cubic feet	

Figure 38 shows the monthly recharge and discharge for the study period. Net recharge generally occurred in the fall, late winter, and early spring when vegetation is dormant and the ground was not frozen. Net discharge occurred in the spring and summer when evapotranspiration was greatest. The gain in recharge in July 1984 was caused by an unusual 8.42-in. rainfall that produced a recharge rate that exceeded the evapotranspiration rate.

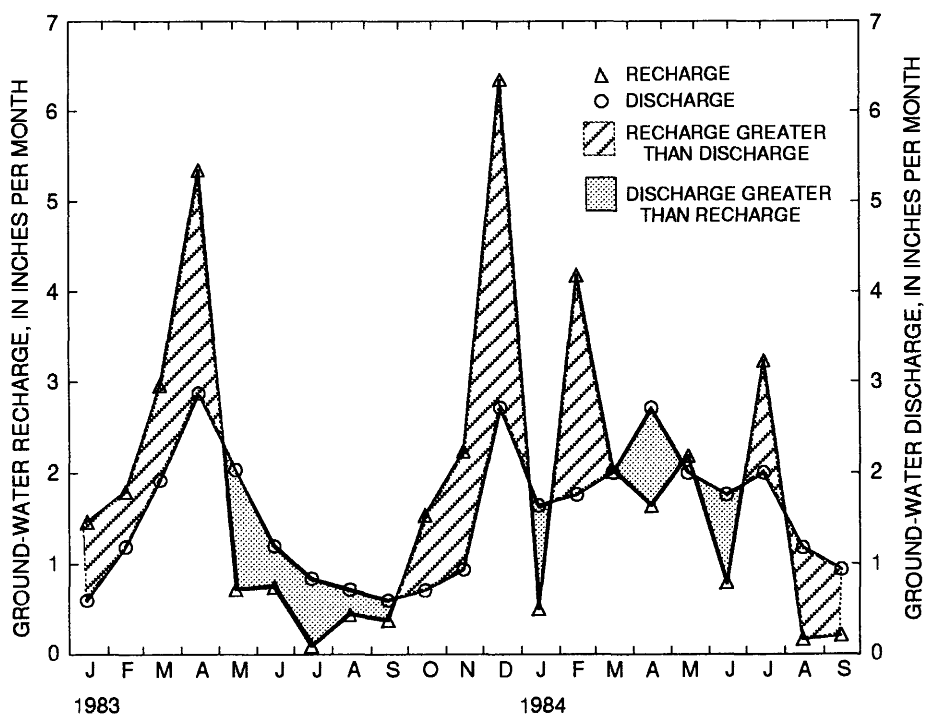


Figure 38. Ground-water recharge and ground-water discharge at Field-Site 1 based on data from well LN 1643.

Quality

Description

Ground-water quality at the site closely reflects the carbonate mineralogy of the aquifer. Table 22 shows the results of analyses from a small number of water samples that were analyzed for major ions to describe ground-water chemistry at the site. Ground water is very hard, ranging from 200 to 530 mg/L as calcium carbonate (Hem, 1985), and is slightly alkaline (pH ranging from 7.0 to 7.7) with a high buffering capacity (alkalinity ranging from 155 to 272 mg/L as calcium carbonate) (Hem, 1985) (table 23). The median molar ratio of calcium to magnesium is 0.94, indicating the presence of dolomitic rock (Hem, 1985). Concentrations of dissolved oxygen in ground water at the site range from 1.4 to 10.6 mg/L at eight sampled wells and the spring.

Specific conductance of samples analyzed for major ions from eight wells and the spring ranged from 413 to 1,010 μS/cm (table 22). Specific conductance generally increased from north to south and from west to east toward the discharge area. The range of specific conductance was controlled primarily by the dissolution of the carbonate materials, as indicated by the concentrations of calcium, bicarbonate, and magnesium in ground water (Hem, 1985) (table 22). However, elevated conductances in some samples from wells LN 1651 and LN 1643 (maximums of 725 and 695 μS/cm, respectively) compared to those for the other wells and the spring possibly were caused by leaching from surface-applied manure, because greater amounts of manure were applied in the vicinity of these wells than were applied at the others. Such applications would increase the availability of ions (such as nitrate, chloride, sodium, and potassium) for leaching to the ground water. Large specific conductances of water samples from well LN 1649 are probably caused by a long ground-water residence time because of the position of the diabase dike near this well, which restricts water flow and increases the time available for dissolution of bedrock.

Water from the six primary observation wells and the spring was sampled for specific conductance, nutrients, and herbicides (table 1). Water samples, except those from well LN 1649, were classified as "nonrecharge" if they were collected at least 1 week after a 0.3-ft water-level rise, or "recharge" if they were collected less than 1 week after a 0.3-ft water-level rise (table 23; general processes discussed by Keith and others, 1983). Water samples from spring LN SP58 (where no water-level measurements were made) were classified the same as those collected from a nearby well (LN 1643) on the same date. Water samples for well LN 1649 could not be classified as nonrecharge or recharge because of the slow response time of water-level changes. The samples from the remaining wells (LN 1643, LN 1645, LN 1646, LN 1650, and LN 1651) were used to assess (1) how ground-water quality varied during short recharge periods compared to nonrecharge or baseline periods, and (2) to what extent recharge, which may be directly influenced by agricultural-activity and meteorologic factors, affects the overall quality of ground water in the flow system.

During nonrecharge periods, specific conductance generally increased or decreased at all sites simultaneously (fig 39). However, these changes did not exhibit a seasonal trend. During single recharge events, large variations in specific conductance of up to 175 μS/cm were noted in samples from wells LN 1643, LN 1646, and LN 1649. In water samples from the other wells and the spring, variations during single recharge events were generally less than 50 μS/cm. The recharge event that produced the largest change in specific conductance for five of the wells and the spring (excluding well LN 1649) began on May 29, 1984, soon after plowing and heavy fertilizer applications.

Median concentrations of dissolved phosphorus for nonrecharge and recharge samples from any of the wells or spring ranged from 0.02 to 0.05 mg/L, and the maximum sample concentration was 0.11 mg/L in a water sample collected at well LN 1651 (table 23). Phosphorus is essentially unavailable for leaching because it is bound to soil particles by chemical precipitation and adsorption, and very little soluble phosphorus was present in soils. Concentrations of soluble phosphorus in soil samples collected in April 1984 were less than 0.25 mg/kg in the top 8 in. of soil.

Total ammonium plus organic nitrogen accounted for only 4.0 percent (median percentage) of the total nitrogen in the ground water; of this percentage, 89 percent of the total nitrogen was dissolved. This distribution is similar for samples from the individual wells or the spring; however, the distribution differed from sample to sample at any one site. Median concentrations of ammonium plus organic nitrogen for nonrecharge and recharge samples from the six observation wells and the spring ranged from 0.32 to 0.51 mg/L; the maximum concentration was 2.0 mg/L (table 23). Fifteen percent (median percentage) of the dissolved ammonium plus organic nitrogen was ammonium; this distribution differs widely (8 to 37 percent) within and among sites. Although ammonium ions tend to be fixed within the soil profile through cation exchange, they can be oxidized to nitrate and become available for leaching to ground water. Little of the organic nitrogen moves to the ground-water-flow system.

Nitrate concentrations in ground water at the site commonly exceeded the USEPA maximum contaminant level (MCL) of 10 mg/L nitrate as nitrogen for drinking water (U.S. Environmental Protection Agency, 1990). Minimum, maximum, and median concentrations of dissolved nitrate in water samples collected from 1983 through 1984 from the six observation wells and the spring, except well LN 1649 where ground water is affected by the diabase dike, were 5.6, 18, and 10 mg/L, respectively (table 23).

Nitrate is the most soluble and mobile species of nitrogen. As the end product in the oxidation of organic nitrogen and ammonium, it is continually available throughout the soil profile for leaching. For all water samples, dissolved nitrate accounted for 97 percent (median percentage) of the dissolved nitrogen and 93 percent (median percentage) of the total nitrogen. These relations varied little at or among sites.

When nitrate data were available for comparison, 99.9 percent of the dissolved nitrate plus nitrite in ground water was consistently nitrate. Therefore, concentrations of nitrate plus nitrite are assumed to be dissolved nitrate for all samples. Nitrite represents a short-lived intermediate oxidation product in the nitrification of ammonium to nitrate. Median concentrations of nitrite for all wells did not differ by more than 0.01 mg/L; the detection limit was the median at all wells except wells LN 1646 and LN 1649. Maximum concentrations of 0.38 and 0.33 mg/L for nonrecharge and recharge samples, respectively, were detected during late fall at well LN 1646. In late fall, soluble nitrite may have been available from oxidation of recently spread manure. Cool soil temperatures reduce the rate of nitrification—hence, the persistence of nitrite.

Nitrate concentrations at seven wells and the spring are shown in figure 40. Nitrate concentrations were significantly greater at well LN 1649 than at other sites. Ground water from this well represents ground water in the northwestern part of the site, which is topographically above the diabase dike. On the basis of the interquartile ranges in concentration, the variation of nitrate concentrations in nonrecharge samples generally was less than that of recharge samples.

Atrazine and metolachlor were the only two herbicides applied during the study period and were the only two detected in all samples from the six wells and the spring (table 22). Concentrations of alachlor and cyanazine in ground water were consistently less than the detection limits (table 2). These are preemergent agricultural herbicides that were applied to the cornfields in May each year after planting. No detectable amounts of atrazine and metolachlor were found in early spring water samples before herbicide application. Atrazine and metolachlor were found in ground water in detectable quantities soon after application in 1984, but neither were detected in 1983 until late summer, probably because the spring and early summer of 1983 were relatively dry and recharge was small (fig. 37). Both herbicides are persistent in the ground water; they were detected in three wells and the spring up to 6 months after application. The maximum concentration of atrazine, 0.4 μg/L, was found at wells LN 1643, LN 1649, and in spring LN SP58. The maximum concentration of metolachlor, 0.3 μg/L, was found at spring LN SP58. Measured concentrations of both atrazine and metolachlor were less than the USEPA lifetime health advisory levels of 3.0 and 100 μg/L, respectively (U.S. Environmental Protection Agency, 1992).

Table 22. Summary statistics for physical and chemical characteristics of water from 10 wells and the spring at Field-Site 1 analyzed for major ions
[mg/L, milligram per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; Min, minimum; Max, maximum; <, less than; --, no data]

Well number	Specific conductance (µS/cm)				pH (units)				Temperature (degrees Celsius)				Dissolved oxygen concentration (mg/L)			
	Median	Min	Max	Number of samples	Median	Min	Max	Number of samples	Median	Min	Max	Number of samples	Median	Min	Max	Number of samples
LN 1643	595	502	695	4	7.5	7.3	7.6	4	12.0	11.0	13.5	3	4.6	1.4	9.4	4
LN 1645	515	470	561	4	7.6	7.4	7.7	4	11.8	11.0	12.5	2	8.7	8.6	9.4	4
LN 1646	502	487	570	5	7.6	7.5	7.7	5	12.0	11.0	14.0	4	8.0	5.8	8.6	5
LN 1647	930	--	--	1	7.0	--	--	1	11.0	--	--	1	--	--	--	--
LN 1648	1010	--	--	1	7.1	--	--	1	10.5	--	--	1	--	--	--	-
LN 1649	678	555	720	5	7.4	7.2	7.5	5	11.8	11.0	12.5	4	10.4	8.5	10.6	
LN 1650	470	430	500	5	7.7	7.4	8.5	5	11.8	11.0	14.0	4	7.6	5.2	8.0	3
LN 1651	611	413	725	5	7.2	7.0	7.4	5	11.8	10.5	12.5	4	9.4	9.2	9.8	4
LN 1652	646	642	650	2	7.5	7.4	7.6	2	13.0	11.0	15.0	2	8.6	--	--	1
LN 1653	627	--	--	1	7.7	7.6	7.7	2	11.0	--	--	1	1.4	--	--	1
LN SP58	565	442	590	9	7.4	7.0	7.7	10	11.5	10.5	13.5	7	8.4	8.4	8.4	2

Well number	Hardness (mg/L as $CaCO_3$)				Acidity (mg/L as $CaCO_3$)				Dissolved calcium concentration (mg/L as Ca)				Dissolved magnesium concentration (mg/L)			
	Median	Min	Max	Number of samples	Median	Min	Max	Number of samples	Median	Min	Max	Number of samples	Median	Min	Max	Number of samples
LN 1643	335	280	360	4	18	8.0	27	4	65	43	72	4	43	40	44	4
LN 1645	270	260	270	4	15	7.0	18	4	52	51	54	4	34	33	34	4
LN 1646	260	230	300	5	12	8.0	20	5	49	42	55	5	33	30	39	5
LN 1647	420	--	--	1	36	--	--	1	86	--	--	1	49	--	--	1
LN 1648	480	--	--	1	27	--	--	1	98	--	--	1	57	--	--	1
LN 1649	330	300	360	5	17	10	20	4	64	59	73	5	41	38	43	5
LN 1650	240	200	250	5	9.0	6.0	11	2	46	30	47	5	30	29	33	5
LN 1651	300	260	320	5	34	24	42	3	59	51	65	5	38	31	39	5
LN 1652	310	300	320	3	16	--	--	1	62	56	63	3	40	38	40	3
LN 1653	270	260	530	3	12	--	--	1	48	38	84	3	40	37	77	3
LN SP58	280	250	300	10	15	10	23	6	56	41	58	10	36	33	37	10

Table 22. Summary statistics for physical and chemical characteristics of water from 10 wells and the spring at Field-Site 1 analyzed for major ions —Continued

[mg/L, milligram per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; Min, minimum; Max, maximum; <, less than; --, no data]

Well number	Dissolved sodium concentration (mg/L as Na)				Dissolved potassium concentration (mg/L as K)				Alkalinity (mg/L as $CaCO_3$)				Dissolved sulfate concentration (mg/L as SO_4)			
	Median	Min	Max	Number of samples	Median	Min	Max	Number of samples	Median	Min	Max	Number of samples	Median	Min	Max	Number of samples
LN 1643	5.6	4.8	20	4	2.7	0.1	4.8	4	250	222	260	4	45	40	100	3
LN 1645	4.2	3.5	22	4	2.0	1.5	2.4	4	210	205	226	3	25	20	35	3
LN 1646	3.7	3.2	19	5	1.7	1.5	2.6	5	204	190	215	5	28	20	35	4
LN 1647	28	--	--	1	6.1	--	--	1	311	--	--	1	180	--	--	1
LN 1648	6.9	--	--	1	2.0	--	--	1	321	--	--	1	40	--	--	1
LN 1649	4.0	3.6	17	5	1.9	1.4	3.1	5	180	158	192	3	60	55	60	
LN 1650	3.3	2.9	19	5	1.4	1.2	2.0	5	181	155	190	4	23	15	45	4
LN 1651	3.6	2.9	16	5	2.3	1.4	3.7	5	235	205	272	3	38	25	40	4
LN 1652	5.3	4.7	7.1	3	2.1	1.9	2.2	3	238	235	240	2	55	30	80	2
LN 1653	4.1	3.7	6.0	3	2.0	1.6	2.6	3	252	--	--	1	53	45	60	2
LN SP58	4.4	3.3	18	10	1.8	.9	2.9	9	215	210	240	7	32	25	55	10

Well number	Dissolved chloride concentration (mg/L as Cl)				Dissolved nitrate concentration (mg/L as N)				Dissolved ammonium concentration (mg/L as N)				Dissolved orthophosphorus concentration (mg/L as P)			
	Median	Min	Max	Number of samples	Median	Min	Max	Number of samples	Median	Min	Max	Number of samples	Median	Min	Max	Number of samples
LN 1643	21	20	23	3	8.1	6.5	13	4	.55	.24	4.1	4	.03	--	--	1
LN 1645	12	11	13	3	11	10	15	4	.02	.01	.09	4	.02	<.01	.02	4
LN 1646	11	10	12	4	9.2	7.5	9.7	5	.46	.27	1.6	5	<.01	<.01	.01	5
LN 1647	15	--	--	1	10	--	--	1	.08	--	--	1	<.01	--	--	1
LN 1648	33	--	--	1	28	--	--	1	.09	--	--	1	<.01	--	--	1
LN 1649	24	22	30	5	20	17	22	5	.21	.04	.47	5	.09	--	--	1
LN 1650	10	9.0	11	5	9.5	6.1	11	4	.79	.19	1.1	4	<.01	<.01	.01	5
LN 1651	13	8.0	17	5	10	9.6	11	5	.12	.05	.37	5	.03	.02	.06	5
LN 1652	17	15	20	3	11	11	12	3	.21	.15	.38	3	<.01	<.01	.02	3
LN 1653	11	10	11	3	5.2	.01	8.1	3	1.1	1.0	1.6	3	<.01	<.01	<.01	3
LN SP58	13	12	13	9	11	8.8	13	10	.02	<.01	.12	10	<.01	<.01	.02	9

Table 23. Summary statistics of specific conductance and nutrient and herbicide concentrations in water samples from six wells and the spring at Field-Site 1, collected during January 1983 through September 1984
[<, less than; NR, nonrecharge; R, recharge]

	LN SP58		LN 1643		LN 1645		LN 1646		LN 1650		LN 1651		LN 1649
	NR	R	NR	R	NR	R	NR	R	NR	R	NR	R	All samples
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER AT 25 DEGREES CELSIUS													
Median	558	580	714	700	545	553	510	533	485	520	628	630	692
Maximum	590	623	782	760	585	595	586	610	607	590	725	660	780
Minimum	370	442	502	553	493	470	482	470	430	475	413	528	555
Number of samples	15	29	13	25	15	25	13	25	13	15	13	25	40
DISSOLVED NUTRIENTS, IN MILLIGRAMS PER LITER AS NITROGEN OR PHOSPHORUS													
Phosphorus													
Median	.03	.03	.03	.03	.03	.03	.02	.02	.02	.02	.05	.05	.02
Maximum	.06	.08	.07	.06	.07	.06	.07	.06	.06	.05	.11	.07	.06
Minimum	.01	.01	.01	.01	.01	.01	<.01	<.01	.01	<.01	<.01	.02	<.01
Number of samples	11	25	13	26	15	27	13	26	13	17	13	27	42
Ammonium plus organic nitrogen													
Median	.38	.36	.47	.50	.35	.49	.51	.50	.32	.32	.40	.50	.40
Maximum	1.1	.70	1.5	1.4	.70	.80	1.9	2.0	1.5	1.2	1.3	1.4	1.8
Minimum	.20	<.20	.24	<.20	.20	<.20	<.20	<.20	<.20	<.20	<.20	<.20	<.20
Number of samples	14	29	13	24	15	26	13	22	13	17	13	26	39
Nitrite													
Median	<.01	<.01	<.01	<.01	<.01	<.01	.01	.02	<.01	.01	<.01	.01	.01
Maximum	.01	.02	.01	.02	.01	.02	.38	.33	.05	.02	.03	.18	.06
Minimum	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01
Number of samples	11	25	13	27	15	27	13	26	13	16	13	27	42
Nitrate plus nitrite													
Median	12	11	13	13	11	11	9.2	9.7	11	11	10	10	20
Maximum	13	14	18	16	15	13	11	13	12	12	11	14	34
Minimum	11	7.8	6.5	8.2	9.8	8.7	7.4	5.8	9.2	6.2	9.5	5.6	15
Number of samples	16	32	13	27	15	27	13	26	13	17	13	27	42
TOTAL HERBICIDES, IN MICROGRAMS PER LITER													
Atrazine													
Maximum	.4	.4	.1	.4	.2	.2	.2	.2	.2	.2	.3	.1	.4
Number above detection limit [1]	6	8	3	7	6	9	4	7	4	6	3	1	14
Number below detection limit	3	4	5	9	3	9	4	8	3	4	6	15	11
Metolachlor													
Maximum	.2	.3	<.2	<.2	.2	.2	.2	.2	.1	.2	.2	.1	.2
Number above detection limit [2]	2	5	0	0	2	6	2	4	2	2	3	1	1
Number below detection limit	7	7	8	16	7	12	6	11	5	8	6	15	24

[1] Detection limit is 0.2 micrograms per liter for 1983 water year and 0.1 micrograms per liter for 1984 water year.

[2] Detection limit is 0.1 micrograms per liter for study period.

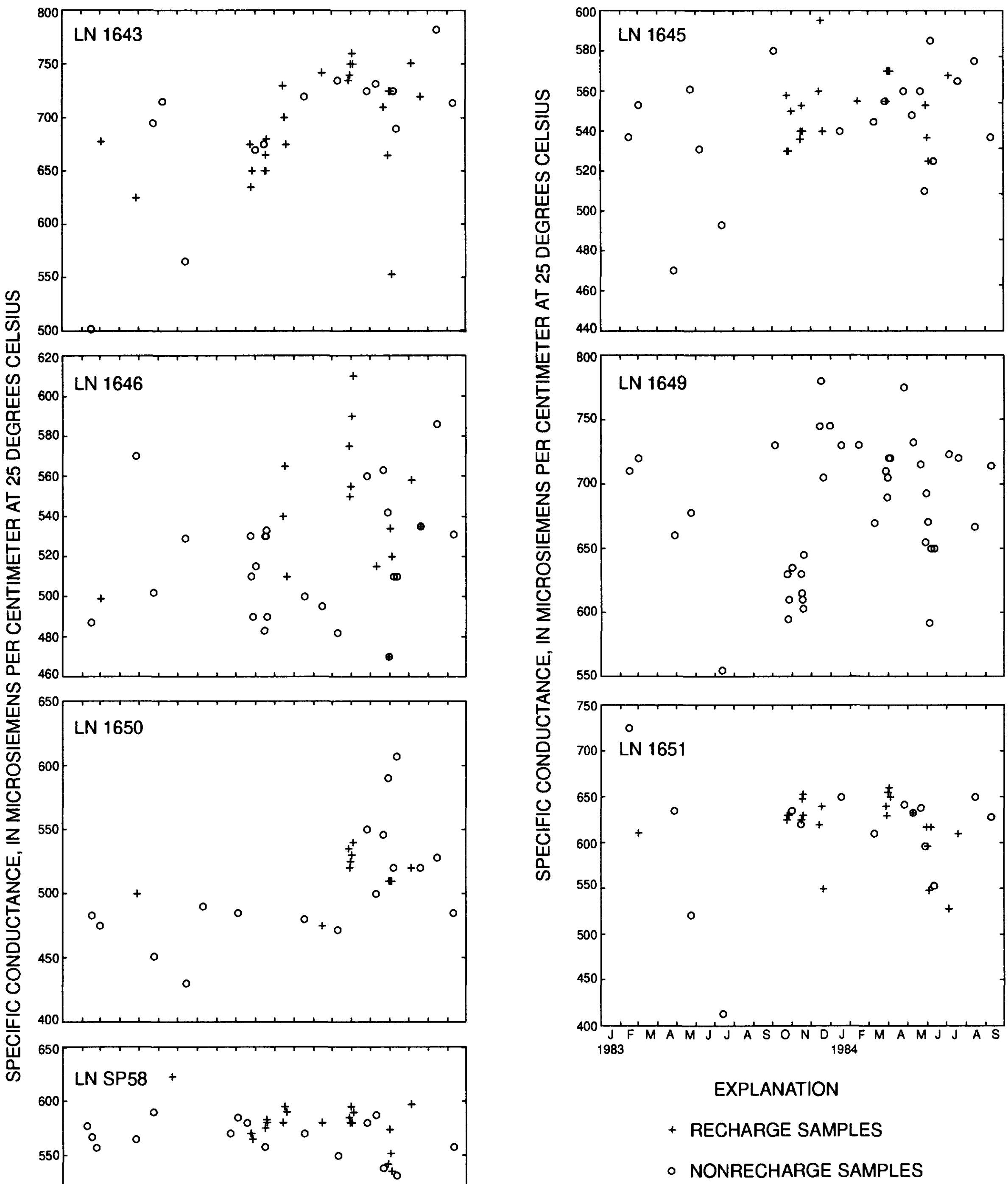


Figure 39. Specific conductances of ground water at six wells and the spring at Field-Site 1. (Samples from well LN 1649 were not separated into recharge and nonrecharge groups because of the anomalous hydrology in that area of the aquifer.)

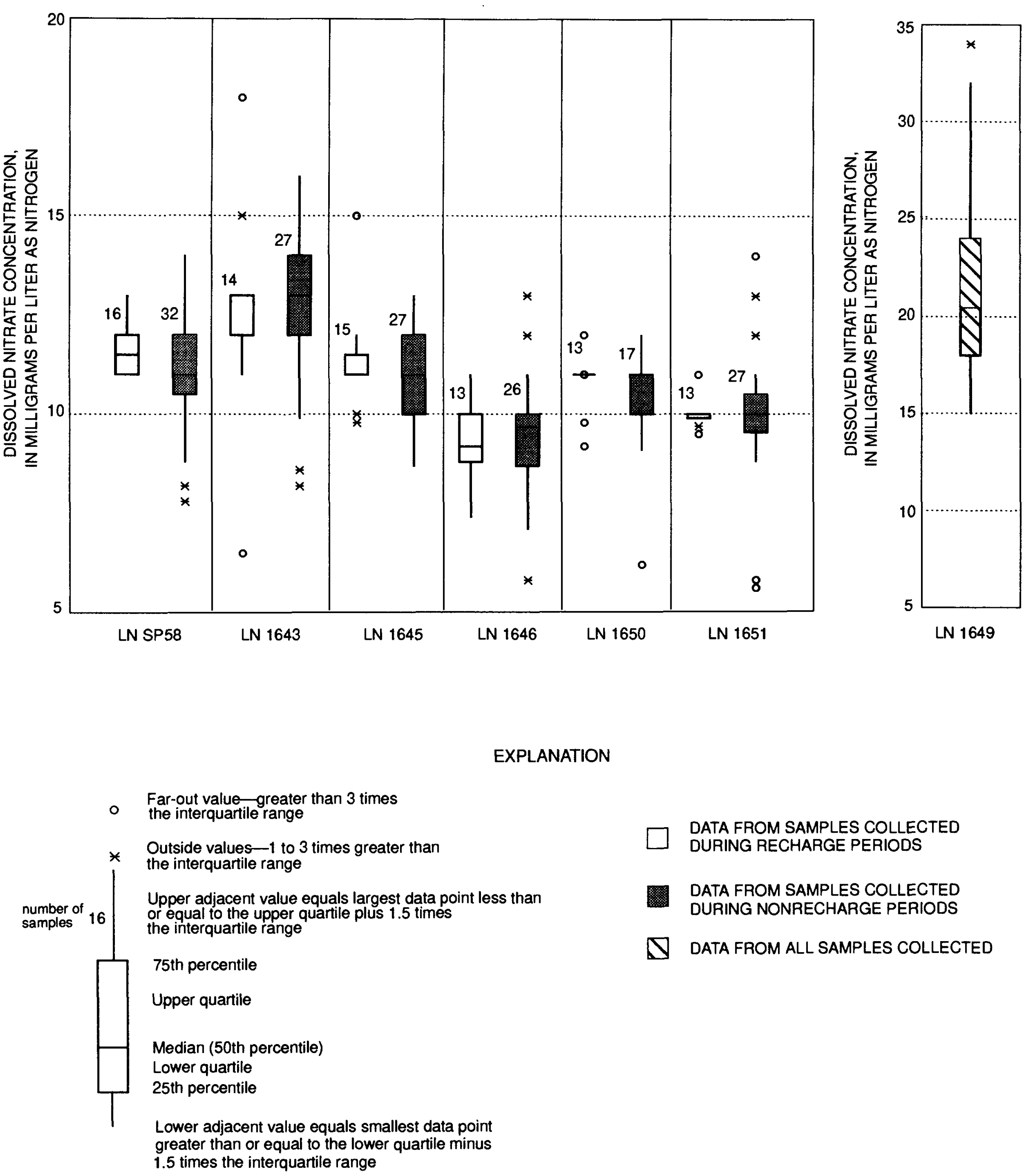


Figure 40. Distribution and concentrations of dissolved nitrate in recharge and nonrecharge samples for five wells and one spring, and in all samples from well LN 1649, January 1983 through September 1984, Field-Site 1.

Relation of Ground-Water Quality to Land Use, Agricultural Activities, and Recharge

Assessment of the effects of agricultural activities and recharge on ground-water quality is complicated by a variety of factors. For example, specific locations of nutrient and pesticide applications and volumes of materials applied are not reported precisely by the farmers. Bacterial processes that convert organic nitrogen to ammonium and nitrate at the land surface, in the soils, and in the unsaturated and saturated zones are affected by changes in temperature and moisture and by herbicide applications (Stevenson, 1982). In addition, recharge can take a complex path from the land surface to the water table (Priebe and Blackmer, 1989). As previously discussed, ground water in the anisotropic, carbonate aquifer at the site follows complex flow paths that are difficult to determine. Despite these complications, important relations between surface-applied materials, recharge, and water quality are evident in data collected at the site.

The effect of surface-applied materials on ground-water quality at the site during the percolation of recharge water to the water table is shown in a graph of atrazine concentrations over time (fig. 41). In the 1984 growing season, atrazine was applied at the site on May 23, 1984. During the first recharge event following application, atrazine was detected in water samples from six of the seven sampling sites (no atrazine was detected at spring LN SP58). At well LN 1645, recharge water delivered atrazine to the water table through approximately 50 ft of soils and weathered material in less than 1 day. Despite no additional applications, atrazine was detected at well LN 1645 through September, suggesting that some of the slow moving recharging waters traveling through the small channels and pores in the unsaturated zone continued to deliver atrazine to the water table (Gerhart, 1986).

Lysimeters were installed at 3-, 6-, and 9-ft depths to ascertain soil-water nitrate concentrations near observation wells. Figure 42 shows the relation between the nitrate concentrations in ground water from well LN 1643 and in soil water from three lysimeters near well LN 1643. Soil-water nitrate concentrations ranged from less than 1 to 43 mg/L and were greatest at the 9-ft depth. Nitrate concentrations in the soil water fluctuated seasonally; the greatest concentrations occurred from October through December 1983--the first major recharge period after the end of the 1983 growing season. This seasonal fluctuation may have been caused by the spreading of manure on fields after harvest and by the leaching of nitrogen left in the soil after the growing season. Ground-water nitrate concentrations at well LN 1643 ranged from 6 to 18 mg/L and increased gradually during the period.

Contributing areas were estimated for the five wells shown in figure 43 in order to relate ground-water quality to applications of manure and commercial fertilizers. The contributing area to a well is the area of diversion of ground water to the well along with any adjacent surface areas that provide recharge to the aquifer within the area of diversion (Morrissey, 1987, p. 10). The contributing areas for this report were defined by use of the following methods and assumptions. First, a ground-water-flow path was located (perpendicular to water-table map contours) upgradient of each well. These flow lines were then expanded into wedge-shaped contributing areas by use of an arbitrary (roughly 65 degree) ratio of longitudinal flow distance to lateral dispersion (Bouwer, 1978). The true flow to dispersion ratios of this aquifer are unknown as no tracer tests were performed at the site. Some degree of dispersion undoubtedly occurs as materials infiltrate through the unsaturated zone, and additional dispersion (anisotropic) occurs during flow through the aquifer as well. Although any nitrogen applications made upgradient of a well can potentially contribute nitrogen to the water beneath that well, applications made closer to the well would be expected to contribute greater loads than applications made at a farther distance from a well because of dispersion during flow through the aquifer. Therefore, the contributing areas were defined to delineate a land area of maximum influence, not the total land area that could have any effect on the nitrate concentration in water samples collected from a well.

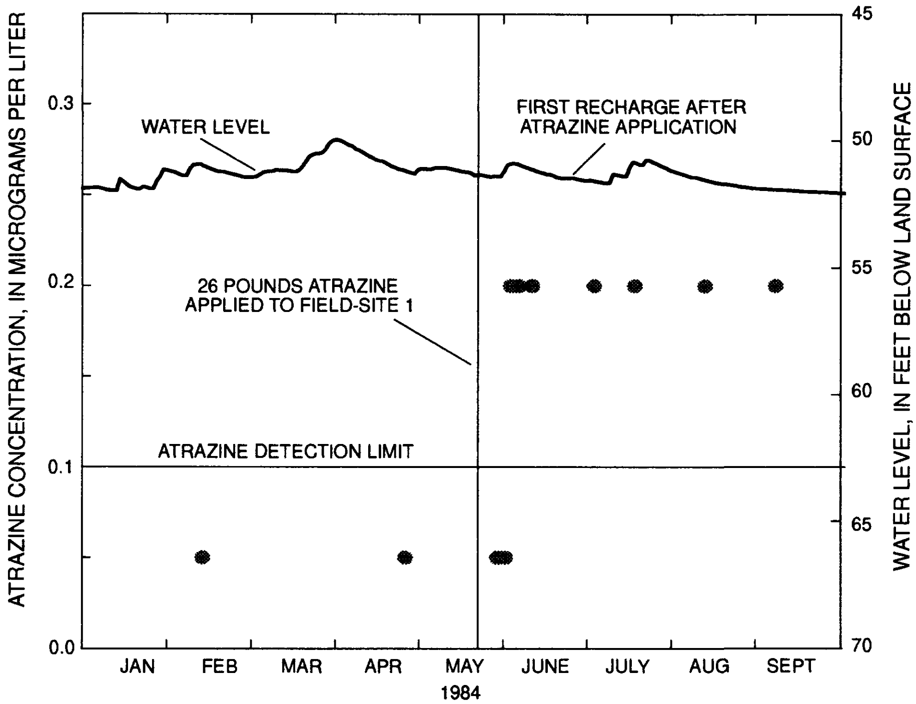


Figure 41. Atrazine concentrations in water samples from well LN 1645 before and after May 23, 1984, application.

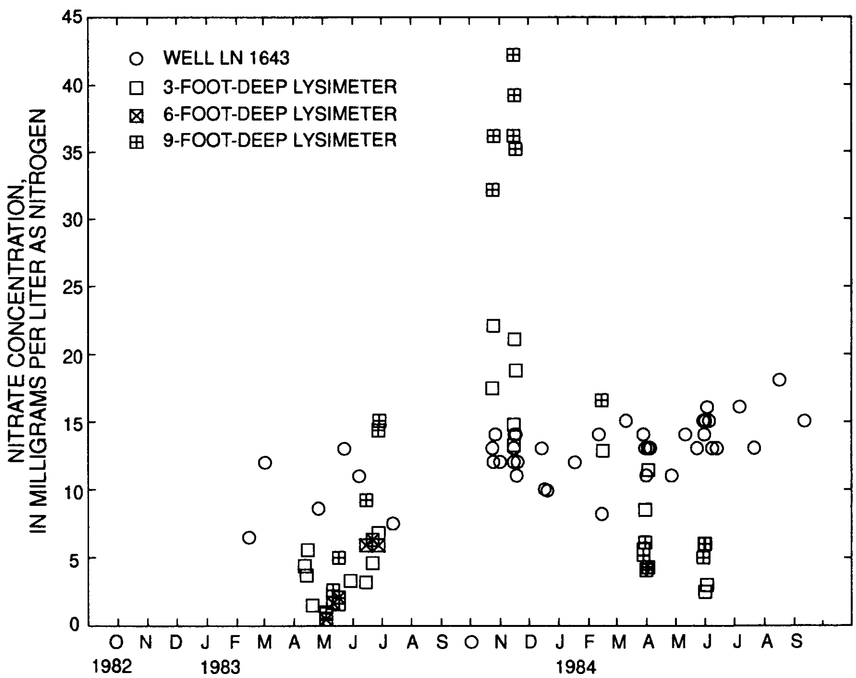


Figure 42. Nitrate concentrations in soil water collected in three lysimeters at different depths near well LN 1643 and in ground water collected from well LN 1643.

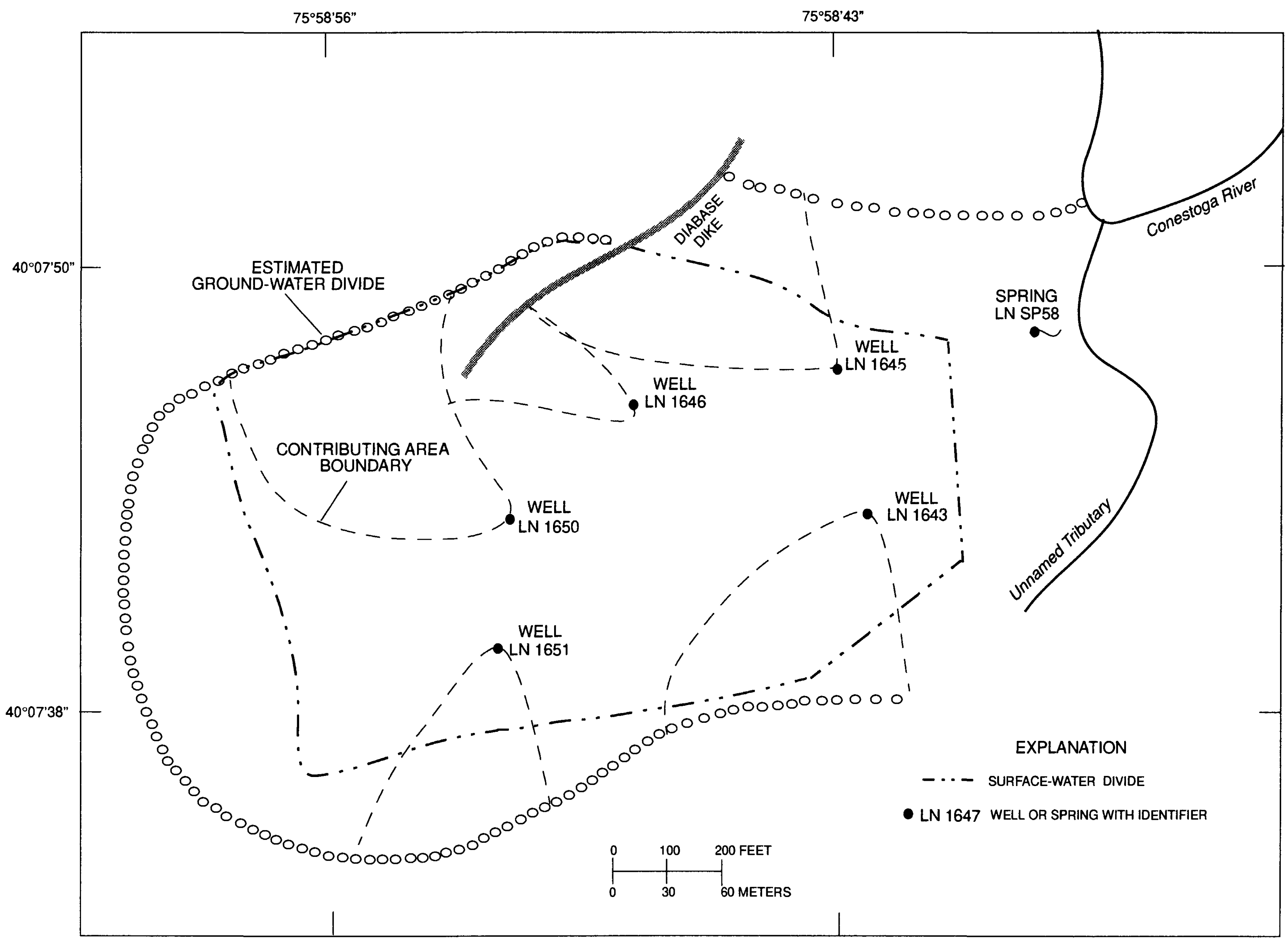


Figure 43. Estimated contributing areas for wells in the Field-Site 1 study area.

Substantially more nitrogen was applied in the contributing area of well LN 1643 than the other sampling sites, so water samples from this well may best reflect the effects of surface application of nitrogen. Fewer applications of nitrogen were made in the contributing area of well LN 1645 and this site is more representative of agricultural activities in the contributing areas of the other sampling locations.

Nitrate concentrations in water samples from well LN 1643 increased throughout the study period. In water collected from all other sampling sites, nitrate concentrations remained relatively constant (figs. 44 and 45). Water samples collected on the same day at the different sampling locations were compared to detect any similarities in nitrate concentration between sites. Correlations of nitrate concentrations between the sampling locations are shown in table 24. Concentrations from well LN 1651 and spring LN SP58 show the only significant correlation. As previously mentioned, this correlation suggests that a solutional passage exists along strike between the two sampling locations. An absence of correlation between nitrate concentrations in water samples from the other locations suggests that local differences in the aquifer (such as thickness of the unsaturated zone) would mask any correction because of lagged changes in nitrate concentrations caused by traveltime, or suggest that nitrate concentrations depend largely on other factors such as local variations in agricultural activities.

Well LN 1643 was sampled during two storm periods, March 27-28, 1984, and May 26-29, 1984, to investigate the effects of recharge on ground-water quality (fig. 46) (Gerhart, 1986). Water-table rises lagged behind precipitation by only a few hours to 1 day, partly because of recharge waters entering the water table directly from the surface through macropores in the soil and unsaturated zone. However, 2 days passed after precipitation began until enough recharge water reached the water table to produce measurable changes in ground-water nitrate concentrations.

Approximately 900 lb of nitrogen from manure was applied in the contributing area to well LN 1643 in January and February 1984, but low temperatures (below 50°F) may have inhibited nitrogen mineralization and nitrification.

No additional manure was spread on the contributing area of well LN 1643 in March, so little soluble nitrogen was available at the surface. Mean nitrate concentration in surface runoff was 0.39 mg/L during the March 28, 1984, storm. Little additional nitrate was evidently leached from the unsaturated zone, because recharge from the March storms diluted the existing unconfined ground water at well LN 1643 at the sampling depth (85 ft below land surface), where a 3 mg/L reduction in nitrate concentration was detected in ground-water samples. As the relatively diluted recharge slug mixed with the ground water, nitrate concentrations in the water samples from the well returned to prestorm concentrations in approximately 1 week.

Water-level and water-quality data also were collected at well LN 1643 during the storms of May 26 and 29, 1984. As in the March storm, water levels peaked about 1 day after precipitation began, and the largest change in nitrate concentration in the well water was about 2 days after precipitation began.

In May, field conditions were quite different near well LN 1643 than they were in March. About 2,300 lb of nitrogen had been applied in the contributing area of well LN 1643 during April and May. Winter and spring nitrogen applications probably would have begun to mineralize and nitrify in the warmer spring temperatures, further increasing the nitrate available for leaching during the May storms.

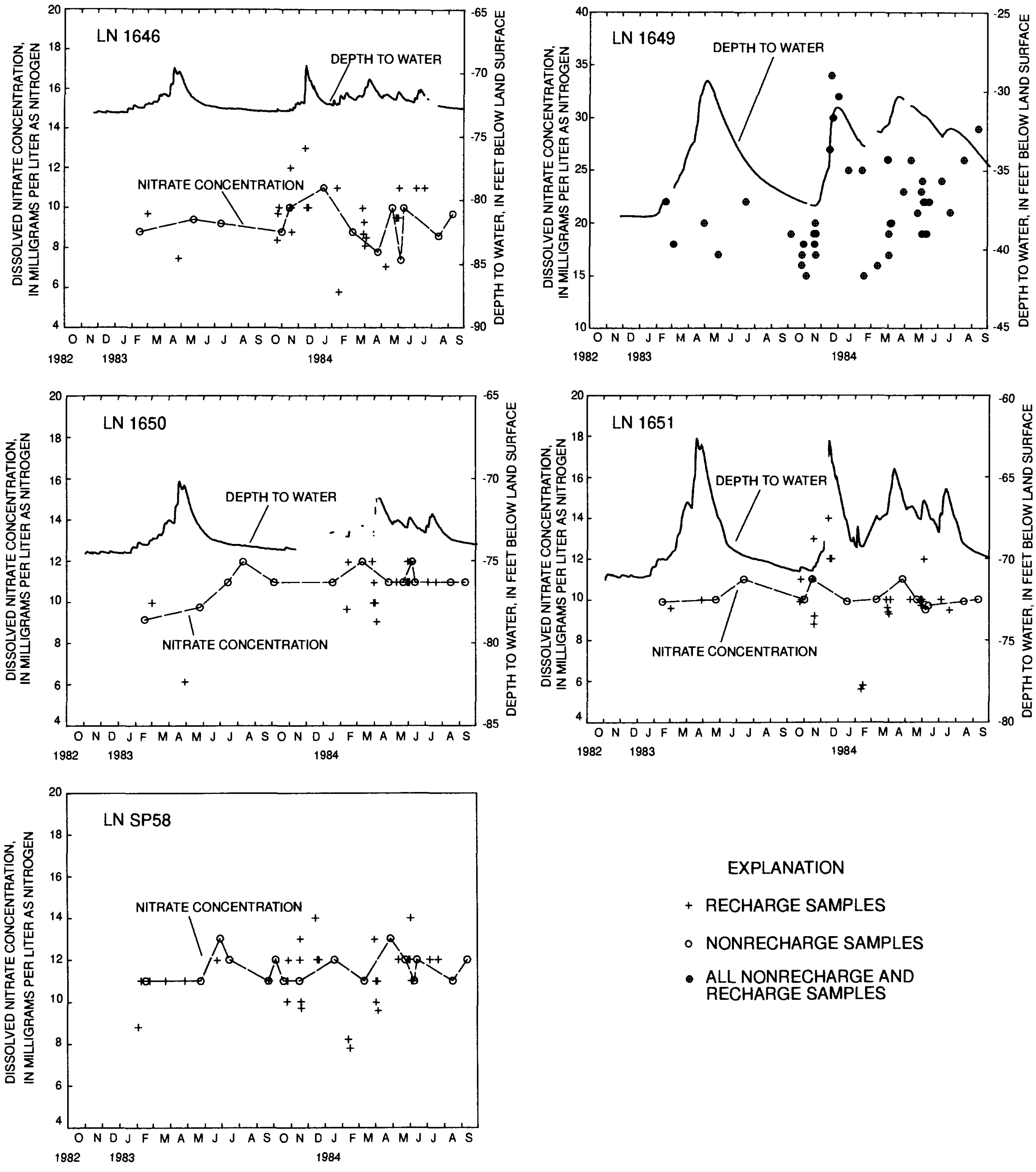


Figure 44. Nitrate concentrations and water levels at wells LN 1646, LN 1649, LN 1650, LN 1651, and nitrate concentrations at spring LN SP58.

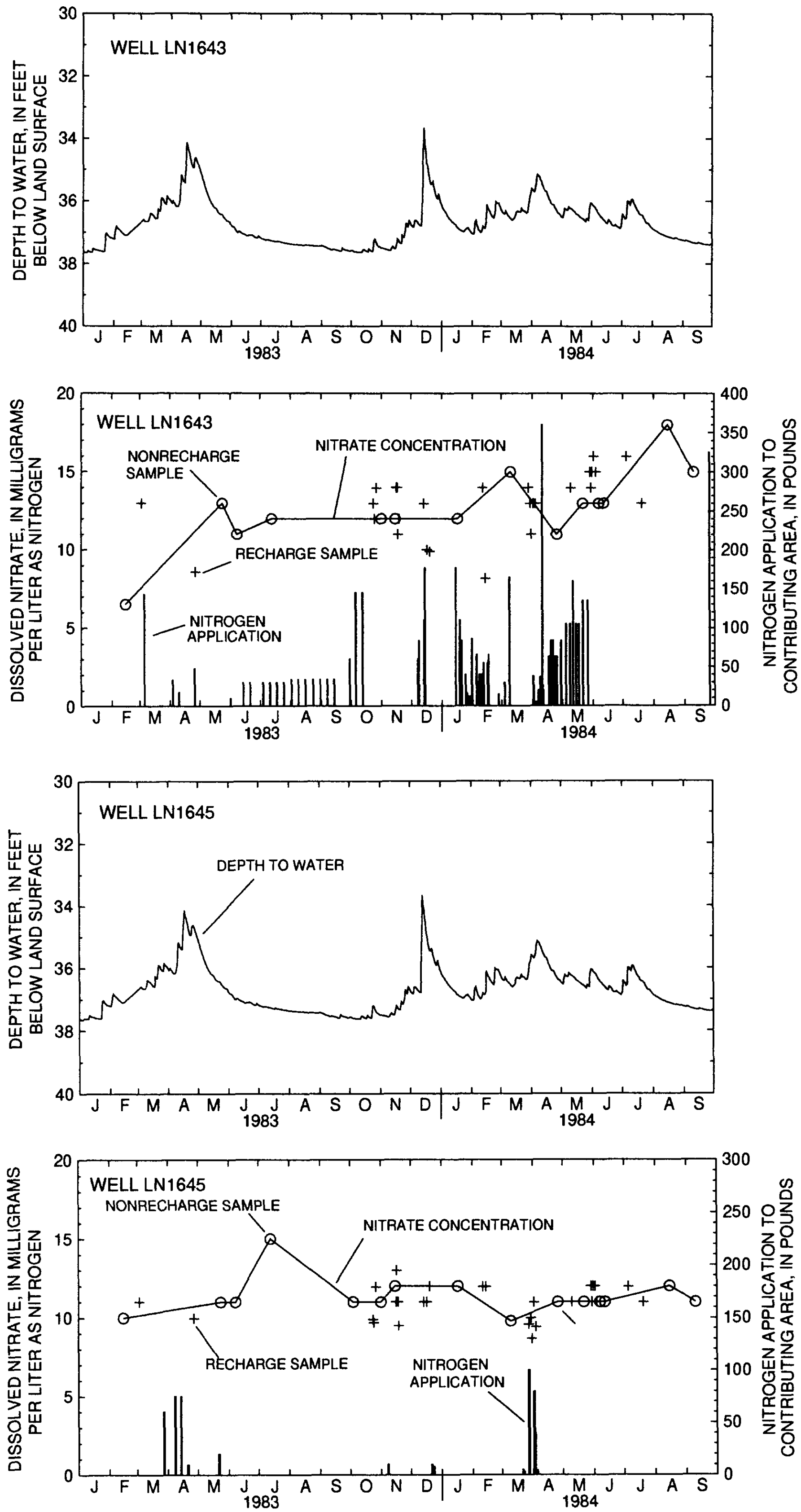


Figure 45. Water levels, nitrate concentrations, and nitrogen applications in the estimated contributing area for wells LN 1643 and LN 1645.

Table 24. Correlation coefficients (R) of nitrate concentrations for all samples between six wells and the spring at Field-Site 1, January 1983 through September 1984

	Well						
	LN SP58	LN 1643	LN 1645	LN 1646	LN 1649	LN 1650	LN 1651
LN SP58	1.00						
LN 1643	.28	1.00					
LN 1645	.22	.03	1.00				
LN 1646	.47	.30	.22	1.00			
LN 1649	.44	.11	.26	.33	1.00		
LN 1650	.23	-.02	.07	-.09	-.02	1.00	
LN 1651	.72	.10	.04	.49	.32	.06	1.00

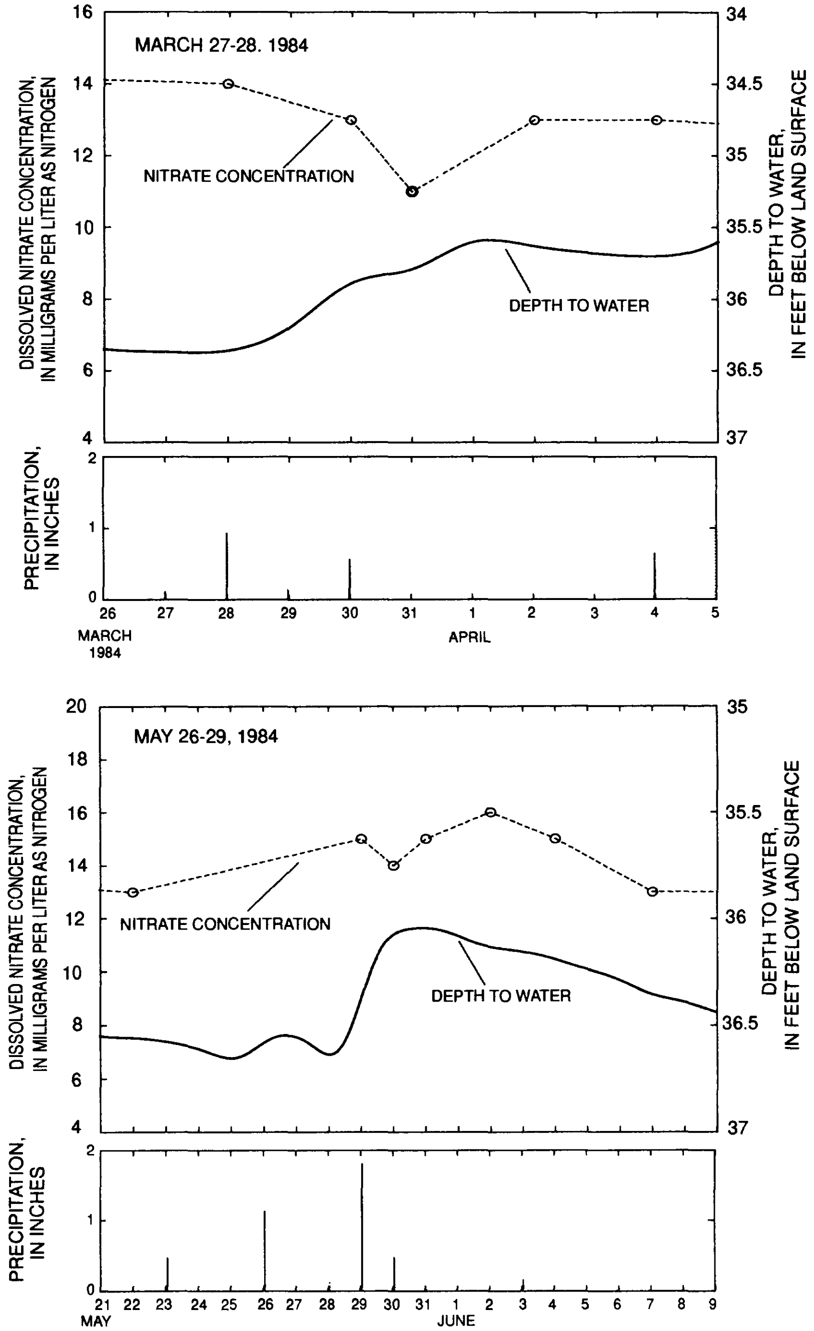


Figure 46. Water level, dissolved-nitrate concentration, and precipitation at well LN 1643 during and following two storms, one on March 27-28, 1984 (top), and one on May 26-29, 1984 (bottom) (Modified from Gerhart, 1986).

In contrast to the recharge from the March storm, which diluted the ground-water nitrate concentrations in water samples from well LN 1643, the recharge from the storms in May increased ground-water concentrations of nitrate by at least 3 mg/L, even though mean nitrate concentration in surface runoff for the May 29, 1984, storm was only 0.48 mg/L. The nitrate concentrations in precipitation infiltrating to the ground water significantly increased during transport through the unsaturated zone. As during the March storm, the effect of rapid recharge was temporary, and nitrate concentrations returned to near prestorm levels in approximately 1 week. Although precise maximums and minimums in ground-water nitrate-concentration data may have been missed because of the discrete nature of the sampling, enough water samples were collected to reflect the general character of the trends.

Nitrate concentrations in nonrecharge water samples from well LN 1643 appeared to reflect climatic and agricultural-activity changes during the study period. From February through May 1983, nitrate concentrations in nonrecharge water samples from well LN 1643 doubled from approximately 6.5 to 13 mg/L (fig. 45). Nitrogen applications made to the contributing area of well LN 1643 in March, April, and May were at least partly mineralized and nitrified in the warm spring temperatures, providing an available source of soluble nitrate at the land surface before the crops were ready to use it. A series of storms in February, March, and April 1983 provided an effective mechanism for this nitrate to be transported from the land surface to the ground water. The summer of 1983 was dry in the study area. Without recharge to affect ground-water quality, nitrate concentrations in water samples from well LN 1643 showed little change from July through October 1983.

Fall (September, October, and November) 1983 water samples from well LN 1643 that reflected recharge contained nitrate concentrations of 11 to 14 mg/L (fig. 45). Nitrogen was applied to the contributing area of well LN 1643 in late September and early October 1983. There probably was insufficient precipitation during the fall to cause a substantial change in nonrecharge nitrate concentrations.

Winter (December, January, and February) recharge samples from well LN 1643 show the greatest range of nitrate concentrations for any season in the study period--approximately 8 to 14 mg/L (fig. 45). Although little nitrate was being produced from applied manure because of low temperatures, leaching of nitrates to ground water probably occurred from residual nitrates left in the soil and unsaturated zone from the previous growing seasons. Heavy applications of manure were made to the contributing area of well LN 1643 in December 1983 and in January and February 1984. This potentially available nitrogen, combined with the large ground-water recharge rates in early December 1983, probably increased the storage of organic nitrogen and ammonium in the soils. Stored nitrogen, together with the heavy spring nitrogen applications, warm temperatures, and plowing that increased soil permeability, probably contributed to the elevated recharge-sample concentrations in the summer of 1984.

The contributing area to well LN 1645 received fewer nitrogen applications than that of well LN 1643 (fig. 45). Relations between agricultural activities and quality of water from well LN 1645 were somewhat difficult to discern; however, these relations are probably typical of the three other wells (LN 1646, LN 1650, and LN 1651 for which contributing areas were estimated) in the study area. Nitrogen-application rates at these four sites were substantially less than those upgradient of well LN 1643 (fig. 8). Although no specific contributing area was defined for spring LN SP58, nitrate concentrations in water from spring LN SP58 appear to be associated with nitrate concentration in water from this group of wells, especially well LN 1651 (as discussed earlier). Nitrate concentrations of recharge-influenced samples from well LN 1645 ranged from 9 to 13 mg/L during the fall of 1983. Most of the measured nitrate probably was caused by leaching of residual nitrate left in the unsaturated zone after the growing season. In November 1983 when precipitation and ground-water recharge increased, leaching probably accelerated and increased ground-water nitrate concentrations. Large nitrogen applications were made in the contributing area of well LN 1645 in April 1984, followed by storms that provided recharge water. Water samples from well LN 1645 collected during recharge periods in May and June contained increased nitrate concentrations relative to those collected in April (fig. 45).

A time lag exists between the time that nutrients are applied at the surface and the time that they are detected in the ground water. The first effects of applications show up as increased nitrate concentrations in ground-water samples collected as soon as several hours after precipitation. Nitrate transport can be rapid if flow is through macropores in the unsaturated zone. Nitrate can become available (because of nitrification) in the unsaturated zone during dry periods and accumulate until a recharge event flushes it out. Substantial changes in nitrate concentrations of nonrecharge water samples occur over periods of 1 to 3 months, probably because of the uptake of nitrate by slow moving ground water that traveled through micropores in the unsaturated zone. Ground water moving through micropores has a substantial contact time with soils and is, therefore, able to oxidize ammonium and leach nitrate if these species are present in the unsaturated zone. At well LN 1643, there was a 2-month lag between the March 1983 applications and the peak in nitrate concentrations in nonrecharge samples collected in May. A similar lag period of about 3 months was observed between nitrogen applications in April and May 1984 and the nitrate concentration maximum in August 1984 (fig. 45). At well LN 1645 this time lag occurred between applications of nitrogen during April 1983 and a ground-water-nitrate concentration peak 3 months later in July (fig. 45). This relation could not be quantified by multiple-regression techniques but can be observed qualitatively on the graphs of figure 45.

Although ground water at well LN 1649 is affected by many of the same processes that prevail at other wells, differences in hydrogeology produce differences in water chemistry between well LN 1649 and the other wells (fig. 44). Water moves slowly around the diabase dike and through a clay-rich low-transmissivity region south of the well, so that ground-water residence times are long and nitrate concentrations are elevated. Precipitation infiltrates slowly to the water table, and water-level and nitrate-concentration peaks lag approximately 1 month behind those at other wells at the site.

The agricultural BMP of nutrient management is to be implemented at the site during the second phase of the study (1987 to 1990). Crop requirements for nitrogen will be calculated, levels of nitrogen present in manure applied to the site will be determined, and soil will be tested for the presence of soluble nitrate. Subsequently, only that amount of manure that will supply crop nutrient needs will be applied to the site. Ground-water nitrate concentrations are expected to decrease as a result of decreased manure applications, and knowledge of the time lag between changes in the surface application of manure and resultant changes in water quality could be gained.

Nitrogen Loads

Total monthly nitrogen loads in ground water were based on data from well LN 1643, one of two wells closest to the discharge area of the site. The water-level record is nearly complete for the 21-month study period at well LN 1643, and the water-table configuration indicates that this well is close to the ground-water discharge area of the site. Ground-water discharges (table 22) were multiplied by the median nitrate concentration of all nonrecharge and recharge samples collected in each month to derive nitrogen loads in ground-water discharge (fig. 47).

For the study period, approximately 2,400 lb of nitrogen discharged with ground water to base flow from the study area. (For all ground-water samples, dissolved nitrate accounted for 93 percent of the total nitrogen, and therefore, nitrate ground-water concentrations are used to calculate estimated nitrogen loads in this budget). The average monthly nitrate load discharged with ground water from the site, estimated from data collected at well LN 1643, was approximately 110 lb; the average daily load was approximately 4 lb or approximately 60 (lb/acre)/yr. For comparison, monthly and annual nitrogen loads also were calculated at well LN 1645, which is located slightly north of well LN 1643 and also is near the discharge area of the site. The average annual nitrogen load discharged with ground-water during the study period on the basis of nitrate-concentration data from water samples collected at well LN 1645 also was about 60 (lb/acre)/yr.

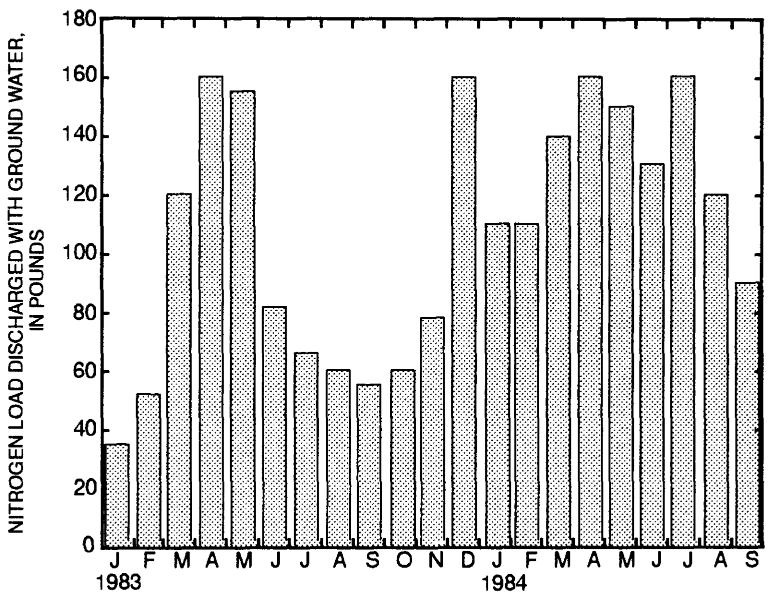


Figure 47. Estimated monthly nitrogen loads leaving Field-Site 1 in ground water.

HYDROLOGIC BUDGET

A water budget expresses quantitatively the major components of the hydrologic cycle. Precipitation entering a basin is balanced by water leaving the basin as runoff, evapotranspiration, and water being recharged to the ground-water-flow system. Assuming annual change in storage is zero, and interflow is intercepted at the flume as runoff, this balance can be expressed as

$$P = R_o + E + R_g, \qquad (4)$$

where P is Precipitation, in inches;
R_o is Surface runoff, in inches;
E is Evapotranspiration, in inches; and
R_g is Ground-water recharge, in inches.

Because the other variables in the equation have been measured or estimated on a monthly basis, evapotranspiration can be calculated as the residual for each month in the study period. The relation between ground-water recharge, surface runoff, and evapotranspiration is shown in figure 48. Estimates of evapotranspiration are only as good as the precipitation, surface runoff, and recharge data. Runoff and recharge are probably underestimated during winter months, causing an overestimated amount of evapotranspiration. Runoff from slowly melting snow cover was largely unmeasured. In addition, water that would under warmer conditions either runoff or recharge the ground water was stored at the surface as snow until the following month. The effects of snow cover are illustrated by data for January 1983 shown in figure 49. Calculated evapotranspiration is 0.87 in.—an amount much larger than the near zero expected value. Additionally, the evapotranspiration calculated for the winter months and for the summer months is substantially less than the estimated potential evapotranspiration for the same months.

For the 9 months of record in the 1983 water year, surface runoff amounted to 1.0 in. (3 percent of total precipitation for the 9-month period), calculated evapotranspiration 15.6 in. (50 percent), and estimated ground-water recharge 14.7 in. (47 percent). For the wet 1984 water year, surface runoff was 7.9 in. (13 percent of total annual precipitation), calculated evapotranspiration 26.9 in. (45 percent), and estimated ground-water recharge 25.0 in. (41 percent). For the study period, surface runoff totaled 8.9 in. (10 percent of precipitation in the study period), calculated evapotranspiration was 42.5 in. (48 percent), and estimated ground-water recharge was 39.7 in. (42 percent).

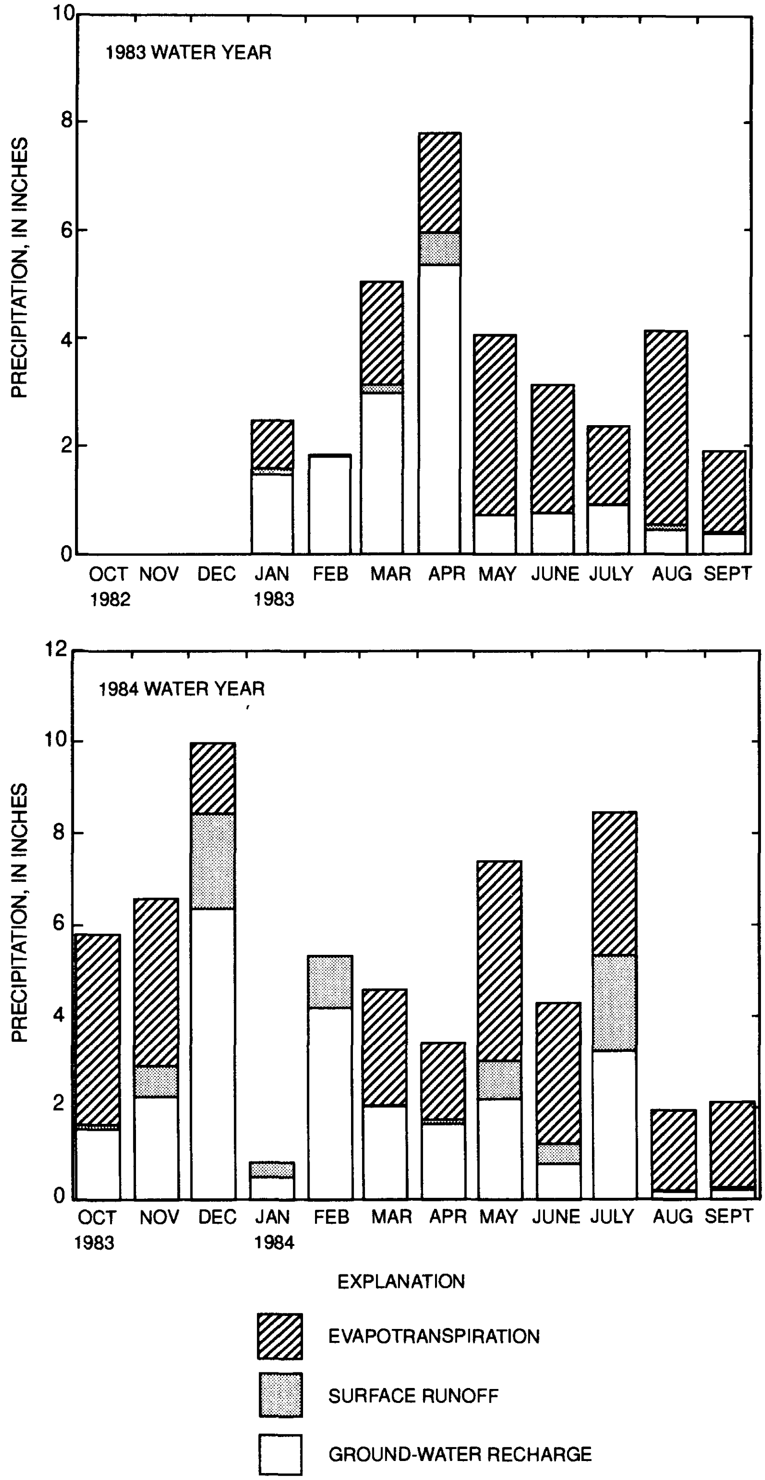


Figure 48. Ground-water recharge, evapotranspiration, and surface runoff from Field-Site 1.

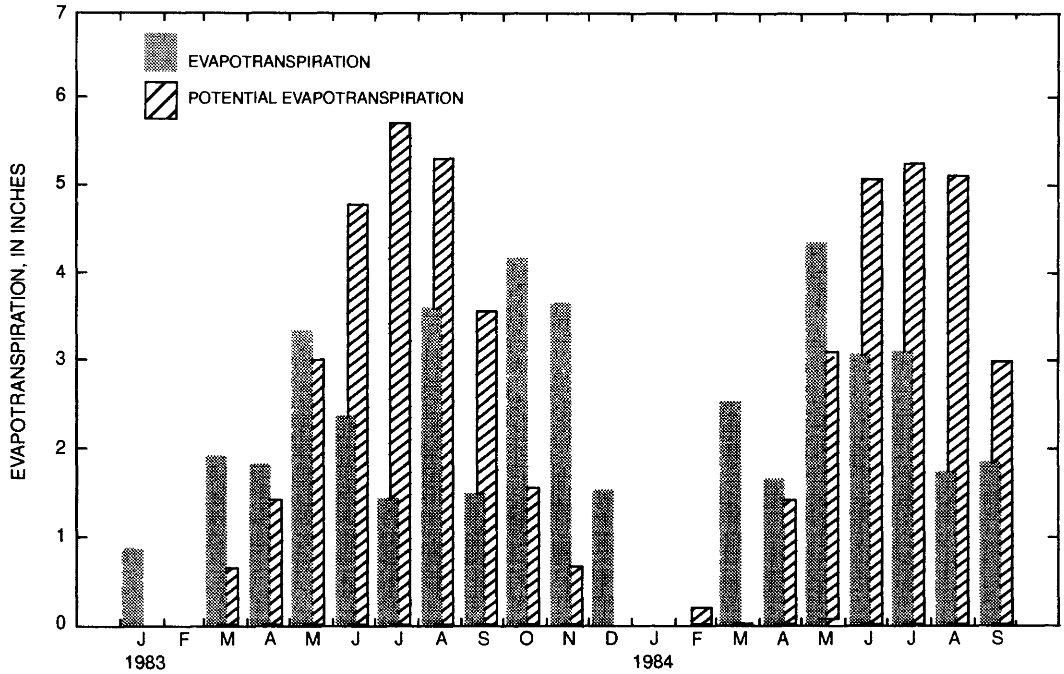


Figure 49. Comparison of estimated monthly evapotranspiration calculated from precipitation, recharge, and runoff data, to potential evapotranspiration calculated by methods described by Thornthwaite (1948) and temperature data from a nearby weather station near Field-Site 1.

INPUTS AND OUTPUTS OF NITROGEN

Inputs and outputs of nitrogen at the site were calculated for the 21-month study period (table 25). The estimation of major inputs and outputs of nitrogen does not represent a complete nitrogen balance for the site. Unquantified errors in the calculation of inputs and outputs of nitrogen may greatly influence the amounts reported in table 25. No attempts were made to quantify denitrification of nitrogen from soil water or ground water, or to quantify the amount or flux of nitrogen in soils. However, this incomplete accounting (Kohl and others, 1978) is a useful tool to determine the relative magnitudes of pools of nitrogen at the site.

Inputs of nitrogen were manure (93 percent of total inputs), commercial fertilizer (5 percent), and precipitation (2 percent). Inputs such as dry deposition of nitrogen from the atmosphere (Baker, 1991) and bacterial fixation of nitrogen in the soil (Hauck and Tanji, 1982) are probably a small percentage of the total nitrogen input to the site and, therefore, have been omitted. Nitrogen was removed by volatilization (39 percent of total outputs), in harvested crops (38 percent), in ground-water discharge (20 percent), and in surface-water runoff (3 percent).

Forty percent of the manure that was applied to the site was estimated to have been lost through volatilization. This value was estimated on the basis of surface-spread, nonincorporated manure applications made at the site in conjunction with estimates of manure volatilization contained in the PaDEP Field Application of Manure manual (Graves, 1986). Rates of nitrogen volatilization from manure range from 0 to greater than 90 percent as a function of manure type, precipitation, soil moisture, soil pH, temperature, wind velocity, humidity, and time until incorporation in the soil.

Table 25. Inputs and outputs of nitrogen at Field-Site 1, from January 1983 through September 1984
[All numbers rounded]

	Inputs			Outputs			
	Manure	Commercial fertilizer	Precipitation	Volatilization	Removal in harvested crops	Ground-water discharge	Surface-runoff discharge
Pounds of nitrogen	11,500	600	300	4,700	4,600	2,400	300
Percentage of total estimated inputs or outputs	93	5	2	39	38	20	3

The harvesting of corn removed about 4,300 lb of nitrogen, which is based on a nitrogen removal rate of 150 lb nitrogen per acre and an estimated yield of 140 bushels per acre (Robert Anderson, Pennsylvania State Extension Service, written commun., 1989). Tobacco and rye removed about 200 and 100 lb of nitrogen, respectively. Although alfalfa usually fixes atmospheric nitrogen, alfalfa grown in nitrogen rich soils may preferentially use soil nitrogen instead of or in addition to atmospheric nitrogen (Knott, 1962). For the purpose of this study, alfalfa was estimated to have removed as much nitrogen as it added, and was, therefore, not counted as an input or an output of nitrogen.

The average monthly nitrogen load discharged in ground water was approximately 110 lb, and the average daily load was approximately 4 lb. This amounts to about 60 (lb/acre)/yr of nitrogen discharged through the ground-water system. For comparison, ground-water loads also were calculated by the use of nitrate concentration data from well LN 1645, another well located near the discharge area of the site. Estimated annual loads of nitrogen in ground water by use of the LN 1645 nitrate data were also about 60 (lb/acre)/yr.

In Iowa, Hallberg (1987) found that nitrogen accumulated in soils during dry years and leached to the ground water during wet years. Although climatic factors apparently can be more significant than land-surface application of nutrients in determining ground-water nitrogen concentrations and loads in a given year, reductions in nitrogen application should eventually cause a corresponding reduction in soil storage and ground-water recharge of nitrogen. Unfortunately, the time required for these changes to occur and for the water-quality data to document these changes is unknown.

SUMMARY

This report describes a study at a 22.1-acre agricultural site, Field-Site 1, in Lancaster County, Pa., to characterize surface-runoff and ground-water quantity and quality during a 21-month period (January 1983 through September 1984), prior to construction of terraces and implementation of nutrient-management practices at the site.

Field-Site 1 is located on parts of two adjacent dairy farms, which drain to an unnamed tributary to the Conestoga River. The site is used primarily for the production of corn and alfalfa. The soils are Hagerstown and Duffield silt loam, which are up to 60 in. deep and moderately to well drained. Field-Site 1 is underlain by dolomitic rocks of the Middle Cambrian Zooks Corner Formation.

Precipitation at the site approximated the 30-year average of a nearby weather station for part of the 1983 water year, although serious soil-moisture deficiencies occurred during June through September, most of the primary growing season. The 1984 water year was approximately 44 percent wetter than the annual long-term average. For the 169 storms occurring during the study period, the median total storm precipitation was 0.29 in. Storms occurred most frequently during the spring. The median 30-minute intensity and precipitation duration of measured storms were 0.13 in. and 2.8 hours, respectively. Precipitation was analyzed for nutrients and was estimated to have contributed 300 lb of nitrogen to the site during the study period.

Agriculture was the only land use at the site; agricultural areas included 14.4 acres of corn, 5.4 acres of alfalfa, and 2.3 acres of other crops. The farmers used conventional-tillage practices. Of the nitrogen and phosphorus applied to the site, 98 and 99 percent, respectively, were applied to the cornfields. The average annual application of nutrients to the cornfields was 410 lb/acre of nitrogen and 110 lb/acre of phosphorus; 95 percent of the nitrogen and all the phosphorus were from manure applied throughout the year. Almost three times more nitrogen and phosphorus were applied to the cornfields during 1984 than during 1983. In May 1983, 14 lb of atrazine and 22 lb of metolachlor were applied to the cornfields; in May 1984, 26 lb of atrazine and 34 lb of metolachlor were applied.

The approximate nitrate concentration in the top 8 in. of soil during the study period was 8.2 mg/kg as nitrogen. A median concentration of 120 lb/acre of nitrate was found in the top 4 ft of soil in the fall of 1983. Atrazine concentrations as great as 545 μg/kg were found in the top 2 in. of soil soon after application but decreased to less than 50 μg/kg by October of 1983 and 1984.

Measurable runoff from the site occurred 97 times during the study period. Median total runoff was 2,130 ft^3. No obvious seasonal variations were present. Data analysis by multiple regression indicated that total runoff was controlled primarily by total precipitation amounts and antecedent moisture conditions, and the mean event and maximum instantaneous discharges were controlled primarily by precipitation intensity and antecedent moisture conditions. Crop cover on the cornfields affected all runoff variables, probably by interception of rainfall and increased evapotranspiration rates. Runoff from the site totalled 714,000 ft^3 (8.9 in.) or 9.8 percent of the total precipitation during the 21-month study period.

Of the total nitrogen found in 417 instantaneous runoff samples representing 54 storms, 72 percent (median percentage) was in the form of total organic nitrogen, 11 percent was in the form of total nitrate, 8.4 percent was in the form of total ammonium, and 1.4 percent was in the form of total nitrite. For 120 samples collected during 23 storms and analyzed for both total and dissolved nutrients, about 50 percent of the total nitrogen was dissolved and 50 percent was suspended. Sixty-four percent (median percentage) of the organic nitrogen was present in the suspended phase; other species of nitrogen were present primarily in the dissolved phase. Suspended phosphorus comprised 91 percent (median percentage) of the total phosphorus.

Total and dissolved constituent concentrations in runoff varied significantly among and during storms. These variations reflected variations in climatic conditions and agricultural activities. However, for most runoff events (1) increased suspended-sediment concentrations were associated with increased instantaneous discharges, and the first sample collected during a storm generally contained a greater suspended-sediment concentration per unit of discharge than did other samples; and (2) total-phosphorus concentrations generally increased as suspended-sediment concentrations increased.

Mean concentrations of suspended sediment in runoff events ranged from 24 to 73,000 mg/L; the median concentration was 2,900 mg/L. Loads of suspended sediment in runoff ranged from less than 0.01 to 50 tons; the median was 0.20 ton. Mean concentrations of total phosphorus in runoff ranged from 0.45 to 24 mg/L; the median concentration was 3.1 mg/L. Loads of total phosphorus in runoff ranged from 0.002 to 18 lb; the median was 0.50 lb. Mean concentrations of total nitrogen in runoff ranged from 1.5 to 55 mg/L; the median concentration was 4.5 mg/L. Loads for total nitrogen in runoff ranged from 0.005 to 62 lb; the median load was 0.72 lb. No seasonal trends in the data were apparent.

Runoff from storms on frozen ground produced the largest loads of nitrogen in runoff. Runoff from four rain-on-snow or snowmelt storms--comprising 12 percent of the total runoff--contributed 31 percent of the estimated total-nitrogen load and 9.5 percent of the estimated total-phosphorus load during the study period. Two herbicides applied during the 1983 and 1984 growing seasons were detected in runoff; maximum concentrations were 73 mg/L of atrazine and 85 µg/L of metolachlor.

Results of multiple-regression analyses indicate that mean nitrogen concentrations in runoff events (1) increased with increases in surface-nitrogen applications made to the site 30 days prior to runoff, and (2) decreased (were diluted) with increased precipitation duration. Implementation of a nutrient-management plan, which recommends applying only the nutrients required by the crop at times as close as possible to the time of plant use, may reduce the concentrations and loads of nitrogen leaving the field in runoff under field conditions similar to those during the study period. Terracing may substantially alter runoff characteristics, thereby changing relations among runoff and other factors described in this report.

Monthly loads of suspended sediment, total nitrogen, and total phosphorus were as much as 109 tons, 76 lb, and 55 lb, respectively. These loads generally varied proportionally with amounts of runoff.

The annual estimated suspended-sediment load from runoff was 6.7 (ton/acre)/yr, or 258 tons for the study period. This exceeds the erosion factor (T) of 4 (ton/acre)/yr recommended by the U.S. Soil Conservation Service. An estimated 8.1 (lb/acre)/yr of nitrogen and 4.6 (lb/acre)/yr of phosphorus was transported from the site in runoff, for a total of 314 lb of nitrogen and 176 lb of phosphorus discharged during the study period. The 9 months of the 1983 water year and 12 months of the 1984 water year differed substantially. Of the total runoff and nutrient loads for the study period, 88 percent of the runoff occurred during the wet 1984 water year (57 percent of the study period), and carried with it 94 percent of the suspended-sediment load and 88 percent of the total nitrogen and phosphorus loads.

Of the nutrients applied to the site as manure and commercial fertilizer during the study period, 2.5 percent of the total nitrogen and 5.5 percent of the total phosphorus left the field in runoff. Ten percent of the total-nitrogen load in runoff could be attributable to nitrate and ammonium from precipitation, if all of the nitrogen in precipitation were associated with precipitation that ran off.

The ground-water basin at the site is slightly larger than the surface-water basin. Mean specific yield of the aquifer underlying the site was estimated to be 0.13. On the basis of the specific yield, ground-water recharge for the study period was estimated to be 39.7 in., or 43 percent of precipitation. Estimated specific capacities of the wells at the site range from less than 1 to 160 (gal/min)/ft; the median was 9 (gal/min)/ft for all wells.

Of the six wells at Field-Site 1 where water levels and water quality were measured, the water level in each well, except that in well LN 1649, responded quickly to recharge; water levels peaked several hours to 1 day after precipitation. Transmissivities estimated for the carbonate-rock aquifer at the six wells ranged from less than 50 to 34,000 ft^2/day. Ground water discharges to the Conestoga River and its unnamed tributary.

Ground-water quality at the site reflects the carbonate mineralogy of the aquifer. Water samples collected for major-ion analysis showed that hardness ranged from 200 to 530 mg/L as calcium carbonate, and specific conductance ranged from 413 to 1,010 µS/cm. Dissolved oxygen concentrations ranged from 1.4 to 10.6 mg/L, and the median molar ratio of calcium to magnesium was 0.94. Nitrate concentrations in ground water commonly exceeded the USEPA MCL of 10 mg/L nitrate as nitrogen for drinking water.

Although recharge samples had slightly wider ranges of nitrate concentrations than nonrecharge samples, ranges and medians for specific conductance, nutrient, and herbicide concentrations did not differ substantially between recharge and nonrecharge samples for any of the wells or the spring. Atrazine and metolachlor were persistent in the ground water; the maximum concentrations of these herbicides were less than USEPA lifetime health advisory levels of 3 and 100 μg/L, respectively. Atrazine quickly leached to the water table during the first storm following application, demonstrating the rapid effect that surface-applied materials can have on water quality. Median dissolved-nitrate concentrations ranged from 9.2 to 13 mg/L for all samples from the five wells and the spring and accounted for 93 percent (median percentage) of the total nitrogen in ground-water samples. The median dissolved-nitrate concentration of water from well LN 1649, where ground-water flow is restricted by a diabase dike, was 20 mg/L. For all the wells and the spring, median dissolved-phosphorus concentrations ranged from 0.02 to 0.05 mg/L; the maximum single sample concentration was 0.11 mg/L.

Nitrate concentrations in ground water were affected by ground-water recharge, nutrient applications, and seasonal factors. Water from the well whose contributing area received the most nitrogen had the greatest variability in nitrate concentrations during the study period--from 8 to 16 mg/L.

Nitrate concentration data from water samples collected from well LN 1643 during two recharge events were analyzed in detail. Recharge from both storms caused a water-table rise at well LN 1643 within hours after the start of precipitation. Recharge waters during one storm diluted nitrate concentrations in ground water whereas recharge from a later storm of similar magnitude enriched the ground water with respect to nitrate. The difference in the effect of recharge on nitrate concentrations in ground-water from one storm to the other probably reflects variations in nutrient availability at the land surface and in the unsaturated zone, which, in turn, are related to the timing of fertilizer applications. A time lag of from 1 to 3 months was observed between the time that nutrients were applied at the surface and the time that they were detected in nonrecharge samples of the ground water.

Approximately 3,187,000 ft^3 of ground water and an associated 2,400 lb of nitrate discharged from the site during the study period.

A simplified hydrologic budget was determined for Field-Site 1. For the study period, 42 percent of the precipitation recharged the water table, 10 percent ran off, and 48 percent evapotranspired. For the study period, inputs of nitrogen were 11,500 lb (93 percent) from manure, 600 lb (5 percent) from commercial fertilizer, and 300 lb (2 percent) from precipitation. Nitrogen outputs from the site were estimated to be 4,700 lb (39 percent) to volatilization, 4,600 lb (38 percent) to crop uptake, 2,400 lb (20 percent) to ground-water discharge, and 300 lb (3 percent) to runoff.

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