Evaluation of Agricultural Best-Management Practices in the Conestoga River Headwaters, Pennsylvania: A Summary Report, 1982–90

United States Geological Survey Water–Supply Paper 2493

Prepared in cooperation with the **Pennsylvania Department of Environmental Protection** and the **U.S. Department of Agriculture, Consolidated Farm Service Agency**

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Evaluation of Agricultural Best-Management Practices in the Conestoga River Headwaters, Pennsylvania: A Summary Report, 1982–90

By PATRICIA L. LIETMAN

Prepared in cooperation with the **Pennsylvania Department of Environmental Protection** and the **U.S. Department of Agriculture, Consolidated Farm Service Agency**

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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	4.047	square kilometer
square mile (mi^2)	2.590	square kilometer
	Discharge	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per acre [(ft^3/s)/acre]	0.007	cubic meter per second per square kilometer
gallon per minute per foot [(gal/min)/ft]	0.2070	liter per second per meter
	Volume	
cubic foot per acre (ft^3/acre)	0.007	cubic meter per square kilometer
million gallons per acre (Mgal/acre)	0.000935	liter per square kilometer
	Mass	
pound (lb)	0.4536	kilogram
ton (short, 2,000 pounds)	0.9072	megagram
pound per acre (lb/acre)	1.123	kilogram per hectacre
ton per acre (ton/acre)	2.241	megagram per hectacre
	Transmissivity	
foot squared per day (ft^2/d)	0.09290	meter squared per day

Abbreviated water-quality units used in report:

- microgram per kilogram (µg/kg)
- microgram per liter (µg/L)
- microgram (µg)
- microsiemens per centimeter at 25 degrees Celsius (µS/cm)
- milligram per liter (mg/L)

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

Evaluation of Agricultural Best-Management Practices in the Conestoga River Headwaters, Pennsylvania: A Summary Report, 1982–90

By Patricia L. Lietman

Abstract

The effects of selected agricultural best-management practices (BMP's) on surface-water and ground-water quality in the Conestoga River Headwaters, Pa., were investigated by the U.S. Geological Survey. This 9-year study was part of the Rural Clean Water Program and was done in cooperation with the Pennsylvania Department of Environmental Protection and the U.S. Department of Agriculture, Consolidated Farm Service Agency.

Surface water and ground water were characterized at three scales—regional (188 square miles), small watershed (5 square miles), and field (22 and 47.5 acres). At the small watershed and field scales, water-quantity and -quality data collected during the characterization phase were compared with similar data collected after implementation of BMP's. Changes in water quantity and quality were evaluated in conjunction with agricultural-activity and precipitation data to evaluate the effects of implementation of BMP's on water resources in the study area.

Water quality in the southern one-third of the Conestoga River Headwaters Basin reflects the carbonate mineralogy. In carbonate parts of the study area, water and associated contaminants move rapidly from the land surface to the ground water through highly permeable soils and fractured bedrock. Changes in ground-water level and chemistry were frequently found within 1 day of the onset of precipitation. Elevated concentrations of sediment, nutrients, and herbicides in surface water and ground water reflect the intensive agricultural land use in the carbonate valleys. In contrast, the northern two-thirds of the basin is underlain by noncarbonate rock, and only a relatively small amount of the land is used for agriculture. Concentrations of nutrients and herbicides were substantially lower in surface water and ground water in the noncarbonate parts of the study area.

Pipe-outlet terracing, installed at a 22-acre field site underlain by carbonate rock, was effective in reducing sediment losses from the site, but total nitrogen and phosphorus losses with runoff were not significantly different before and after terracing. Although no measurable overall change in the relative amounts of runoff and recharge resulted from terracing, median concentrations of dissolved nitrate at four of six ground-water sampling locations increased after terrace installation.

Nutrient applications were reduced at a 47.5-acre field site and a 1.4-square-mile subbasin of the small watershed after implementation of nutrient-management practices. At the field site, where discharge of dissolved nitrate in ground water was 98 percent of the total nitrogen leaving the site with water, dissolved nitrate concentrations in ground water from most of the sampled wells decreased significantly after implementation of nutrient management. In the 1.4-square-mile subbasin, nutrient management was beneficial in preventing increased concentration of dissolved nitrate plus nitrite in the base flow of streams in the subbasin.

Findings of this study indicate that agricultural-management practices to improve water quality are most effective if their overall effects on surface- and ground-water systems are considered in their design. This consideration is particularly important in areas underlain by carbonate rock, in which ground water is highly susceptible to contamination by agricultural chemicals applied to the land surface.

INTRODUCTION

In 1979, the U.S. Department of Agriculture (USDA) began the experimental Rural Clean Water Program (RCWP), in response to an act of the U.S. Congress, to accelerate the voluntary implementation of agricultural best-management practices (BMP's) to improve surface- and ground-water quality. A BMP can be a single conservation practice or a system of practices. Cost-share funds were allocated to selected project areas to implement these practices. As part of the RCWP, the U.S. Geological Survey (USGS), in cooperation with the Pennsylvania Department of Environmental Protection[1] (PaDEP) and the USDA, Consolidated Farm Service Agency[2], studied the effects of agricultural BMP's on surface- and ground-water quality in the Conestoga River Headwaters, Pa.

In 1981, the RCWP designated the Conestoga River Headwaters (fig. 1) as 1 of 20 projects approved for remedial action to improve and document surface- and ground-water quality. Five of the 20 project areas, including the Conestoga River Headwaters project area, were selected for comprehensive monitoring and evaluation (CM&E). This area was

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

[2]Prior to 1995, the Consolidated Farm Service Agency was known as the Agricultural Stabilization and Conservation Service.

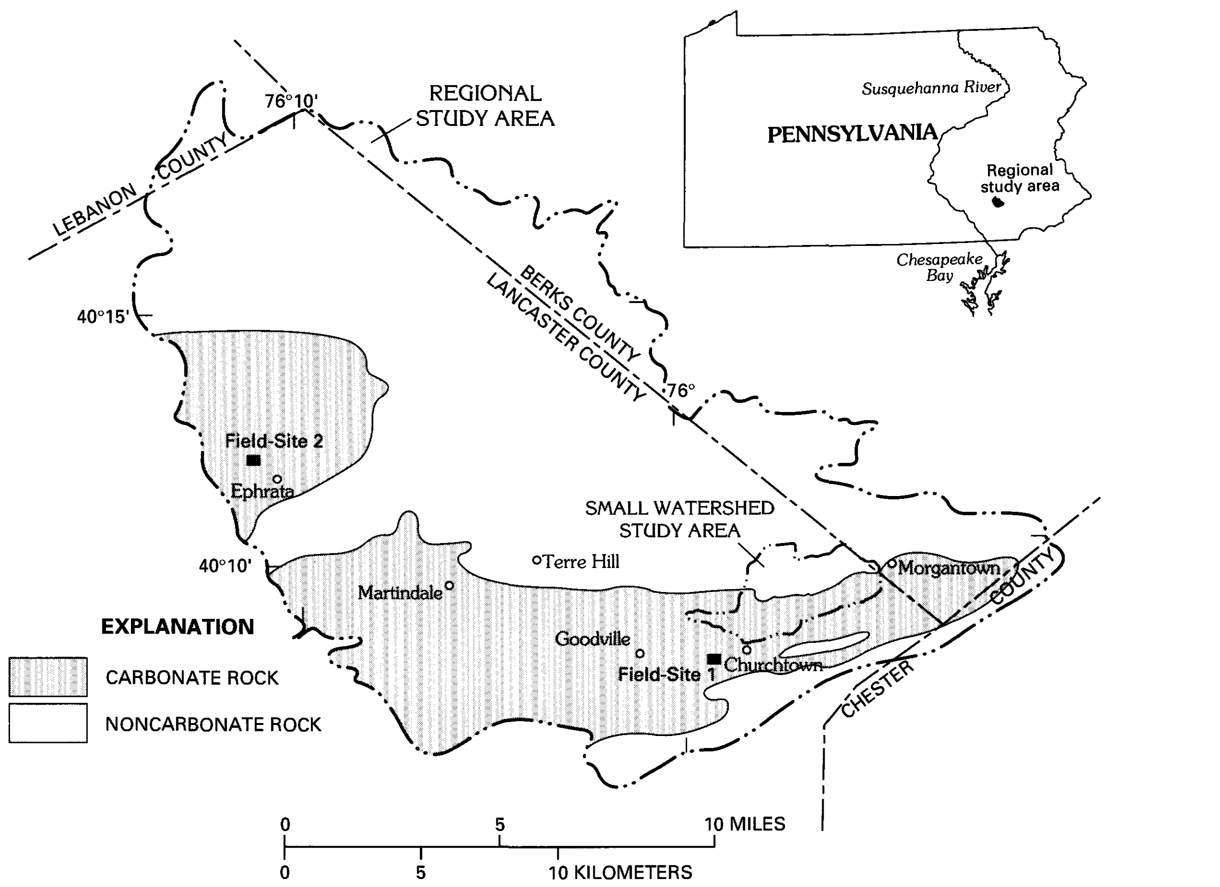


Figure 1. Location of Conestoga River Headwaters regional study area and intensive study areas. (Modified from Chichester, 1988.)

chosen because it had previously been designated as the top-priority watershed in Pennsylvania's Agricultural 208 Plan (part of the 1972 Federal Water Pollution Control Act). The Conestoga River Headwaters regional study area contains 132 mi of streams that currently are used or potentially are usable for public water supply, livestock watering, fish, wildlife, and recreation; ground-water use for public water supplies in the area also is substantial. Previous studies (U.S. Department of Agriculture, 1982; Lancaster County Conservation District, 1982; Pennsylvania Department of Environmental Resources, 1983) have demonstrated increasing degradation of surface- and ground-water quality due to large nonpoint discharges of suspended sediment and nutrients. In addition, Hall (1934) indicated that nitrate concentrations in ground water in southeastern Pennsylvania generally were elevated in comparison with nitrate concentrations in ground water in other parts of the United States, although the origin of these elevated concentrations was not apparent. Meisler and Becher (1966, 1971) and Poth (1977) reported elevated concentrations of nitrate in ground water in the carbonate-rock areas of Lancaster County, Pa. Poth (1977) also stated that flow of water in carbonate-rock areas is rapid and that contamination of water by human activities in carbonate aquifers can be widespread. The major water-quality problems in the Conestoga River Headwaters regional study area, 50 percent of which is underlain by carbonate rock, are nutrients from manure and commercial-fertilizer applications, herbicides from applications to cropland, and sediment from erosion of intensively cropped land.

Because erosion and elevated concentrations of nutrients are major problems in the project area, the BMP's to be implemented and evaluated as part of the Conestoga River Headwaters project were nutrient management, animal-waste storage, and pipe-outlet terracing. Nutrient management involves the selection of proper rates and timing of manure and commercial-fertilizer applications to reduce the amount of unused nutrients that become available for transport to streams and ground water. Animal-waste storage, which is used in conjunction with nutrient management, involves accumulating manure in a concrete or earthen structure and then applying it to fields at the proper times for crop uptake. Pipe-outlet terracing involves contouring land surfaces and installing drainage systems. Terrace construction is intended to keep soil on fields and, thus, reduce the concentrations of suspended sediment and associated nutrients in runoff.

Water quantity and quality were monitored in the Conestoga River Headwaters over a 9-year period (1982–90) in four areas: (1) the regional study area, 188 mi^2, which represented the entire Conestoga River Headwaters and encompassed all the other study areas; (2) a small watershed study area, 5.82 mi^2; and (3) two field-site study areas—Field-Site 1, 23.1 acres, and Field-Site 2, 47.5 acres (fig. 1). These areas (except for the regional study area) were monitored before and after implementation of BMP's to characterize the water quality of the study areas and to determine the effects of BMP's on surface- and ground-water quantity and quality. Water samples were analyzed for nutrients (nitrogen and phosphorus), suspended sediment, and herbicides. A detailed description of the monitoring design can be found in Chichester (1988). Numerous reports were written on the project, study sites, and effects of agricultural-management practices on water quality throughout the study area. These reports are listed in the appendix.

Throughout project development and implementation, the Conestoga River Headwaters RCWP was a combined effort of the following Federal, State, and local agencies:

Eastern Lancaster County School District

Lancaster County Conservation District

North Carolina State University

Pennsylvania Department of Environmental Protection

Pennsylvania Fish Commission

Pennsylvania State University

Susquehanna River Basin Commission

U.S. Department of Agriculture
- —Agricultural Research Service
- —Consolidated Farm Service Agency
- —Economic Research Service
- —Natural Resources Conservation Service[3]

U.S. Environmental Protection Agency

U.S. Geological Survey

These agencies were involved in planning, providing technical assistance to farmers, implementing BMP's, monitoring and evaluating water quality, and analyzing economic data.

Purpose and Scope

This report (1) describes and evaluates the design of a monitoring network to determine changes in agricultural activities on the basis of experiences in the Conestoga River Headwaters project and the RCWP, (2) characterizes the quantity and quality of surface water and ground water in the Conestoga River Headwaters Basin, and (3) describes the effects of agricultural BMP's on the water resources in three intensive-monitoring areas—two field sites and a small watershed.

The description of the monitoring design of the project includes the design at the time the project was planned and changes in design that were made as the project evolved. The evaluation of the design focuses on successes and problems of the monitoring design and includes suggestions for future monitoring designs.

The description of quantity and quality of surface water and ground water in the Conestoga River Headwaters is based on analyses of data from the regional study area. Water quality at each of the three intensive-monitored sites—the two field sites and the Small Watershed—is compared to water quality for the regional project area to examine documented variations within the basin. The effects of agricultural BMP's on surface-and ground-water quality based on analysis of precipitation, soil, manure, agricultural-activity, and water-quality data are summarized.

[3]The Natural Resources Conservation Service was formerly known as the Soil Conservation Service.

Methods

Detailed information on methods of data collection and sample and data analysis are given in Chichester (1988) and Lietman and others (1989). Some modifications to the procedures described in these reports were made for data collection and sample and data analysis. These modifications are described in reports in the series, "Evaluation of Agricultural Best-Management Practices in the Conestoga River Headwaters, Pennsylvania," listed in the appendix. All water samples collected for the project were analyzed by the PaDEP, Bureau of Laboratories, except for triazine herbicide samples collected from September 1, 1988, through December 31, 1988, which were analyzed by the USGS National Water Quality Laboratory in Arvada, Colo. All suspended-sediment and particle-size samples were analyzed by the USGS Sediment Laboratory in Lemoyne, Pa. Soil samples were analyzed by the Pennsylvania State University, Soils and Environmental Chemistry Laboratory, University Park, Pa. Manure samples were analyzed by A&L Eastern Agricultural Laboratories, Inc., Richmond, Va.

Acknowledgments

Many farmers cooperated with the RCWP in the Conestoga River Headwaters project area. Their voluntary efforts in the implementation of BMP's on their land, their willingness to allow their land and water resources to be monitored, and their patience with the inconveniences associated with monitoring—farming around monitoring equipment, having technical personnel on their land day and night, and keeping records of their agricultural activities for use in data analysis—are greatly appreciated. The project could not have been done without their help.

This study was made possible through the efforts of many individuals from various government agencies. The author acknowledges the contributions of these individuals, who often extended themselves beyond their assigned duties to accomplish the project objectives.

PROJECT DESIGN

The monitoring design evolved throughout the project in response to initial monitoring results and to changes in types and extent of BMP's being implemented in the Conestoga River Headwaters. The RCWP was experimental and, therefore, adaptable to necessary changes.

Comparison of Original and Final Monitoring Strategies

The original monitoring strategy was planned in 1982. Parts of the monitoring strategy changed through 1988. Monitoring was completed in 1990. Original strategies summarized in the following paragraphs are described in the latest revision of the Comprehensive Monitoring Plan (U.S. Department of Agriculture, 1982). Details of the final monitoring designs are described in a series of published reports, "Evaluation of Agricultural Best-Management Practices," listed in the appendix.

Regional Study Area

Original strategy. A long-term regional data-collection network composed of surface- and ground-water sites was to be established to (1) document background water quality for a base of comparison when BMP's were implemented (areas of voluntary implementation were not known when monitoring was planned and begun); (2) locate areas of the basin most heavily affected by agricultural activities to target further BMP implementation and intensive monitoring; and (3) determine the effects of all implemented BMP's in controlling nonpoint-source contamination of water in the 188-mi^2 regional study area. The regional data-collection period was to begin in 1982 and to continue through September 1986. Site selection was to be based on monitoring drainage areas of major tributaries to the Conestoga River, as well as the main stem, and on the knowledge that concentrations of nitrate in surface water and ground water were elevated in areas underlain by carbonate rock. Nitrate was a primary constituent of concern in the project because concentrations greater than the drinking-water criterion of 10 mg/L as N, the maximum contaminant level (MCL) (U.S. Environmental Protection Agency, 1992), can produce adverse health effects in humans and animals. Elevated concentrations in streams can lead to eutrophication in impounded areas—a condition that adversely affects aquatic life.

According to the original strategy, the regional surface-water-monitoring network would consist of four sites. Two surface-water sites, whose drainage areas are about 50 percent underlain by carbonate rock, would be continuously monitored for streamflow. Suspended-sediment samples would be collected daily during base flow and more frequently during stormflow. Samples for pH, alkalinity, acidity, specific conductance, dissolved oxygen, major ions, species of nitrogen and phosphorus, coliform bacteria, and selected herbicides would be collected monthly and during several storms each year. After the first year of data collection, the sampling frequency would be decreased by 75 percent by decreasing the number of storm samples. The other two surface-water sites, which are on major tributaries to the Conestoga River whose drainage areas are underlain almost entirely by noncarbonate rock, would be sampled for the same properties and constituents monthly during base flow. Three precipitation stations would be installed in the regional study area to record precipitation quantity. The fisheries and benthic communities of streams in the regional study area also would be evaluated several times at many stream locations but concentrated in the carbonate areas.

The ground-water network would consist of about 40 wells cased to bedrock. Wells whose depths range from 100 to 250 ft below land surface would be selected to represent regional ground-water quality. The ground-water sites would be sampled four times a year. Two-thirds of the ground-water sites would be located in areas underlain by carbonate rock and further concentrated in the drainage areas of the two continuous surface-water sites. Within these constraints, the sites would be located to represent the distribution of geologic formations in the study area. Water levels would be measured in each well at the time of water-quality sampling; samples would be analyzed for the same properties and constituents as surface water, except for suspended sediment. The sampling frequency possibly would be decreased after the first year of study.

Final design and changes from original. The four surface-water sites were established and monitored as planned (tables 1 and 2; fig. 2). One continuous-record site was on the Conestoga River near Terre Hill (USGS station 01576105) (fig. 2); data collection began in April 1982. The other was on Little Conestoga Creek near Churchtown (USGS station 01576085) (fig. 2); data collection began in May 1982. When the Little Conestoga Creek site was established, its drainage area was being intensively targeted by Natural Resources Conservation Service (NRCS) for BMP implementation. The two surface-water sites draining noncarbonate areas of the Conestoga Headwaters were established on Muddy Creek near Martindale (USGS station 01576240) (fig. 2) and on Cocalico Creek near Ephrata (USGS station 01576330) (fig. 2); base-flow data collection at both sites began in April 1982. Three precipitation stations were installed near Churchtown, Martindale, and Goodville (fig. 2).

A network of 77 domestic wells and 1 spring was established to monitor ground-water quality (table 3). These sites were sampled for all the planned properties and constituents except herbicides in September 1982 (table 2). Water-level and water-quality data from this initial sampling were used to decrease the network to 42 wells and 1 spring for continued water-level and water-quality monitoring (fig. 2), including herbicides. Thirty-two of the wells and the spring are in areas underlain by carbonate rock. The sampling frequency was revised to three times per year—spring, summer, and fall—instead of the planned four times per year because below-freezing temperatures would preclude winter sampling. (Purged well water frozen on sidewalks and driveways could cause difficulties for the homeowners.) Analyses for bacteria were discontinued because unidentified substances in most of the well-water samples interfered with the analytical method.

Table 1. Locations and descriptions of surface-water data-collection sites in the Conestoga River Headwaters regional study area, Pennsylvania

[mi^2, square miles. Data from Chichester, 1988]

U.S. Geological Survey station identification number	Site name	Site type	Drainage area (mi^2)	Latitude (in degrees, minutes, and seconds)	Longitude (in degrees, minutes, and seconds)
01576085	Little Conestoga Creek near Churchtown, Pa. (Small Watershed study area)	Continuous record	5.82	40 08 44	75 59 20
01576105	Conestoga River near Terre Hill, Pa.	Continuous record	49	40 08 44	76 04 41
01576240	Muddy Creek near Martindale, Pa.	Partial record	49	40 10 12	76 06 21
01576330	Cocalico Creek near Ephrata, Pa.	Partial record	43	40 11 39	76 09 09

Table 2. Description of data-collection network in the Conestoga River Headwaters regional study area, Pennsylvania

Number and type of data-collection sites	Measured characteristic	Frequency
2 continuous-record stations	Suspended sediment, nutrients, major ions, bacteria, and herbicides	Monthly base flow and major storms
	Fish and benthic macroinvertebrates	Once per study period
2 partial-record stations	Suspended sediment, nutrients, major ions, bacteria, and herbicides	Monthly base flow
	Fish and benthic macroinvertebrates	Once per study period
42 wells and 1 spring[1]	Water level, nutrients, pH, specific conductance, alkalinity, acidity, major ions, bacteria	4 times per year
	Herbicides	3 times per year
3 precipitation stations	Precipitation intensity, total accumulation	4-minute intervals

[1]The initial ground-water network consisted of 77 wells and 1 spring but was decreased to 42 wells and 1 spring in March 1983.

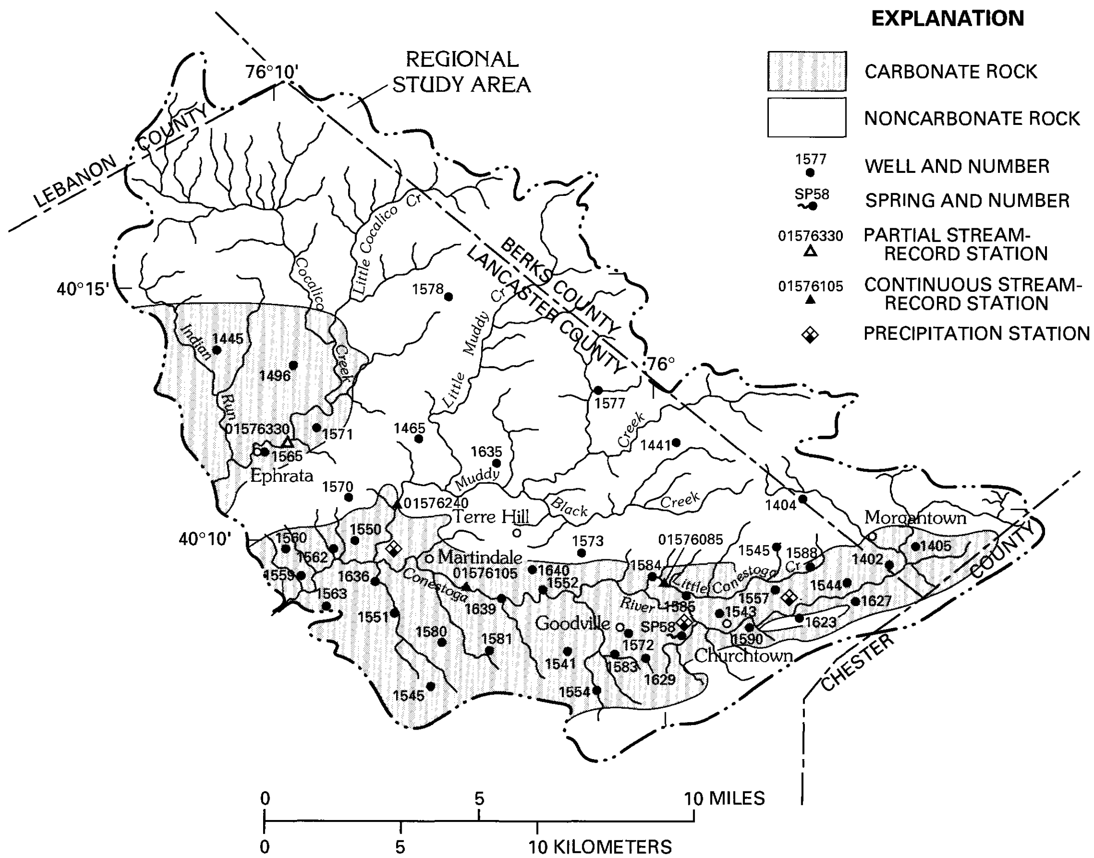


Figure 2. General geology of the Conestoga River Headwaters regional study area, Pennsylvania, and locations of data-collection stations. (Modified from Chichester, 1988.)

Sampling for chemical analysis at three of the four surface-water sites in the regional study area ended in April 1983, after 1 year. Sampling continued at the other site, Little Conestoga Creek near Churchtown, because a measurable change was most likely in this small basin, which was targeted for voluntary BMP implementation. If a significant water-quality change had been documented in the Little Conestoga Creek Basin within a few years, and if BMP implementation had been widespread throughout the regional study area, then the monitoring at the other sites would have been reestablished to determine whether water quality had changed throughout the study area. Surveys of benthic macroinvertebrate communities at the four surface-water sites were done in 1982 and again near the end of the project in 1988 and 1989. Sampling of the ground-water network was discontinued after October 1983. The ground-water quality was not expected to be affected sufficiently to detect changes during the 9 years of the project because overall implementation of BMP's in the regional study area was projected to be very low. Additionally, ground-water data collected from the carbonate areas of the regional study area are probably related to local lithology, land-use practices, and position of the well in the flow path. Therefore, data from the wells sampled could not represent the overall regional ground-water quality.

Analysis of data from the regional study area was limited to data summaries and qualitative interpretation because of the small amount of data collected. Fishel and Lietman (1986) report concentrations of nitrate and herbicides for the 42 wells and 1 spring in the regional ground-water network. Surface-water, fish, benthic-invertebrate, and ground-water data from the regional study area are listed and summarized in a report published by the U.S. Department of Agriculture (1991).

Table 3. Locations, land use, and rock types of ground-water data-collection sites in the Conestoga River Headwaters regional study area, Pennsylvania

[ft, feet; C, carbonate; NC, noncarbonate; A, agricultural; NA, nonagricultural; --, no data available; ---, not classified]

Well number	Latitude (in degrees, minutes, and seconds)	Longitude (in degrees, minutes, and seconds)	Reported well depth (ft)[1]	Reported casing depth (ft)[1]	Static water level		Rock type	Land use[2]
					Depth below land surface (ft)	Date measured (month/year)		
BE 1401	40 16 45	76 03 03	125	50	37	03/83	NC	---
BE 1402	40 08 51	75 53 08	--	--	--	08/82	C	A
BE 1403	40 10 25	75 51 01	220	103	44.4	08/82	NC	---
BE 1404	40 10 12	75 55 22	140	84	19.3	08/82	NC	NA
BE 1405	40 09 13	75 52 23	305	61	40	07/79	C	A
BE 1406	40 09 25	75 51 22	595	60	73.2	08/82	C	---
BE 1407	40 16 48	76 04 59	140	60	38.8	08/82	NC	---
BE 1408	40 14 08	76 01 10	160	--	13.7	09/82	NC	---
BE 1409	40 12 59	76 57 02	--	--	--	--	NC	---
BE 1410	40 18 03	76 07 11	120	41	37.6	03/83	NC	---
LN 1441	40 11 35	76 58 51	--	--	54.8	08/80	NC	NA
LN 1442	40 08 50	75 57 21	408	--	48.1	08/80	NC	---
LN 1446	40 13 38	76 11 07	220	--	62.6	08/80	C	A
LN 1465	40 11 42	76 05 47	220	68	75.4	08/80	NC	A
LN 1496	40 13 18	76 08 58	300	26	59.6	09/80	C	A
LN 1541	40 07 15	76 01 55	160	72	45	10/77	C	NA
LN 1543	40 07 58	75 57 49	160	86.5	65	03/81	C	NA
LN 1544	40 08 34	75 54 16	120	--	51.3	07/82	C	A
LN 1545	40 09 20	75 56 13	140	--	60.0	05/80	NC	NA
LN 1546	40 06 37	76 05 32	200	--	79.1	08/82	C	A
LN 1547	40 06 58	76 06 37	200	--	188	06/81	C	---
LN 1548	40 07 25	76 06 22	170	--	27.7	08/82	C	---
LN 1549	40 07 59	76 01 54	265	--	41.3	08/82	C	---
LN 1550	40 09 38	76 07 28	125	--	33.0	08/82	C	A
LN 1551	40 08 08	76 06 24	200	50	27.3	03/83	C	A
LN 1552	40 08 33	76 02 36	220	21	33.3	08/82	C	A
LN 1553	40 06 27	76 01 35	289	60	190	08/78	C	---
LN 1554	40 06 28	76 01 13	280	70	32.4	08/82	C	A
LN 1555	40 06 08	76 01 28	135	71	79.5	08/82	C	---
LN 1557	40 08 28	75 56 16	198	80	75.2	10/83	C	NA
LN 1558	40 08 26	75 56 40	220	36	116	08/82	C	---
LN 1559	40 08 55	76 08 57	--	--	--	03/83	C	A
LN 1560	40 09 32	76 09 25	317	--	82.3	08/82	C	A
LN 1562	40 09 27	76 08 01	340	46	27.7	10/83	C	A
LN 1563	40 08 13	76 08 19	75	64	48.0	10/83	C	A
LN 1565	40 11 27	76 09 49	150	20	18.8	03/83	C	NA
LN 1566	40 11 52	76 10 12	175	41	46.8	03/83	C	---
LN 1568	40 11 35	76 07 27	200	43	35.6	08/82	NC	---
LN 1569	40 14 57	76 07 39	150	132	20.5	03/83	NC	---
LN 1570	40 10 32	76 07 39	125	102	20.0	03/83	NC	NA

Table 3. Locations, land use, and rock types of ground-water data-collection sites in the Conestoga River Headwaters regional study area, Pennsylvania—Continued

[ft, feet; C, carbonate; NC, noncarbonate; A, agricultural; NA, nonagricultural; --, no data available; ---, not classified]

Well number	Latitude (in degrees, minutes, and seconds)	Longitude (in degrees, minutes, and seconds)	Reported well depth (ft)[1]	Reported casing depth (ft)[1]	Static water level: Depth below land surface (ft)	Static water level: Date measured (month/year)	Rock type	Land use[2]
LN 1571	40 11 57	76 08 27	175	111	57.2	10/83	C	A
LN 1572	40 07 34	76 00 15	160	60.7	40.0	05/78	C	NA
LN 1573	40 09 18	76 01 30	180	80	46.5	03/83	NC	A
LN 1574	40 12 15	76 11 54	--	--	--	09/82	C	---
LN 1575	40 10 16	76 00 05	150	81	8.82	03/83	NC	---
LN 1576	40 11 14	76 01 34	140	61	20	05/79	NC	---
LN 1577	40 12 40	76 00 53	150	102	21.6	03/83	NC	A
LN 1578	40 14 36	76 04 51	180	60	93.5	03/83	NC	NA
LN 1579	40 09 06	76 00 18	273	68.5	55.2	09/82	C	---
LN 1580	40 07 30	76 05 16	120	63	38.8	10/83	C	A
LN 1581	40 07 27	76 03 56	250	--	--	--	C	A
LN 1582	40 06 06	76 00 33	135	102	17.0	03/83	C	---
LN 1583	40 07 12	76 00 45	300	--	11.8	10/83	C	A
LN 1584	40 08 47	75 59 35	340	--	39.8	09/82	C	A
LN 1585	40 08 23	75 58 48	175	--	51.3	09/82	NC	A
LN 1586	40 08 53	75 55 21	--	--	--	10/83	C	A
LN 1588	40 06 44	75 58 57	442	21.5	106	03/83	C	---
LN 1589	40 06 48	75 58 38	213	77	88.4	03/83	NC	---
LN 1590	40 07 44	75 56 56	120	--	19.0	10/83	C	A
LN 1623	40 07 57	75 55 38	318	63	85.9	06/83	NC	NA
LN 1625	40 09 54	76 09 35	150	50	3.50	03/83	NC	---
LN 1626	40 08 30	76 04 46	400	--	54.2	09/82	C	---
LN 1627	40 08 09	75 54 06	120	107	34.1	03/83	C	A
LN 1628	40 08 10	75 59 28	396	30	59.8	09/82	C	---
LN 1629	40 07 02	75 59 50	--	--	--	--	C	A
LN 1630	40 07 08	75 58 28	175	140	70.1	03/83	C	---
LN 1631	40 06 03	75 58 04	138	120	75.3	03/83	NC	---
LN 1632	40 06 08	75 58 27	200	71	80.7	09/82	NC	---
LN 1633	40 17 08	76 08 04	125	82	42.6	03/83	NC	---
LN 1634	40 16 20	76 11 33	180	133	22.1	03/83	NC	---
LN 1635	40 11 09	76 03 42	150	69	9.87	03/83	NC	A
LN 1636	40 08 48	76 06 53	75	57	25.6	10/83	C	A
LN 1637	40 09 43	76 06 05	--	--	--	09/82	NC	---
LN 1638	40 09 59	76 05 10	100	--	4.47	03/83	NC	---
LN 1639	40 08 34	76 03 30	--	--	--	--	C	A
LN 1640	40 08 58	76 02 48	--	--	--	10/83	C	A
LN 1641	40 08 09	76 00 16	521	11.7	90	02/59	C	---
LN SP58	40 07 44	76 58 39	--	--	--	--	--	A

[1]Owner-reported well and casing depths are in feet below land surface.

[2]Only the 42 wells and 1 spring selected for continued sampling were classified by land use.

Intensive-Monitoring Study Areas

Original strategy. Surface water, soil profile (unsaturated zone), and shallow ground water were to be monitored at a minimum of four small study areas in carbonate terrain to determine the effects of BMP implementation on water quality. Baseline monitoring was to be done before implementation for 1 to 3 years (preferably 2 years), intensive monitoring after BMP implementation for 2 to 4 years, and followup monitoring for an additional 2 years (table 4). The duration and intensity of monitoring during any phase would depend on monitoring results. If water quality in one of the small study areas stabilized rapidly after BMP implementation, then monitoring would be concluded more quickly than planned and additional study areas could be monitored with remaining resources.

According to the original strategy, three types of BMP's would be monitored: nutrient management (with an emphasis on manure-management systems), pipe-outlet terraces, and conservation-tillage systems. These practices were expected to be the most commonly applied in the basin or to have the greatest effect on the amount of nitrates entering ground water. More than one BMP could be installed at a site, but they would be installed sequentially so that effects of each BMP could be determined. Ideally, more than one site would be monitored for the same BMP in order to strengthen confidence in the results.

The timeline for intensive monitoring (table 4) was based on the assumption that most BMP's would be implemented after the fall harvest. According to the original strategy, monitoring of one site would begin between October 1982 and March 1983; monitoring of two or more additional sites would begin between October 1983 and March 1984. Because the conservation-tillage/manure-management system was expected to have the greatest overall effect on ground-water quality, it would be monitored through the end of the project period in 1990. To provide minimal but sufficient data to determine gradual responses in water quality that might occur following changes in agricultural activities, sampling frequency would be decreased in 1988 and 1989 and then returned to previous frequencies in 1990.

Movement of nutrients, herbicides, and coliform bacteria from surface application to surface runoff, through the soil profile, and to the ground water would be monitored to maximize the chances of documenting changes in water quality due to BMP implementation. The following criteria were outlined for site selection: (1) Surface- and ground-water drainage area would be between 30 and 100 acres; (2) the site would be isolated from outside contamination sources; (3) land use would be the same for 5 years prior to monitoring; (4) sites would be underlain by carbonate rock with no major fractures; (5) the maximum depth of ground water would be preferably less than 20 ft and no deeper than 60 ft; (6) soils would be typical of Lancaster County; (7) the surface slope would allow for one-point runoff sampling; (8) farming practices would be typical of the Conestoga River Headwaters area; (9) the farmer would be experienced at farming; (10) the landowner would agree to the monitoring plan and would provide agricultural-activity records; and (11) the selected sites would be cost-efficient to monitor.

Ground-water boundaries would be defined by use of wells drilled and cased to bedrock around the perimeter of the study areas, just across the estimated ground-water boundary, and downstream from the study area. Wells also would be located along several cross sections of the site. Some wells would be sampled, and others would be used only to measure water level. If ground-water monitoring showed that ground water was not rapidly affected by a BMP, sampling possibly would be discontinued.

Experimental controls were incorporated into the original monitoring plan. The pre-BMP period of the site used to determine the effects of conservation tillage was to span parts of the pre- and post-BMP periods of the other intensive BMP monitoring site and, therefore, serve as a control for data analyses. At the pipe-outlet terrace study area, ground water would be continuously monitored upslope from the construction limits to provide long-term monitoring of an area unaffected by the terrace system.

At all study areas, streamflow or surface runoff, ground-water levels, and precipitation quantity would be monitored continuously. Samples collected from surface water and ground water would be analyzed at least for suspended sediment (surface water only), nutrients, herbicides, and coliform bacteria. Surface water would be sampled for at least five storms during different phases of the growing season. Ground-water samples would be collected monthly and after each of the five storms for which surface water was sampled. Precipitation-quality samples would be collected four to six times per year and analyzed for nutrient concentration.

Table 4. Data-collection schedule for original water-quality monitoring design based on planned implementation of best-management practices in the Conestoga River Headwaters, Pennsylvania

[BMP, best-management practice]

BMP	Sampling	Water year								
		1982	1983	1984	1985	1986	1987	1988	1989	1990
Pipe-outlet terrace	Baseline (pre-BMP)	■	■							
	Intensive (post-BMP)			■	■	■	■			
Conservation tillage and manure management (control site)	Baseline (pre-BMP)		■	■	■	■				
	Intensive (post-BMP)						■			■
	Followup (post-BMP)							■	■	
Nutrient management	Baseline (pre-BMP)		■	■	■					
	Intensive (post-BMP)					■	■			

Land-use changes and agricultural activities would be recorded by the farmer. Rates, locations, and times of applications of fertilizer, manure, and herbicides would be recorded daily. Manure samples collected from storage near application times would be analyzed for nutrient content.

Soils would be characterized in the fall and the spring before BMP implementation at each site and again after implementation if structural practices, such as terraces, were installed. The soils would be sampled within each horizon five times a year between March and October, initially, and then on a schedule determined by initial results. Soil samples would be analyzed for nutrients and herbicides.

Soil-water samples would be collected every 2 to 3 weeks and after five storms by use of suction lysimeters installed in groups at two to four depths ranging from just below land surface to just above the water table. Eight groups of lysimeters would be distributed across the site. Soil water would be analyzed for the same properties and constituents as for ground water.

The designated data-collection frequency and timing would be reevaluated on the basis of site-by-site monitoring results. The specific properties and constituents that were to be determined are listed in table 5.

The study areas would be characterized before and after BMP implementation, and the water-quantity and -quality data would be analyzed along with agricultural-activity data. Statistically significant changes in water quantity or quality during the study would be documented and interpreted. Soil-characterization data would be used to determine infiltration rates, bulk density, and cation-exchange capacity. Chemical data from analysis of shallow soil samples would be used to determine the remaining nutrient requirements and lime application needed for crop growth. Soil-horizon chemical data would be used to relate soil chemistry and nutrient inputs to soil-water quality in the unsaturated zone and to identify trends. Soil-water chemical data were expected to respond to chemical changes in unsaturated-zone water in response to BMP implementation. This combination of data was expected to allow the effects of BMP's to be documented in the soil profile before changes in ground-water quality were evident. Surface-runoff and ground-water-quantity and -quality data would be used to determine (1) the effectiveness of a BMP in reducing nonpoint contamination of the water system, and (2) the chemical and water budget of the site. A budget would be developed to identify paths of use or loss for selected constituents.

Table 5. Properties and constituents to be determined under the original strategy at intensive-monitoring study areas, Conestoga River Headwaters, Pennsylvania

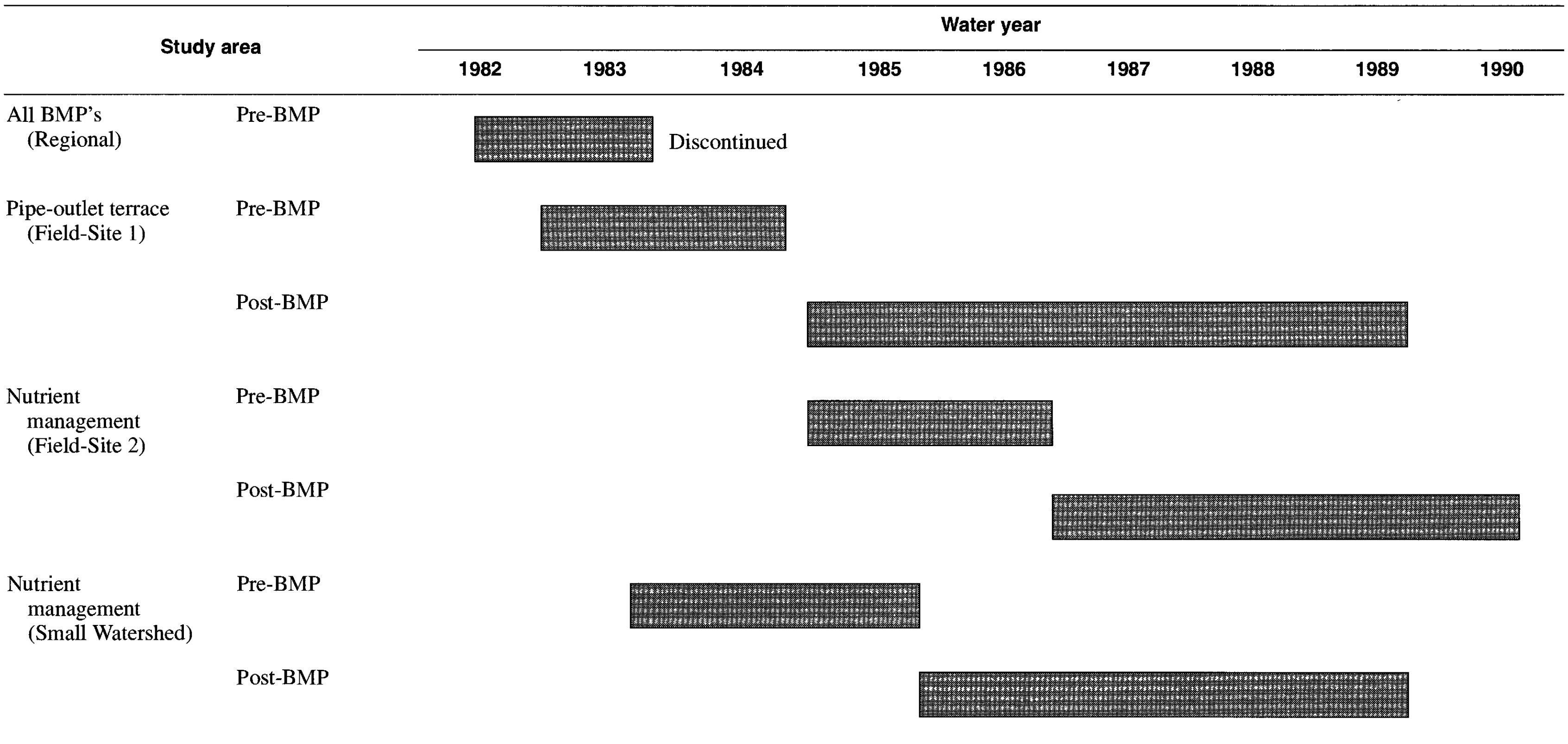
Water samples:
Suspended sediment[1 2]
Specific conductance[2]
pH
Alkalinity/acidity
Dissolved oxygen
Fecal coliform[2]
Fecal streptococci[2]
Dissolved solids
Major ions including calcium, sodium, potassium, magnesium, chloride, and sulfate
Nutrients including total and dissolved organic plus ammonia nitrogen, ammonia, nitrate plus nitrite, nitrite, and phosphorus and dissolved orthophosphorus[2]
Herbicides including atrazine, simazine, alachlor, metolachlor, cyanazine, and toxaphene[2]
Manure and precipitation:
Nutrients
Quantity (rain or snow)
Percent moisture (manure)
Soils:
Soil properties (including cation-exchange capacity, depth, and soil type)
Nitrogen
Herbicides (triazine)
Soil amendments including nitrogen, phosphorus, potassium, pH, magnesium, and calcium
Land use and agricultural activity:
Cropping history
Land-use changes
Crop yield
Cultivation practice
Timing and application of nitrogen, phosphorus, manure, and herbicides

[1]Not monitored in ground water.
[2]Essential constituents to be monitored.

Final design and changes from original. Most major elements in the original strategy for intensive-monitoring BMP sites took place during the study. At three study areas, intensive monitoring was done for 2 years before BMP implementation (pre-BMP) and for 3.5 or more years after BMP implementation (post-BMP) (table 6). The objective at each of the study areas was to determine the effects of BMP's on surface- and ground-water quality. The BMP's investigated were pipe-outlet terracing at Field-Site 1 (23.1 acres) and nutrient management at the Small Watershed (5.8 mi^2) and Field-Site 2 (47.5 acres).

Table 6. Data-collection schedule for final monitoring design for the four study areas, Conestoga River Headwaters, Pennsylvania

[BMP, best-management practice]



A study area to monitor conservation tillage and manure management could not be located. Surface water was intensively monitored at all three study areas, and ground water was intensively monitored at the two field sites. Sampling frequency was fairly constant throughout the study period at all sites, although the number of properties and constituents and number of sampling locations decreased over time. Land use and agricultural activity were recorded for the field sites and for part of the Small Watershed. Constituent concentrations and loads in surface water and concentrations in ground water before and after BMP implementation were compared with respect to changes in land use or agricultural activity. Inputs and outputs of water and nutrients were estimated for each field site. A major change from the original design was that the soil profile and soil water were monitored only infrequently.

The original strategy was changed in response to the availability of suitable study areas, initial monitoring results, increased understanding of monitoring designs, and funding limitations. Some of these factors resulted in immediate changes to the original strategy, and others resulted in changes during the study on an individual site basis.

The final monitoring design for each of the three intensive BMP studies is discussed in the paragraphs that follow. The data-collection network for each study area is described in table 7. Changes during the study and factors that influenced a decision for change are also discussed.

BMP's. The BMP's planned for Field-Site 1 were pipe-outlet terracing and nutrient management. Field-Site 1, consisting of parts of two dairy farms, is conventionally tilled cropland primarily used for the production of corn and alfalfa. The site has a 6-percent average slope and is underlain by carbonate rock. Pipe-outlet terracing was selected to reduce erosion and, thus, retain sediment and associated nutrients on the site. The nutrient-management BMP, augmented by use of a manure-storage facility, was selected to reduce nutrients available for runoff and recharge by reducing excess nutrients applied to the site and allowing the nutrients to be applied closer to the time of crop uptake. The terraces and a manure-storage facility were constructed and a nutrient-management plan was developed for the site after 2 years of pre-BMP data collection. However, as discussed in Lietman and others (1997), the timing and quantity of nutrient applications at the site did not vary substantially. Therefore, pipe-outlet terracing was the only BMP evaluated at Field-Site 1.

Because monitoring was discontinued in the regional study area, the Small Watershed, which was part of the regional network, was chosen for evaluation of the combined effects of many BMP's on water quality. Preliminary data analysis from the regional study and additional reconnaissance sampling of stream base flow and ground water in the Small Watershed showed that the primary water-quality problems in the Small Watershed were (1) elevated concentrations of nitrate in ground water and base streamflow because of excessive nutrient applications to cropland (attributed to manure disposal from high-density animal operations and use of commercial fertilizer), and (2) suspended-sediment and phosphorus loading to the stream during stormflow from erosion of cropland and streambanks. The Small Watershed was designated as a critical watershed for BMP implementation; the upper half was targeted for nutrient-management implementation and the lower half for implementation of other BMP's. For measurable changes in water quality to be documented within the time period of the study, about 75 percent of the farmers would have needed to participate in BMP implementation. Thirty-five farms in the Small Watershed (5.8 mi^2) were visited by teams of the NRCS and USGS personnel to discuss BMP implementation. Nearly all the farmers in the eastern 1.4 mi^2 of the Small Watershed (Nutrient-Management Subbasin) were willing to participate in nutrient-management planning. However, there was little interest among the farmers in the remainder of the Small Watershed and no interest among the farmers in another small subbasin (Nonnutrient-Management Subbasin) (1.4 mi^2) in the watershed. As a result of farmer response in the two small subbasins, a paired-watershed component was added to the monitoring design for evaluation of nutrient management in the Small Watershed.

During the first year of monitoring, emphasis on BMP implementation in the Conestoga River Headwaters changed from a combination of standard erosion-control BMP's to nutrient management in response to the documented problem of elevated nitrate concentrations in ground water. Erosion control and management BMP's other than nutrient management were not being implemented at the expected rate.

Table 7. Description of data-collection network at two field sites and the Small Watershed, Conestoga River Headwaters, Pennsylvania

[Modified from Koerkle and others, 1996a; Hall and others, 1997; Lietman and others, 1997]

Number and type of data-collection sites	Constituent or property	Frequency
Field-Site 1 (monitoring period January 1983–July 1989)		
1 runoff gage	Suspended sediment and nutrients	Major storms
	Herbicides	Selected storms
6 wells and 1 spring	Nutrients and specific conductance	Monthly and during an average of 3 recharge events per year
	Herbicides	Selected months
		Selected months, concentrating around application and growing periods and during a few selected recharge events; 3 of the wells and 1 spring discontinued in water year 1985
Soil (number of locations varied)	Nutrients and herbicides	Spring, summer, and fall
17 soil-water sample locations	Nutrients and herbicides	Periodically; discontinued September 1984
Manure from barn, wagon, or storage facility	Nutrients	At time of application
1 precipitation station	Precipitation intensity and total accumulation	5-minute intervals
	Nutrients	Periodically
2 farms	Agricultural-activity data (plowing, planting, harvesting, timing and rate of nutrient and herbicide application)	Biweekly
Field-Site 2 (monitoring period October 1984–September 1990)		
1 runoff gage	Suspended sediment	Major storms
	Nutrients	Selected storms
4 wells and 1 spring	Nutrients and specific conductance	Monthly and during 3 recharge events per year
2 wells	Nutrients and specific conductance	Quarterly
3–17 soil-sample locations	Nutrients	Spring, summer, and fall
4 manure-storage locations	Nutrients	At time of selected applications
1 precipitation station	Precipitation intensity and total accumulation	5-minute intervals
	Nutrients	Periodically
1 farm	Agricultural-activity data (plowing, planting, harvesting, timing, and rate of nutrient applications)	Monthly
Small Watershed (monitoring period April 1984–September 1989)		
2 continuous-record stations	Suspended sediment and nutrients	Monthly base flow and major storms
	Herbicides	Once per study period
5 partial-record stations (2 stations discontinued October 1984)	Suspended sediment, nutrients, and herbicides (at 1 station)	Monthly base flow
6 wells and 2 springs (discontinued November 1987)	Nutrients	3 times per year
7 soil-sample locations	Nutrients	Spring and fall
1 precipitation station	Precipitation intensity and total accumulation	5-minute intervals
13 farms	Agricultural-activity data (plowing, planting, harvesting, timing, and rate of nutrient and herbicide application)	Spring and fall

Therefore, nutrient management was selected for evaluation at Field-Site 2. Field-Site 2, 47.5 acres of a farm supporting a beef, hog, and poultry operation, was predominantly corn cropland having a 2- to 9-percent slope. The emphasis at this study area was on shallow ground-water quality. Runoff from the study area was minimal because pipe-outlet terracing and no-till cropping were already established.

Properties and constituents. The lists of properties and constituents for which water samples were analyzed varied throughout the study period and from site to site. For initial characterization of surface and ground water, samples were analyzed for major ions, specific conductance, pH, acidity, alkalinity, and dissolved oxygen. Because they were not expected to change significantly as a result of BMP implementation, sampling for these properties and constituents was discontinued to conserve funding for other aspects of the study. Nutrients, suspended sediment, and herbicides were the primary constituents for which samples were analyzed throughout the study. Nutrients included total and dissolved forms of ammonia, ammonia plus organic nitrogen, nitrite, nitrate plus nitrite nitrogen, and phosphorus. Herbicides included total atrazine, simazine, metolachlor, alachlor, cyanazine, and propazine. The number of nutrient species analyzed and sample-collection frequency were reduced at each sampling site throughout the study period. On the basis of preliminary data analysis, these changes were made to meet project objectives within the funding constraints. For example, at Field-Site 1, ground-water samples were collected monthly from six wells. During the first 2 years of the study, all samples were analyzed for all total and dissolved nutrient species; during the next 3 years, all samples were analyzed for dissolved nitrate plus nitrite and dissolved ammonia plus organic nitrogen; one sample was additionally analyzed for the other dissolved nutrient species once every 3 months. During the last 2 years, all samples were analyzed for dissolved nitrate plus nitrite, and samples from one well were additionally analyzed for ammonia plus organic nitrogen. The decision for these changes was based on concentrations and variability of each constituent measured during the first 2 years of the study. This same process of streamlining data collection was used at each study area. Enough data continued to be collected after BMP implementation to verify any change in the conclusions made on the basis of the preliminary data. Because data analysis indicated a time lag in water-quality response to agricultural-activity changes, funding was requested for some additional monitoring beyond the planned post-BMP period to allow sufficient time to document BMP-related water-quality changes. The specific properties and constituents sampled for at each sampling site are listed in Koerkle and others (1996a), Hall and others (1997), and Lietman and others (1997).

Surface water. Based on previous studies in similar areas (Lietman and others, 1983; Ward, 1987) and on data from the regional study, large variations in concentrations and loads of nutrients, suspended sediment, and herbicides were expected because of seasonality of agricultural activities and variation in runoff and streamflow caused by climatic factors (temperature and precipitation quantity, intensity, and duration). Therefore, in the Small Watershed, base flow was sampled every 3 weeks throughout the year at seven sites (table 8; fig. 3). After the first year, samples were collected monthly, and the number of sites was decreased to five because data from two of the sites were virtually identical to data from two other nearby sites. Stormflow was sampled during most of the major storms at two sites in the Small Watershed—at the mouth of the Nutrient-Management Subbasin and at the mouth of the entire watershed. Stormflow could not be sampled at the mouth of the Nonnutrient-Management Subbasin because the low relief of the land did not provide a well-defined stream channel. Runoff from each of the field sites was channeled to one location and sampled during most storms (Field-Site 1, USGS station 01576083; Field-Site 2, USGS station 01576335) (figs. 4 and 5). Surface-runoff or streamflow quantity was recorded continuously at the outlet of all three intensive-monitoring study areas.

Data from storm sampling were sufficient for statistical comparisons of nutrient and suspended-sediment concentrations from the pre- to the post-BMP periods and for computation of annual loads. Samples for herbicide determinations collected in the Small Watershed and at Field-Site 1 generally were collected from the late spring through the early fall. This monitoring strategy was based on previous studies in a similar agricultural carbonate basin; these studies indicated that herbicide loads in base flow and stormflow are greatest soon after spring application and decrease to low, constant levels by the fall (Lietman and others, 1983; Ward, 1987).

Table 8. Surface-water data-collection stations in the Small Watershed, Conestoga River Headwaters, Pennsylvania

[RCWP, Rural Clean Water Program; mi^2, square miles; --, not applicable. Modified from Koerkle and others, 1996a]

RCWP report station number	U.S. Geological Survey station number	Station name	Station type	Drainage area (mi^2)	Latitude (in degrees, minutes, and seconds)	Longitude (in degrees, minutes, and seconds)
1	015760831	Little Conestoga Creek, site 1, near Morgantown, Pa.	Partial record	0.34	40 09 22	75 55 14
--	015760832	Little Conestoga Creek, Site 2, near Morgantown, Pa. (discontinued October 1984)	Partial record	.60	40 09 06	75 55 05
2	0157608325	Little Conestoga Creek, site 2A, near Morgantown, Pa.	Partial record	.99	40 08 58	75 55 06
--	015760833	Little Conestoga Creek, site 3, near Morgantown, Pa. (discontinued October 1984)	Partial record	1.34	40 08 50	75 55 24
3	0157608335	Little Conestoga Creek, site 3A, near Morgantown, Pa. (Nutrient-Management Subbasin)	Continuous record	1.42	40 08 47	75 55 37
4	015760839	Unnamed tributary to Little Conestoga Creek, site 9, at Churchtown, Pa. (Nonnutrient-Management Subbasin)	Partial record	1.43	40 08 20	75 58 14
5	01576085	Little Conestoga Creek, near Churchtown, Pa. (Small Watershed study area)	Continuous record	5.82	40 08 41	75 59 20

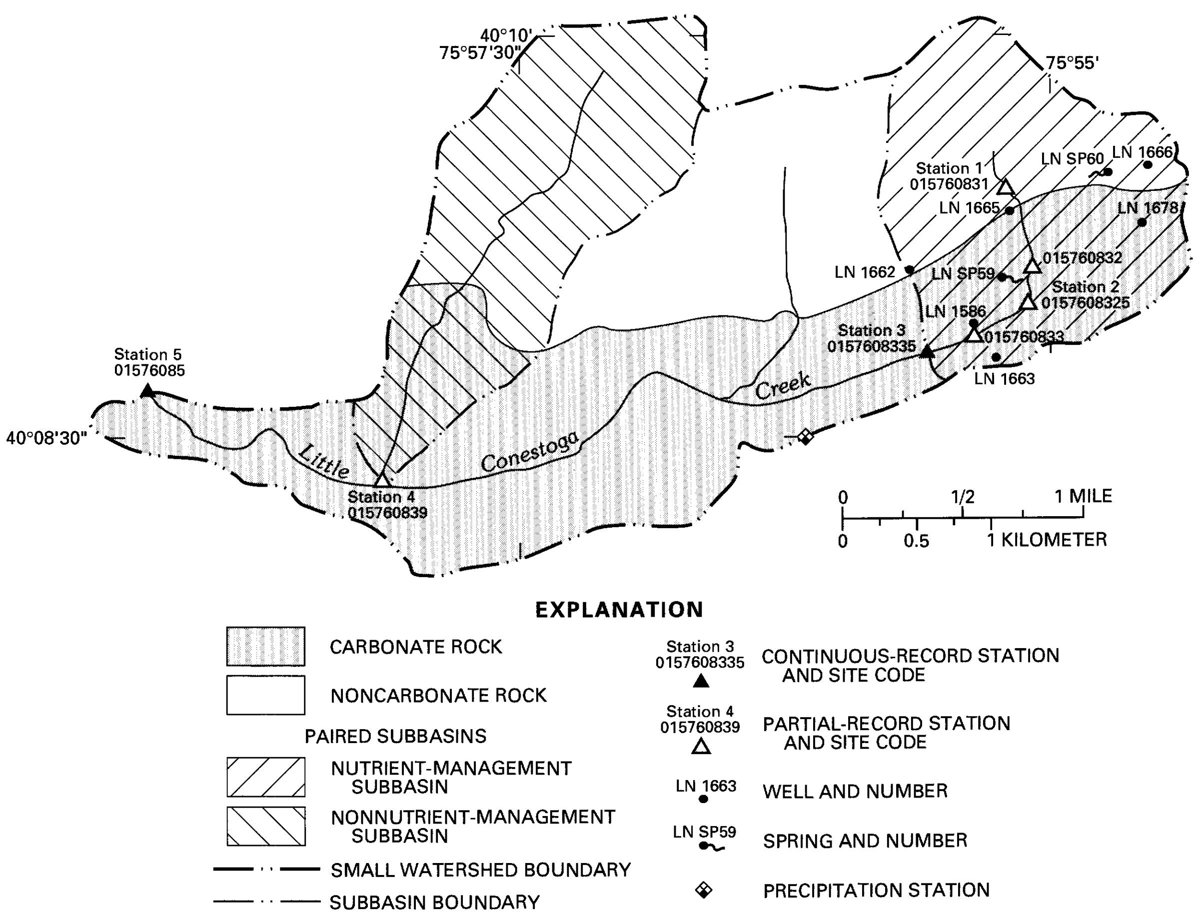


Figure 3. General geology of the Small Watershed study area and locations of management subbasins and data-collection stations, Conestoga River Headwaters, Pennsylvania. (Modified from Chichester, 1988.)

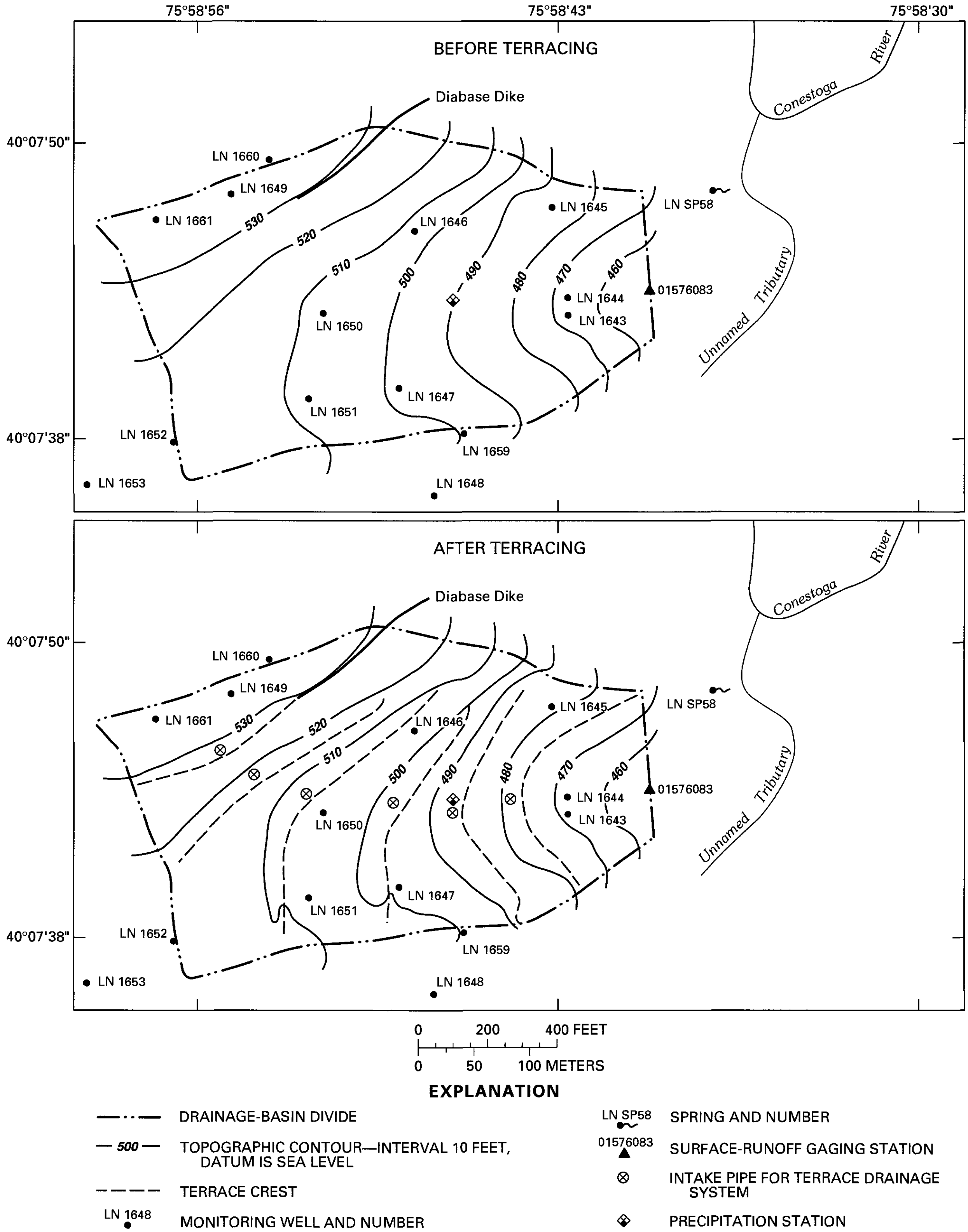


Figure 4. Locations of data-collection stations before and after terrace construction at Field-Site 1, Conestoga River Headwaters, Pennsylvania. (Modified from Lietman, 1992.)

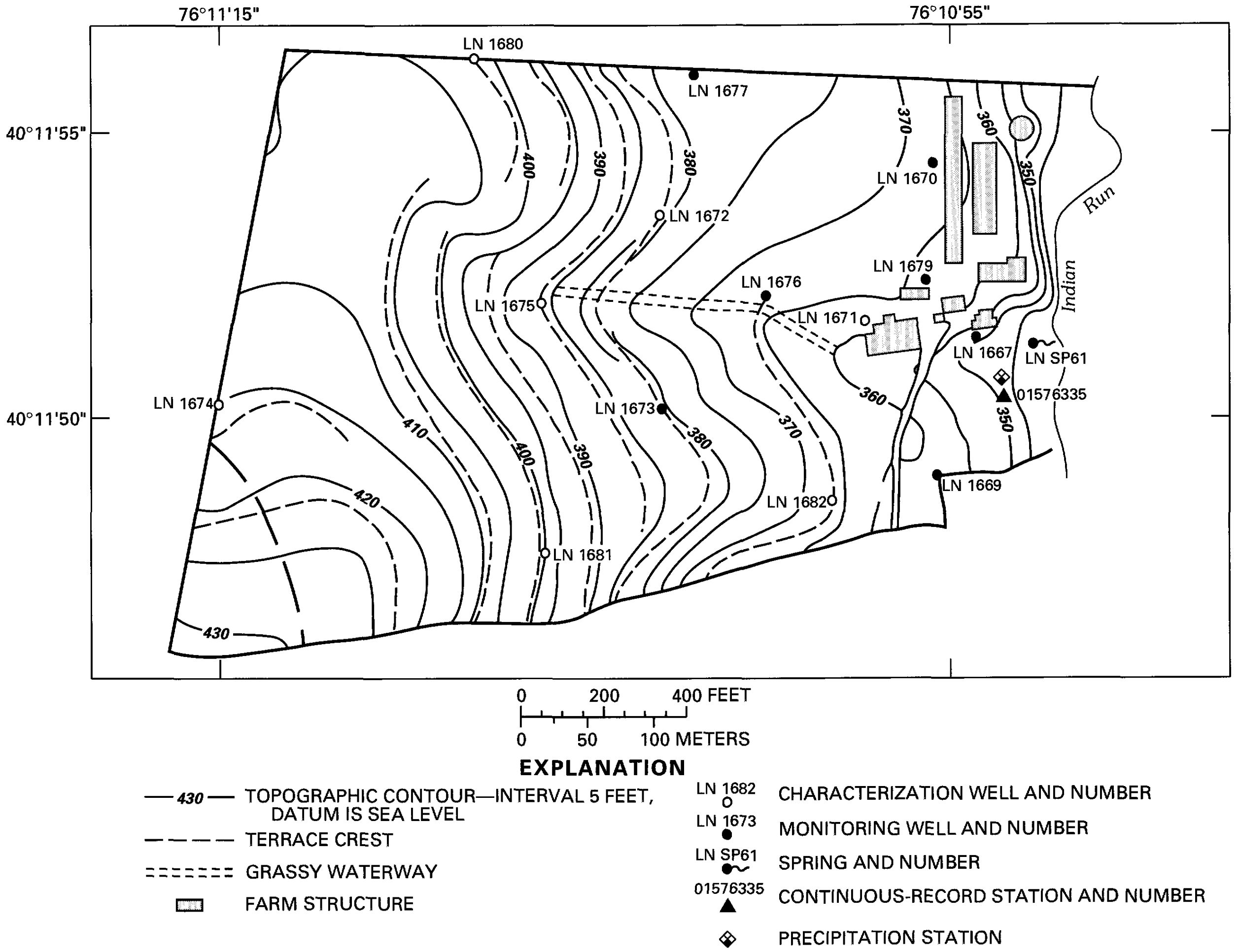


Figure 5. Locations of data-collection stations at Field-Site 2, Conestoga River Headwaters, Pennsylvania. (Modified from Chichester, 1988.)

Herbicide sampling was discontinued at Field-Site 1 during the last 2 years of the study to conserve monitoring resources because preliminary data analysis indicated that a comparison of herbicide concentrations would not be useful in evaluating the effects of BMP's. In addition to substantial variability in the data, which makes statistically significant changes difficult to detect, the types of herbicides applied changed during the study period.

Ground water. During the first 3 years of the study, ground water was sampled quarterly for analysis of nitrate concentrations at six domestic wells and two springs in the Nutrient-Management Subbasin of the Small Watershed (table 9; fig. 3). These data were used only to document general ground-water quality of the subbasin.

Table 9. Locations and geology of ground-water network stations in the Small Watershed, Conestoga River Headwaters, Pennsylvania

U.S. Geological Survey local identification number	Latitude (in degrees, minutes, and seconds)	Longitude (in degrees, minutes, and seconds)	Rock type
LN SP59	40 09 03	75 55 15	Carbonate
LN SP60	40 09 26	75 54 45	Sandstone and shale
LN 1586	40 08 53	75 55 21	Carbonate
LN 1662	40 09 10	75 55 44	Sandstone and shale
LN 1663	40 08 43	75 55 27	Carbonate
LN 1665	40 09 22	75 55 11	Sandstone and shale
LN 1666	40 09 26	75 54 36	Sandstone and shale
LN 1678	40 09 18	75 54 39	Carbonate

Ground water was monitored intensively at both field sites. To define the ground-water table and to estimate the ground-water flow directions, 14 spatially distributed wells were installed at Field-Site 1 and 13 were installed at Field-Site 2 at various times during the first year of study (table 10; figs. 4 and 5). The wells were drilled as open holes and were cased to solid bedrock. A few geochemical samplings and aquifer tests were done to help estimate the hydrogeologic characteristics of the sites. Continuous water-level recorders were installed on some wells, and intermittent water-level measurements were made at other wells (table 10). Water levels were used to estimate recharge at the site and to relate recharge to variations in water quality. Initially, water samples were collected from all the wells at each site, but the sampling was reduced to six wells and a spring at each site by the end of the first year of sampling. The wells to be monitored for water quality were chosen on the basis of reactivity of the well to recharge events and spatial coverage of the site. Monthly ground-water samples were collected at each site during nonrecharge periods and were analyzed for nutrients at both field sites, and for herbicides as well at Field-Site 1, from early spring through late fall each year. The sampling schedule was based on considerations of autocorrelation, data variability, number of samples required for statistical analysis, and efficiency of the monitoring effort. Ground water also was sampled for the same constituents during several recharge periods per year to determine the variability in concentration during rapid recharge periods and to help understand the transport processes at the site. Sampling of one well at Field-Site 1 was discontinued after about 2 years because the well was upgradient from a diabase dike near the ground-water basin boundary and was not representative of the general quality of ground water in the carbonate aquifer at the site. Also, a well at Field-Site 2 was sampled only quarterly after 1 year of monitoring because water quality in the well was affected by an ammonia spill on the site before the study began.

Soil water. Twenty lysimeters were installed near monitor wells at Field-Site 1. Data from analysis of the lysimeter samples were to be used to help understand the transport of nutrients and herbicides through the unsaturated zone. However, most lysimeters did not work in the clay-rich soils at the site. Because of the same problem, lysimeters were not installed at Field-Site 2.

Precipitation quantity. Rainfall and snowfall were measured continuously at the three study areas. Quantity, intensity, and duration of precipitation were related to runoff and recharge quantity and quality. Precipitation-quality samples were collected about three times per year at each site and were used to estimate wetfall nutrient loads to the site.

Agricultural activities. Timing and methods of plowing, planting, and harvesting, as well as timing and quantities of applications of manure, commercial fertilizer, and herbicides, were documented by way of field inspections and information collected from the farmers. Initially, the farmers at Field-Site 1 were requested to mail a form biweekly with all data recorded. Because this method did not work well at Field-Site 1, the farmers at both field sites were interviewed by field personnel to obtain agricultural-activity data. Recorded data were reviewed and field-checked about once every 2 to 4 weeks during the active agricultural season and less frequently in the off-season. The same procedure was used on a quarterly basis for farmers in the Nutrient-Management Subbasin of the Small Watershed. Agricultural-activity information was not documented for the farms in the remainder of the Small Watershed. Manure samples from cattle, hogs, and poultry were collected from barns and storage facilities just before application; samples were analyzed several times during the studies to estimate the amounts of nutrients applied to a site.

Soil nutrients. Soil-sample collection varied throughout the study and in each study area. Initially, at Field-Site 1, composite samples of the top 2 in. of soil were collected four times a year and analyzed for total and soluble nutrients and herbicides. Sampling for determination of herbicides continued in this manner. However, sampling for determination of nutrients evolved to the collection of 4-ft cores at several locations in the spring and fall in all the study areas and 2-ft cores at the same locations in the summer at the field sites. The soil samples were split into 0- to 8-in., 8- to 24-in., and 24- to 48-in. segments and were analyzed for soluble nutrients to help understand the movement of nutrients to the ground-water system.

Data analysis. Surface- and ground-water quality for each of the three intensive study areas were characterized before BMP implementation. Water-quantity and -quality data were statistically evaluated for changes from the pre- to post-BMP periods.

Table 10. Ground-water data-collection sites at Field-Sites 1 and 2, Conestoga River Headwaters, Pennsylvania

[All depths shown in feet below land surface; [(gal/min)/ft], gallons per minute per foot; <, less than; E, estimated value; NA, not applicable; --, no data; N, nutrient data only; NWL, nutrient and continuous water-level data; WL, intermittent water-level data only; NWLP, nutrient, continuous water-level, and herbicide data. Modified from Koerkle and others, 1996b; Lietman and others, 1997]

U.S. Geological Survey well number	Latitude (in degrees, minutes, and seconds)	Longitude (in degrees, minutes, and seconds)	Depth of well	Depth of bottom of casing (overburden thickness)	Depth to bedrock	Depth to water-table surface, 1983–89		Specific capacity [(gal/min)/ft]	Types of data collected	Sampling depth
						Maximum (lowest water level)	Minimum (highest water level)			
					Field-Site 1					
LN SP58	40 07 44	75 58 39	Spring	NA	NA	NA	NA	NA	N	NA
LN 1643	40 07 41	75 58 43	100	68.9	20	38.75	33.66	20	NWL	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	62
LN 1646	40 07 44	75 58 47	125	99.4	5	73.21	69.47	130	NWLP	107
LN 1647	40 07 40	75 58 49	75	37.3	17	--	--	<.25	WL	65
LN 1648	40 07 38	75 58 46	100	7.2	2	--	--	50	WL	72
LN 1649	40 07 44	75 58 54	85	38.7	35	37.94	29.35	14	NWL	72
LN 1650	40 07 41	75 58 51	125	89.7	63	74.52	70.14	36	NWL	112
LN 1651	40 07 39	75 58 51	105	71.7	68	71.27	62.65	20	NWL	92
LN 1652	40 07 38	75 58 53	125	79.5	12	--	--	<.25	WL	83
LN 1653	40 07 37	75 58 56	132	105.1	27	--	--	3.0	WL	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
					Field-Site 2					
LN SP61	40 11 52	76 10 53	Spring	NA	0	NA	NA	20	N	NA
LN 1667	40 11 52	76 10 55	Unknown	--	--	--	--	20	N	From pump
LN 1669	40 11 49	76 10 55	100	11	6.5	19.61	10.29	<1	NWL	85
LN 1670	40 11 56	76 10 57	75	9.8	5.5	19.70	8.57	<1	NWL	65
LN 1671	40 11 52	76 10 58	28	18.8	13	--	--	<1	NWL	--
LN 1672	40 11 52	76 11 05	100	10.9	10	--	--	<1	NWL	--
LN 1673	40 11 48	76 11 03	46	13.8	12	10.68	3.21	<1	NWL	35
LN 1674	40 11 45	76 11 15	125	25.2	19	21.60	19.73	<1	NWL	35
LN 1675	40 11 50	76 11 07	55	17.2	14	--	--	<1	NWL	--
LN 1676	40 11 52	76 11 01	40	8.8	11	24.82	17.05	<1	NWL	35
LN 1677	40 11 56	76 11 05	50	30	28	32.37	22.04	20	NWL	35
LN 1679	40 11 52	76 11 57	60	13.4	10	21.26	15.39	20	NWL	35
	40 11 56	76 11 09	60	7.8	--	--	--	<1	NWL	--
LN 1681	40 11 47	76 11 08	60	8.8	--	--	--	<1	NWL	35
LN 1682	40 11 48	76 10 59	350	18.6	18	--	--	<1	NWL	35

Statistical procedures including summary statistics, hypothesis testing, regression analysis, analysis of variance, and analysis of covariance were used to characterize and analyze data. Specific data-analysis procedures used to obtain the results summarized in this report are described in detail in individual site reports listed in the appendix. The data were examined for quantitative relations between water quality and agricultural activities. If quantitative relations could not be established, qualitative analysis of water-quality and agricultural-activity data was used to evaluate the effects of the agricultural-management practices.

Water and nitrogen budgets were estimated for the two field sites by use of surface- and ground-water-quantity and -quality data, agricultural-activity data, and referenced data for inputs of precipitation and atmospheric nitrogen inputs, nitrogen uptake and removal by crops, and loss of nitrogen through volatilization. Because of the lack of soil-water data and the large variability in soil-nutrient data, the soil data were primarily used for site characterization and for qualitative assessment of the effect of soil nutrients on water quality.

Evaluation of Monitoring Design

Although the final, overall monitoring design incorporated the original design concepts of the project, the scope of the project was reduced. Throughout the project, monitoring procedures were modified to (1) increase the probability of success (of meeting the objectives) of determining the effects of agricultural BMP's, and (2) improve the efficiency of the project. As a result, the regional study area was not monitored during the planned post-BMP period, only two of the three selected BMP's were monitored in intensive studies, soil water was not successfully monitored, soil sampling and analyses were decreased, collection of major ion and bacteria data was eliminated after initial analysis, and collection of herbicide data was curtailed. However, three study areas were intensively monitored, post-BMP periods were extended, and a paired-watershed component was added.

The experimental RCWP was one of the first nationwide efforts to evaluate the effectiveness of management practices on water quality. Approaches to monitoring design were being developed throughout the 10-year program by those responsible for the water-quality monitoring at each of the project sites.

Through the RCWP as a whole, and through the Conestoga River Headwaters project in particular, much was learned about monitoring design. Some of this knowledge was applied to the project during the course of the study; other information could not be applied after the sites were selected and instrumented or after the initial pre-BMP periods were completed. Lessons learned about project design that will be considered in similar monitoring efforts in the future are summarized as follows.

Experimental Design

- Effective monitoring designs allow enough time for evaluating the system over a full range of hydrologic conditions before and after a change in agricultural activity. The project should be long enough to allow water quality to respond to agricultural-activity changes.
- If a specific BMP is to be evaluated, then only one BMP should be implemented at a site. Implementation of more than one BMP diminishes the possibility of evaluating each individual BMP and makes information gained from the study less widely applicable.
- Ancillary data, such as precipitation, soil, and agricultural-activity data, should be collected throughout an investigation in the control subbasin and in the treatment subbasins.
- Paired-watershed studies require care in site selection so that data from the sites are comparable. The sites should be similar in geology, hydrologic responses, land use, and agricultural activities over time.
- Controlled study designs facilitate data interpretation. Controlled designs include water-quality monitoring upstream and downstream from an agricultural-activity change, paired watersheds, or in the case of ground water, monitoring upgradient and downgradient from an agricultural-activity change.
- Observing similar water-quality responses to a BMP at several locations helps to determine cause and effect.
- Quantitative relations between water-quality and agricultural-activity data provide the strongest evidence of cause and effect.

- BMP cause-and-effect studies are probably not feasible in areas much larger than several farms because of the difficulty of implementing and monitoring agricultural-activity changes.
- Process-oriented studies lead to an improved understanding of the transport mechanisms of agricultural chemicals and ultimately to the development of effective BMP's.

Site Selection

- Beneficial uses of water and related water-quality problems should be identified before a water-quality study begins.
- Site selection should be preceded by a reconnaissance of the area that includes sampling of water sources and determination of surface-water and ground-water flow.

Data Collection and Analysis

- Flexibility of a monitoring design is necessary to accommodate monitoring-site logistics, changes indicated by preliminary data analyses, changes in protocol, and the availability of new technology; however, any monitoring strategy should be consistent enough to ensure proper data analyses.
- Constituents selected for analysis should be reevaluated periodically to determine whether they are useful indicators for meeting the project objectives.
- Statistical-analysis methods should be selected during project planning so that types and frequency of data will meet requirements for data analyses.
- Water-quality and agricultural-activity data should be collected for at least 2 years before BMP implementation in order to gain an initial understanding of the system and to document hydrologic responses during the range of hydrologic conditions possible during post-BMP monitoring.
- Instream base-flow data relate not only to ground-water quality but also to streambed processes that are affected by surface conditions; therefore, ground-water-quality data for wells near a stream may prove more informative than instream base-flow data in establishing relations between agricultural activities and water quality.
- Establishing agricultural-activity records for comparison to water-quality data is difficult and time consuming. Defining the proximity of agricultural activity to water sources, determining the nutrient content of livestock manures and the part that is available for transport to surface or ground water, and developing a data-management system to track agricultural-activity data and compile data are some of the problems that may be faced. Agricultural-activity data are most accurate when farmers are interviewed frequently and when the information is verified by field inspection.
- Agricultural-activity and soil-nutrient data are not as precise as water-quality data and, therefore, limit the possibilities of establishing cause-and-effect relations.
- Information on ammonia, organic nitrogen, and content of soils in addition to data collected on soil nitrate would be helpful in understanding the movement of nitrogen through soils.

Farmer and Interagency Cooperation

- Farmer cooperation is essential to the successful evaluation of BMP effectiveness. Personal preferences and financial considerations may divert farmers away from implementation goals and thereby complicate analysis of data.
- An ideal scientific study for evaluating the effects of changes in agricultural activities is one in which researchers have complete control of farm management.
- Coordination between agencies implementing and monitoring the agricultural-activity changes is essential to project success. Project planning should include funding for technical assistance from information exchanges between agencies.
- Effective cooperation and coordination between agencies involved in a project may be compromised by differences in project objectives and perceptions of how specific activities should be done. For example, one agency may evaluate the program on the number of contracts being written with farmers, whereas another agency may evaluate the program on whether or not BMP's are being used according to plans.

CHARACTERIZATION OF STUDY AREAS AND WATER QUANTITY AND QUALITY

The Conestoga River Headwaters Basin ($188\ mi^2$) was characterized on the basis of geology, land use, precipitation, and ground- and surface-water quantity and quality data collected during the regional network study. In-depth characterization of the intensive-monitoring study areas for 2-year periods before implementation of BMP's provides a detailed perspective of the similarities and variabilities in subbasins of the Conestoga River Headwaters Basin and serves as baseline data for comparison of data collected from each study site after BMP implementation. Detailed characterizations of Field-Site 1, Field-Site 2, and the Small Watershed are given in Lietman and others (1996), Koerkle and others (1996b), and Fishel and others (1992), respectively.

Geology and Soil Type

The Conestoga River Headwaters is predominantly in the Piedmont Province. The northern two-thirds is underlain by conglomerate, shale, sandstone, and diabase; the predominant land use is forest. The southern one-third consists of intensively farmed carbonate valleys. The weathered and fractured carbonate bedrock contains voids and sinkholes. The Hagerstown and Duffield silt-clay loam soils are formed in residuum that is weathered from limestone. These well-drained soils predominate in the carbonate valleys (U.S. Department of Agriculture, 1985) and are as much as 60 in. deep.

The two field sites and the southern half of the Small Watershed are underlain by weathered and fractured carbonate bedrock. Field-Site 1 (23.1 acres) is underlain by dolomitic rocks of the Zooks Corner Formation. Half of Field-Site 2 (47.5 acres) is underlain by limestone of the Milbach Formation of Cambrian age; the other half is underlain by dolomite of the Snitz Creek Formation. The northern half of the Small Watershed is underlain by Triassic diabase and conglomerates, shales, and sandstones of the Stockton Formation, and the southern half is underlain by limestone of the Buffalo Springs Formation of Cambrian age and Stonehenge Formations of Ordovician age. Soils in the carbonate areas of all three intensive-monitoring study areas are predominantly Hagerstown and Duffield silt-clay loams.

Land Use and Agricultural Activities

Land uses in the Conestoga River Headwaters were about 50 percent agricultural cropland (primarily corn and hay), 10 percent pasture, 25 percent woodland, and 15 percent urban or other land use. The average farm size was about 50 acres and the animal density was approximately 2.0 animal units (1,000 lb of animal) per tillable acre. The U.S. Department of Agriculture (1982) has designated farms whose livestock densities exceed 1.5 animal units per acre as critical sources of nutrient contamination. In general, animal manure was applied to cropland of the farm where it was produced and was the major nutrient source in the basin; however, manure applications were commonly supplemented with commercial fertilizer. Atrazine was the most widely applied herbicide in the basin during the study period; metolachlor and cyanazine also were commonly applied.

Land-use and agricultural-activity data collected from farms in the two field sites, the Nutrient-Management Subbasin of the Small Watershed and the entire Small Watershed are summarized in table 11. Most farms used conventional tillage. Corn was the predominant row crop at each study site; alfalfa was the predominant hay crop. Varying amounts of tobacco, small grains, and vegetables were planted at the sites from year to year. Farmers fertilized croplands with a variety of animal manures; in addition, commercial fertilizers were applied to some farms. Manure applications usually were surface-spread or injected. Nutrient-application rates varied from farm to farm and depended on animal density and amount of acreage available to receive applications. For 10 farms in the Nutrient-Management Subbasin, average annual application rates to corn ranged from 17 to 590 lb/acre of nitrogen and from 6 to 170 lb/acre of phosphorus. Average annual nitrogen and phosphorus application rates to corn were 400 and 100 lb/acre, respectively, at Field-Site 1 and 570 and 130 lb/acre, respectively, at Field-Site 2. Atrazine, metolachlor, and cyanazine were the herbicides most commonly applied in the Nutrient-Management Subbasin of the Small Watershed and at Field-Site 1. Alachlor also was applied in the Nutrient-Management Subbasin. Because herbicide concentrations in water would not be affected by the nutrient-management BMP, herbicide data were not collected at Field-Site 2.

Table 11. Land-use and agricultural-activity data for the intensive-monitoring study areas, Conestoga River Headwaters, Pennsylvania, before implementation of best-management practices

[Land use expressed in percentage of total basin/field site; mi^2, square miles; lb/acre/yr, pounds of nutrient applied per acre per year; --, no data]

Site characteristic or activity	Field-Site 1	Field-Site 2	Small Watershed	Nutrient-Management Subbasin of Small Watershed
Drainage area	23.1 acres	47.5 acres	5.8 mi^2	1.4 mi^2
Land use:				
Agricultural	100	100	68	78
Row crops	75	86	34	41
Hay	25	0	15	17
Pasture	0	0	5	6
Noncropland	0	14	14	14
Forested	0	0	24	21
Other	0	0	8	1
Agricultural activity:				
Tillage practices	Conventional	No-till/minimum-till	Conventional	Conventional
Nutrients applied to cropland:				
Nitrogen (lb/acre/yr)	320	470	--	210
Phosphorus (lb/acre/yr)	82	100	--	47

Precipitation

The long-term average precipitation in the study area was about 42 in/yr, on the basis of the 30-year record (1951–80) from Morgantown, Pa. (National Oceanic and Atmospheric Administration, 1983). During the study period (1982–90), annual precipitation ranged from about 35 to 60 in/yr. Precipitation was rain most of the year, but snow was common in the winter. For the 2 years of the pre-BMP periods, annual precipitation at Field-Site 1 was about average (1983 water year) and 44 percent above average (1984 water year). At Field-Site 2, annual precipitation was 17 percent (1985 water year) and 11 percent (1986 water year) below average. At the Small Watershed, annual precipitation was 14 percent (1984 water year) and 5 percent (1985 water year) below average.

Soil Nutrients

Soil data for cropland at the two field sites and in the carbonate areas of the Small Watershed indicated substantial amounts of soluble nitrogen (nitrate) in the soil column at depths of as much as 8 ft. After harvest in the fall, nitrate concentrations in the crop root zone (0 to 4 ft) ranged from 30 to 460 lb/acre. An additional 40 to 500 lb/acre of nitrate was detected in samples from the 4- to 8-ft soil zone. Baker (1986) has recommended that nitrate concentrations in the root zone not exceed 45 lb/acre for soils of this type because nitrate concentration in gravitational water leached to the water table is at risk of exceeding 10 mg/L as N, the drinking-water MCL. Nearly all the soil samples collected during the study contained soluble nitrogen concentrations in excess of 45 lb/acre in the root zone.

Most of the soluble phosphorus detected in the root zone was in the top 8 in. of soil. After fall crop harvest, soluble phosphorus concentrations in the root zone ranged from 1.0 to 60 lb/acre.

At Field-Site 1, the top 2 in. of soil was sampled for determination of herbicides. Atrazine concentrations in samples collected soon after herbicide applications (late spring) were as great as 545 µg/kg; however, by the end of the growing season (early fall), atrazine concentrations in samples of the top 2 in. of soil were less than 50 µg/kg.

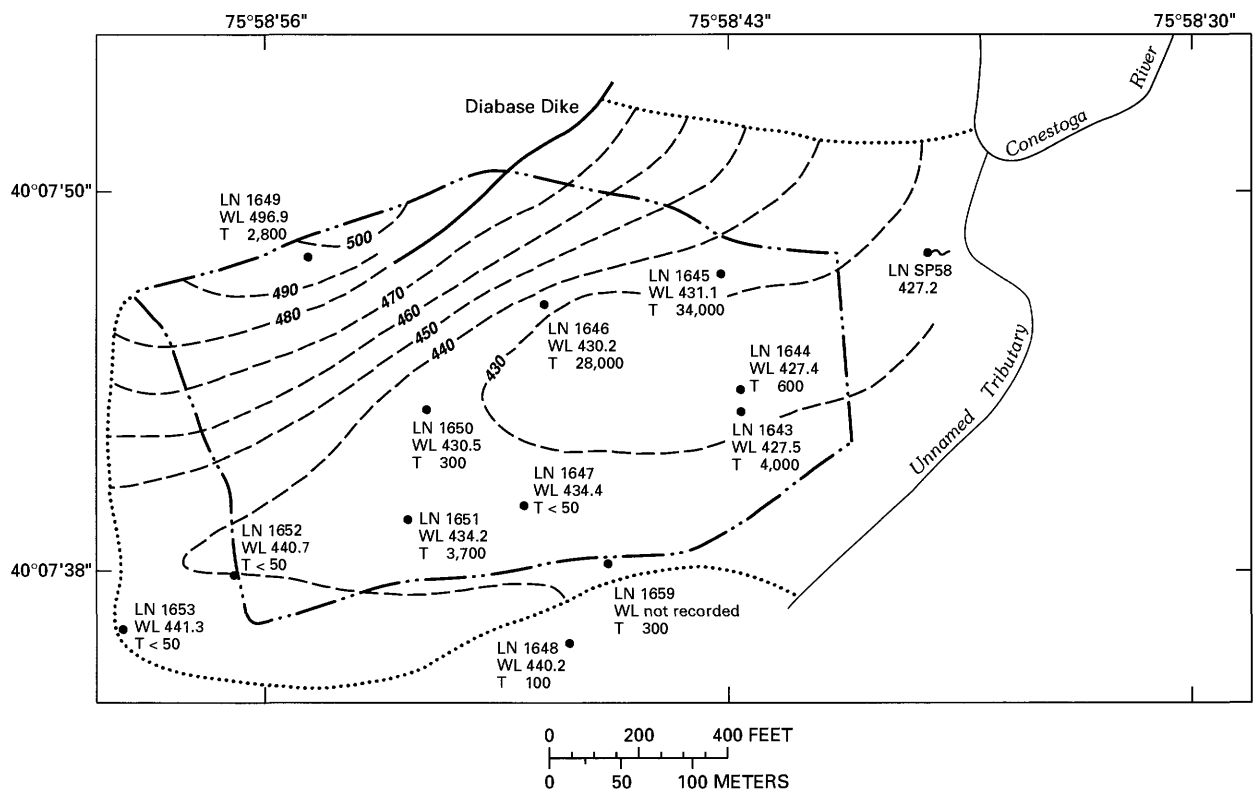
Ground Water

The unconfined aquifer underlying the Conestoga River Headwaters is a complex fractured-bedrock ground-water-flow system. In general, the water table is a subdued image of surface topography. Most ground water discharges to numerous local streams (Gerhart and Lazorchick, 1984).

At Field-Site 1, the ground-water basin was just slightly larger than the surface-water basin (fig. 6). The northern, western, and southern flow boundaries approximated the surface-water boundaries; the eastern flow boundary was poorly defined. All recharge to the shallow aquifer at the site was from precipitation. All ground water discharged across the eastern boundary of the site to nearby streams. Depths to bedrock ranged from 5 to 68 ft below land surface; specific capacities of the wells ranged from less than 0.25 to 160 (gal/min)/ft of drawdown; specific yields ranged from 0.03 to 0.18; and transmissivities ranged from less than 50 to 34,000 ft^2/d.

At Field-Site 2, the ground-water basin boundaries extended beyond the 47.5 acres of the 55-acre farm where nutrient management was implemented. A ground-water-flow model (McDonald and Harbaugh, 1988) was used to estimate ground-water inflow and outflow across the site. According to model results, about 16 percent of the ground water was inflow across the eastern boundary (Koerkle and others, 1996b); the remainder of the ground water discharged across the northern, eastern, and southern boundaries of the site. Depth to bedrock ranged from 5 to 28 ft below land surface; specific capacities ranged from less than 1 to 20 (gal/min)/ft of drawdown; specific yields of wells ranged from 0.05 to 0.10; and transmissivities ranged from 10 to 10,000 ft^2/d.

The estimated water-table configurations for the two field sites (based on water-level measurements) are shown in figures 6 and 7. For some wells, the water table fluctuated from above to within the bedrock. For deeper wells, the water table always



EXPLANATION

—··—	DRAINAGE-BASIN DIVIDE
··········	ESTIMATED GROUND-WATER DIVIDE
— 430 —	WATER-TABLE CONTOUR—INTERVAL 10 FEET, DATUM IS SEA LEVEL
LN 1648 ●	WELL AND NUMBER
WL 440.2	MEASURED WATER LEVEL, IN FEET ABOVE SEA LEVEL
T 100	TRANSMISSIVITY, IN FEET SQUARED PER DAY
LN SP58	SPRING AND NUMBER

Figure 6. Estimated water-table configuration at Field-Site 1 on November 2, 1982, and transmissivities of the Zooks Corner Formation, Conestoga River Headwaters, Pennsylvania. (From Lietman and others, 1997.)

remained in bedrock (table 10). At both field sites, ground-water levels responded rapidly to recharge from precipitation. Water levels commonly rose within 2 hours of the onset of precipitation and, in general, stabilized within 2 weeks. Rapid flow through the ground-water system resulted in short-term storage.

The ground-water basin of the Small Watershed was not defined; however, topographic and geographic features in and around the Small Watershed suggest that an unknown proportion of the ground water at the eastern end of the watershed may discharge to the Conestoga River rather than to Little Conestoga Creek.

In the regional study area, data for the 75 wells, with water levels from 7 to 126 ft below land surface when sampled (table 12), indicated that ground-water quality from areas underlain by carbonate rock was affected by the carbonate mineralogy of the aquifer.

Table 12. Summary statistics of water-level data for wells sampled in the regional study area, Conestoga River Headwaters, Pennsylvania

[n, number of samples; Min, minimum; Max, maximum]

Type of sampling	n	Water level, in feet below land surface				
		Min	25th percentile	Median	75th percentile	Max
Fall 1982	40	11.6	30.4	42.8	57.2	124
Spring 1983	35	7.0	21.1	32.6	54.5	93.4
Summer 1983	33	10.0	26.1	34.0	53.4	99.5
Fall 1983	33	11.8	27.9	38.8	57.6	126

In general, ground water from the carbonate areas had higher pH, specific conductance, alkalinity, hardness, and concentrations of calcium and magnesium than ground water from areas underlain by noncarbonate rock (table 13). In addition, effects of surficial fertilizer and herbicide applications can

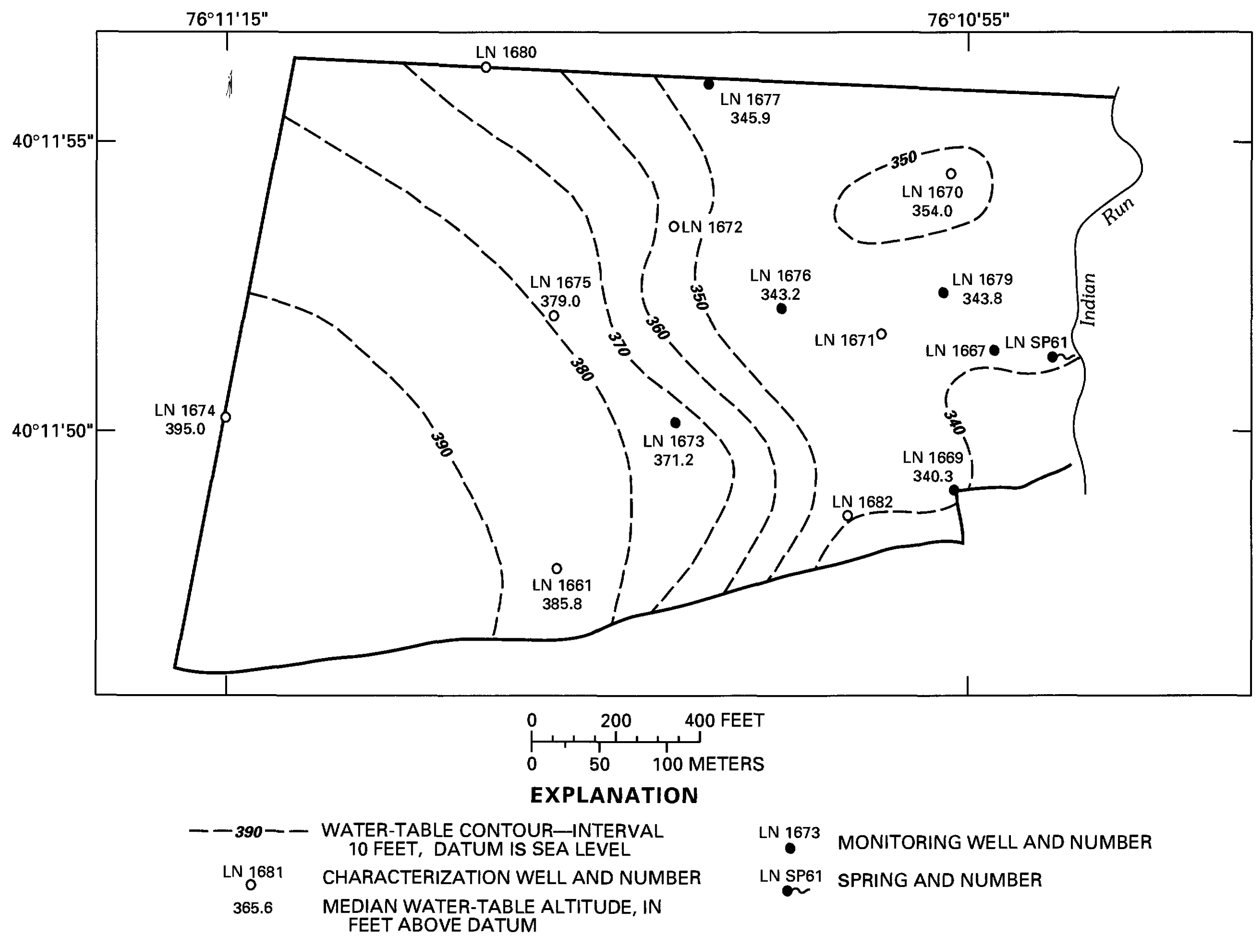


Figure 7. Median water-table altitude at Field-Site 2, Conestoga River Headwaters, Pennsylvania, during 1985–86. (From Koerkle and others, 1996b.)

be seen in the ground-water quality of the regional-network wells in carbonate-rock areas. Dissolved nitrate concentrations in ground water were elevated in carbonate-rock areas regardless of land use and commonly exceeded the MCL of 10 mg/L as N for drinking water (table 14). Herbicides were detected in many wells in agricultural areas underlain by carbonate rock, and atrazine was detected in samples collected year round (tables 14 and 15; Fishel and Lietman, 1986). In water samples from wells underlain by noncarbonate rock where agricultural practices were not intensive, dissolved nitrate concentrations rarely exceeded 10 mg/L, and no herbicides were detected.

Table 13. Water-quality characteristics of ground water from 75 wells in the regional study area, Conestoga River Headwaters, Pennsylvania, fall 1982

[n, number; pH, in standard units; C, carbonate; NC, noncarbonate; specific conductance in microsiemens per centimeter at 25 degrees Celsius; chemical concentrations in milligrams per liter except for herbicides, which are in micrograms per liter; fecal streptococci and fecal coliform in colonies per 100 milliliters; ≤, less than or equal to]

Property or constituent	Rock type[1]	n	Minimum	25th percentile	Median (50th percentile)	75th percentile	Maximum
pH	C	46	6.8	7.3	7.4	7.6	8.2
	NC	29	5.1	5.9	6.4	7.0	7.8
Alkalinity, as $CaCO_3$	C	46	29	205	232	253	330
	NC	29	4.2	14	56	104	344
Acidity, as $CaCO_3$	C	46	0	8.8	16	22	48
	NC	29	3.0	14	32	46	97
Specific conductance	C	46	193	586	665	816	1,020
	NC	29	31	96	190	362	928
Dissolved solids	C	46	106	382	421	505	792
	NC	29	28	78	158	262	728
Calcium, as Ca	C	46	18	54	73	92	136
	NC	29	1.4	6.4	18	42	112
Magnesium, as Mg	C	46	6.9	20	31	38	48
	NC	29	.6	2.4	4.8	9.8	50
Hardness, as $CaCO_3$	C	46	86	269	303	354	470
	NC	29	7.2	24	71	142	420
Sodium, as Na	C	46	1.6	4.7	8.2	14	68
	NC	29	1.1	2.5	6.5	8.4	23
Potassium, as K	C	46	.76	1.5	2.2	3.6	12
	NC	29	.46	.75	1.0	1.4	6.3
Chloride, as Cl	C	46	3.0	13	20	35	545
	NC	29	2.0	3.0	7.0	10	50
Sulfate, as SO_4	C	46	5.0	20	32	65	410
	NC	29	.86	5.0	15	28	345
Nitrate, as N	C	46	.02	4.5	8.3	12	40
	NC	29	.06	1.3	3.4	6.1	10
Orthophosphorus, as P	C	46	≤.01	≤.01	≤.01	≤.01	.09
	NC	29	≤.01	≤.01	.04	.07	.16
Fecal streptococci	C	45	1	4	12	58	10,000
	NC	29	1	6	9	20	320
Fecal coliform	C	43	≤1	≤1	≤1	4	900
	NC	29	≤1	≤1	≤1	≤1	36

[1]Rock-type classifications were done by locating the wells on detailed geologic/topographic maps. If the wells are near formation intersects, the ground water from that well may be affected by another rock type.

Table 14. Percentage of wells in regional study area in which dissolved nitrate concentration exceeded the maximum contaminant level for drinking water[1] and the percentage of wells and one spring containing detectable concentrations of atrazine, Conestoga River Headwaters, Pennsylvania

	Agricultural, carbonate rock (27 wells and 1 spring)	Non-agricultural, carbonate rock (5 wells)	Agricultural, non-carbonate rock (4 wells)	Non-agricultural, non-carbonate rock (6 wells)
Percentage exceeding maximum contaminant level (10 milligrams per liter as N)				
Fall 1982	46	40	0	0
Spring 1983	48	60	0	0
Summer 1983	75	40	25	33
Fall 1983	54	40	0	0
Percentage containing detectable concentrations of total atrazine (greater than or equal to 0.2 microgram per liter)				
Spring 1983	36	0	0	0
Summer 1983	46	0	0	0
Fall 1983	39	20	0	0

[1]U.S. Environmental Protection Agency, 1992.

Ground-water quality at both field sites also was affected by the carbonate-aquifer mineralogy and surficial applications of fertilizer and herbicides. Dissolved nitrate concentrations in water samples from wells at Field-Site 1 during the pre-BMP study period (January 1983–September 1984) ranged from 5.6 to 34 mg/L as N, and at Field-Site 2 during the pre-BMP period (October 1984–September 1986) ranged from 7.4 to 130 mg/L as N (fig. 8). Dissolved nitrate accounted for more than 90 percent of the total nitrogen in ground-water samples from both field sites. The median dissolved phosphorus concentration in samples from wells at both field sites for the pre-BMP period was less than or equal to 0.10 mg/L as P. When atrazine, metolachlor, or cyanazine were applied at Field-Site 1, they generally were detected in ground water at maximum concentrations (1.7, 0.6, and 1.6 µg/L, respectively) during the first recharge period after application; atrazine was persistent throughout most of the year in ground water (fig. 9). (Ground water at Field-Site 2 was not sampled for herbicides.)

Two types of recharge were thought to occur at the field sites: (1) Direct recharge through soil macropores, such as wormholes, near-surface fractures, and sinkholes; and (2) gradual recharge through soil micropores—small channels and pore spaces in the unsaturated zone (Gerhart, 1986). Variations in nitrate and herbicide concentrations during recharge and nonrecharge periods are evidence that at least some precipitation and associated chemical constituents from a storm reached the ground water as recharge during a single storm and that surface-applied materials can affect ground water in carbonate areas. Nitrate concentrations in ground water substantially increased or decreased within 2 to 3 days after storms, continued to change during the recharge period, and returned within 1 to 2 weeks to about the same concentrations as detected before the recharge period. Changes in dissolved nitrate concentrations in samples collected between recharge periods lagged changes in nitrate concentration that were measured during the recharge period by several months (fig. 10). This relation is illustrated by data collected from a well at Field-Site 1 from March through August 1984, a period that includes two sampled recharge events, in late March and late May 1984. From January through March, only about 250 lb of nitrogen had been applied to the site as manure. Nitrate concentration in water from the well

Table 15. Percentage of wells in which detectable concentrations of selected herbicides were found in three samplings (spring, summer, and fall 1983), by rock type and land-use setting, Conestoga River Headwaters, Pennsylvania

[Conc., concentrations; µg/L, micrograms per liter; Max, maximum; DL, detection limit; <, less than; ≥, greater than or equal to]

Herbicides	Agricultural, carbonate rock (27 wells and 1 spring, 84 samples)		Nonagricultural, carbonate rock (5 wells, 15 samples)		Agricultural, noncarbonate rock (4 wells, 12 samples)	Nonagricultural, noncarbonate rock (6 wells, 18 samples)
	Percentage	Max conc. (µ/gL)	Percentage	Max conc. (µ/gL)	Percentage	Percentage
Total atrazine[1] (DL ≥ 0.2)	41	3.0	7	0.2	0	0
Total alachlor[1] (DL ≥ 0.05)	12	3.0	0	<.05	0	0
Total metolachlor[1] (DL ≥ 0.1)	7	.4	<.1	0	0	0

[1]The lifetime health advisory levels are atrazine, 3 µg/L; alachlor, 2 µg/L; and metolachlor, 100 µg/L (U.S. Environmental Protection Agency, 1992).

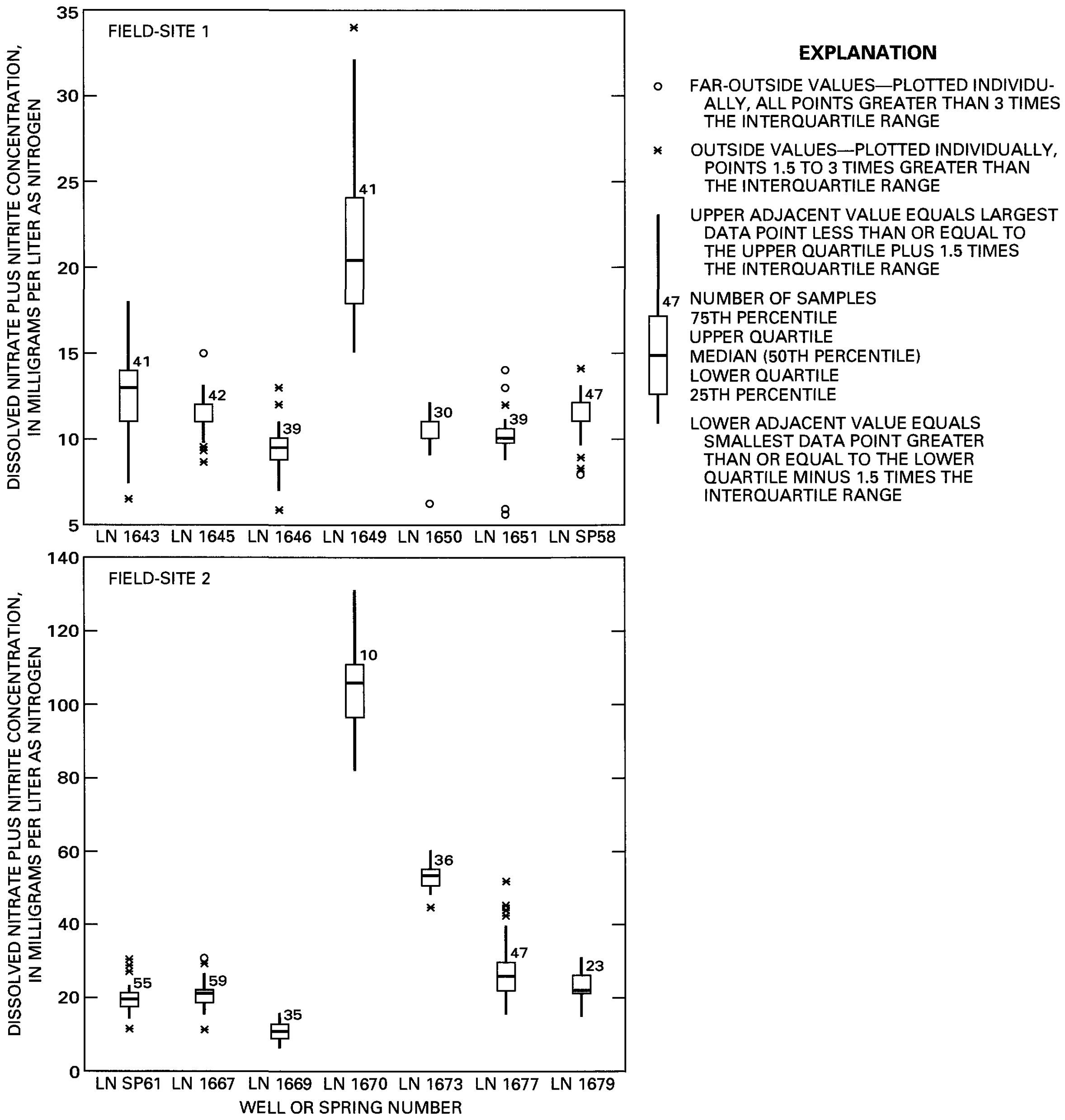


Figure 8. Distribution of dissolved nitrate plus nitrite concentrations in samples of spring and well water before implementation of best-management practices at Field-Site 1 (January 1983–September 1984) and Field-Site 2 (October 1984–October 1986), Conestoga River Headwaters, Pennsylvania.

decreased substantially during the March recharge event. The next sample, collected at a lower water level in early May, contained nitrate at a concentration near the minimum detected during the recharge period. In April and May, about 1,250 lb of manure nitrogen had been applied to the site. Nitrate concentrations in water from the well increased during the late-May recharge event. The sample collected at a lower water level in July reflected the maximum concentration detected during the recharge period (Gerhart, 1986). Data from wells at Field-Site 2 were similar to those for Field-Site 1 (D.C. Chichester, U.S. Geological Survey, written commun., 1985). In addition, atrazine, which had been below detection limits before application, was detected in wells at Field-Site 1 within 1 day of the first water-level rise after surface application (fig. 11) and was present in most subsequent samples collected during the growing season.

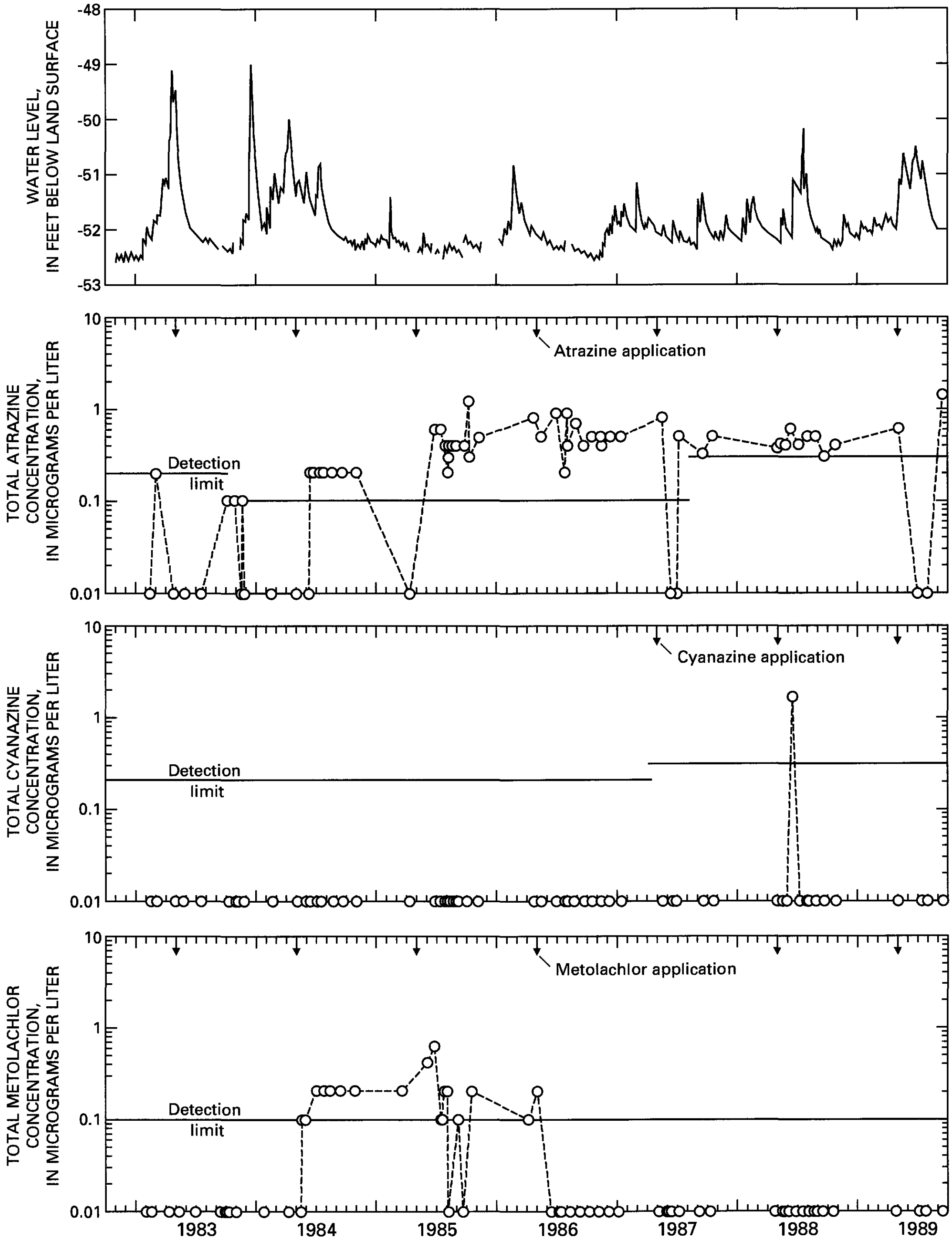


Figure 9. Water levels and herbicide concentrations in water from well LN 1645 at Field-Site 1, Conestoga River Headwaters, Pennsylvania. (Detection limits changed based on changes in laboratory instrumentation.)

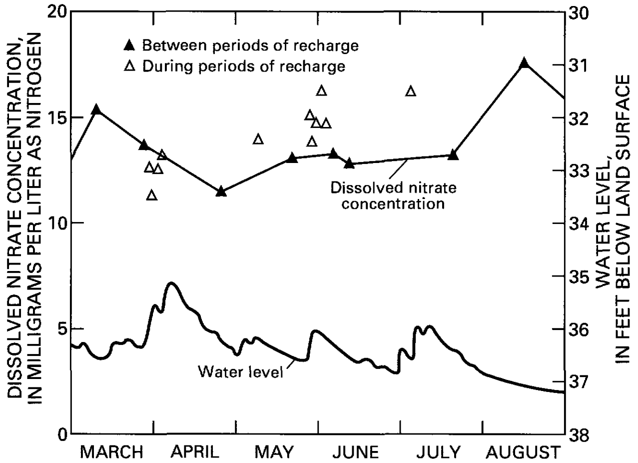


Figure 10. Water levels and dissolved nitrate concentrations in water samples collected from well LN 1643 at Field-Site 1, Conestoga River Headwaters, Pennsylvania, March–August 1984. (From Gerhart, 1986.)

Streamflow and Surface Runoff

Streamflow characteristics were similar at the regional stream sites that drained areas half underlain by carbonate rock, Conestoga River near Terre Hill (USGS station 01576105) and Little Conestoga Creek near Churchtown (USGS station 01576085) at the mouth of the Small Watershed (fig. 2). Streamflow varied seasonally at all monitored sites. In general, base flow was highest during the spring ground-water recharge period and lowest in late summer and early fall. Small storms produced runoff when the ground was frozen, but much larger storms did not produce measurable runoff when the crops were well established by the middle of the summer. This was evident at Field-Site 1, where as little as 0.1 in. of rain produced runoff on frozen ground in February 1984 and as much as 1.1 in. of rain produced no runoff in June 1983. When the crops were well established, the canopy reduced raindrop impact, roots and stalks intercepted the rain, and evapotranspiration was maximum. At all sites, large spring storms, which occurred before plowing, and high-intensity summer thunderstorms produced large amounts of runoff.

In the Small Watershed, streamflow response to precipitation was generally rapid. Discharges from the Nutrient-Management Subbasin typically peaked within 1 hour of periods of maximum precipitation intensities. Storm discharge at the mouth of the Small Watershed peaked about 0.5 hours after discharge from the Nutrient-Management Subbasin peaked. Peak stormflows in this stream were greater than base flows by one to three orders of magnitude. Stormflows subsided within 24 to 48 hours after rainfall ended. Streamflow averaged about 15 in., or 40 percent of precipitation during the

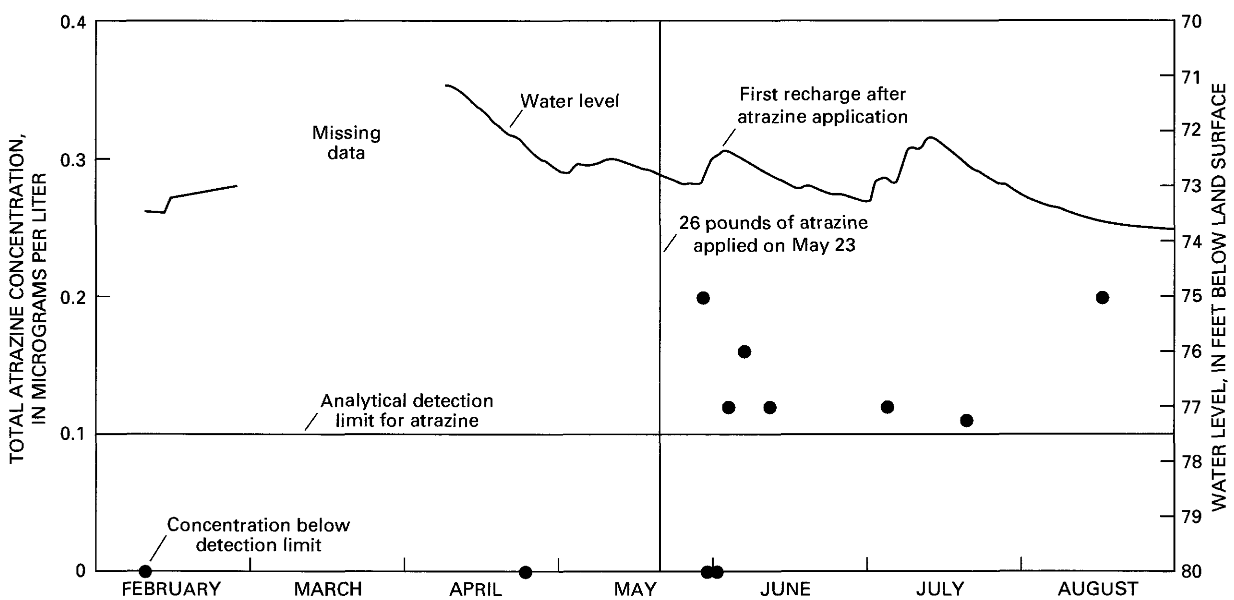


Figure 11. Atrazine concentrations in water samples from well LN 1650 at Field-Site 1, Conestoga River Headwaters, Pennsylvania, before and after May 23, 1984, application. Samples with concentrations below the detection limit are plotted on the X axis. (From Lietman and others, 1997.)

pre-BMP period (April 1984–March 1986); about 43 percent of annual streamflow was stormflow. The maximum discharge from the Nutrient-Management Subbasin was 283 ft^3/s, or 0.32 (ft^3/s)/acre, and from the Small Watershed Basin was 997 ft^3/s, or 0.27 (ft^3/s)/acre; maximum discharges from both basins were recorded during summer thunderstorms.

Although streamflow from the two sites in the Small Watershed reacted similarly to storms, large differences in runoff from individual fields caused by varying slopes, crops, tillage practices, and conservation practices such as grassy waterways or terraces, were evident from runoff data from the two intensive-monitoring field sites. Field-Site 1, during the pre-BMP period (January 1983–September 1984), was conventionally tilled on about a 6-percent slope without conservation practices. At Field-Site 1, very small storms (0.1–0.4 in. of rain) commonly produced runoff through gullies. Numerous flashy peaks in the hydrograph indicate runoff of varying intensity throughout the storm. The numerous runoff peaks also indicate that runoff from various parts of the field—the cornfield upgradient from the alfalfa strip, the alfalfa field, and the cornfield downgradient from the alfalfa strip (average slope, 6 percent)—reached the gaging station at the lower edge of the field at different times. During the 21-month pre-BMP period, 97 storms produced runoff at Field-Site 1; the maximum discharge was 26 ft^3/s [1.2 (ft^3/s)/acre] during an early summer thunderstorm. Annual runoff averaged about 10 percent of precipitation. For storms on thawed soil, total runoff amounts increased as total precipitation amounts and antecedent soil moisture increased; runoff rates also increased as precipitation intensities and antecedent soil moisture increased. Additionally, crop cover affected all runoff variables, probably because of interception of rainfall and increased evapotranspiration rates (Lietman and others, 1997). Storms on frozen soil reacted differently; however, data were insufficient to explore relations between runoff and precipitation variables.

The 27-acre portion of Field-Site 2 that was monitored for runoff was primarily cropped with no-till corn on a well-established pipe-outlet terrace system (average slope, 5 percent). Any runoff bypassing the terraces drained through a grassy waterway. The hydrograph generally consisted of a sharp rise, a single peak, and a gradual recession. Runoff was infrequent at Field-Site 2 and was about 1.2 percent of precipitation. During the 24-month pre-BMP period (a different time period from that at Field-Site 1), 36 storms of 0.5 in. or more produced measurable runoff. The maximum discharge was 1.6 ft^3/s [0.058 (ft^3/s)/acre] during a storm in February 1985 on snow-covered, frozen ground, which produced 79 percent of the 1985 annual runoff. Five storms under similar conditions in 1986 produced 46 percent of the 1986 annual runoff. One intense thunderstorm in July 1986 produced 46 percent of the 1986 annual runoff. Similar to Field-Site 1, total storm discharge at Field-Site 2 depended primarily on total storm precipitation and antecedent soil moisture, and the relation between discharge and precipitation differed for thawed and frozen soil (Koerkle and others, 1996a).

The water-quality characteristics of base flow generally reflected ground-water-quality characteristics. Base flow of streams in the regional study area that drained areas half underlain by carbonate rock (Conestoga River near Terre Hill, Pa., USGS station 01576105, and Little Conestoga Creek near Churchtown, Pa., at the mouth of the Small Watershed, USGS station 01576085; fig. 2) generally had higher specific conductances, alkalinities, hardness, and concentrations of calcium and magnesium than base flow of streams draining nearly all noncarbonate rock areas (Muddy Creek near Martindale, Pa., USGS station 01576240, and Cocalico Creek near Ephrata, Pa., USGS station 01576330). In addition, nitrate concentrations were higher and herbicide concentrations were more frequently detected in base flow of the streams flowing through primarily agricultural, carbonate areas (figs. 12 and 13) than through primarily nonagricultural, noncarbonate areas of the regional study area. Intensive agricultural land use provides a large source of nitrates. Rapid water movement through the permeable soils and fractured carbonate bedrock provides a mechanism for transport of highly soluble nitrate to the ground-water system.

A more detailed characterization of water quality within the drainage area of the Little Conestoga Creek site, as part of the Small Watershed study, produced similar results. During the 2-year, pre-BMP characterization period (April 1984–March 1986), the median nitrate concentration in base flow was 2.7 mg/L as N at the most upstream site (015760831)

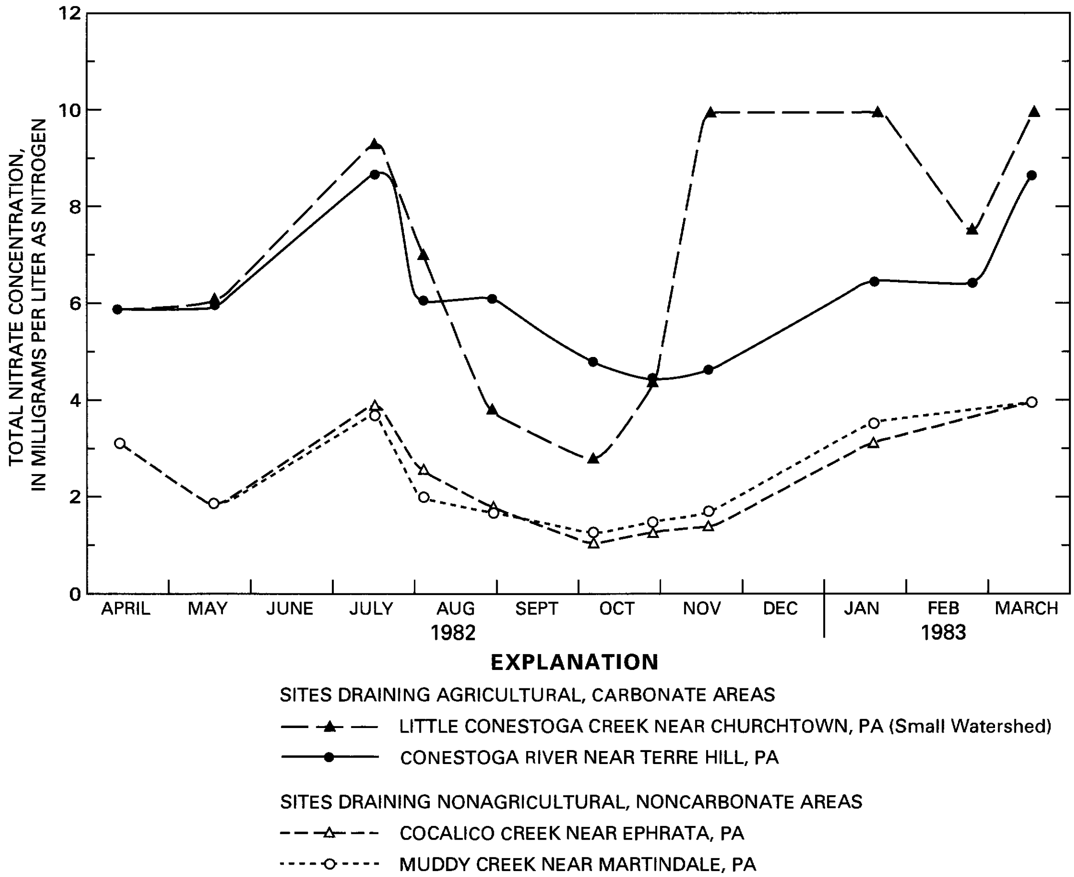


Figure 12. Total nitrate concentrations in base-flow samples from regional surface-water sites, Conestoga River Headwaters, Pennsylvania.

in the nonagricultural, noncarbonate area; 8.1 mg/L as N at the site in the agricultural, carbonate area draining the nutrient-management subbasin (0157608335); and 7.0 mg/L as N in the Little Conestoga Creek at the most downstream site in the Small Watershed (01576085) (fig. 3). Similarly, nitrate concentrations in ground water from the agricultural, carbonate areas of the Small Watershed were generally higher than in ground water from the nonagricultural, noncarbonate areas of the Small Watershed, frequently exceeding the drinking-water MCL of 10 mg/L as N. The median concentrations of total phosphorus in base flow were 0.04 mg/L as P in the nonagricultural, noncarbonate area; 0.14 mg/L at the site draining the Nutrient-Management Subbasin; and 0.16 mg/L at the mouth of the Small Watershed. In the agricultural areas, nearly all the pastures are adjacent to streams, and cattle have direct access to the streams. Sources of nitrogen and phosphorus to the stream in addition to ground-water discharge of nitrate were manure, which livestock deposited directly into streams, nutrient-rich streambank sediments from cattle trampling the banks, and nutrient-laden sediments deposited into the streams by surface runoff.

Distinct seasonal variation was evident in the concentrations of dissolved nitrate and total phosphorus in base flow in the Small Watershed. Dissolved nitrate concentrations were greatest in the winter and least in the summer. In contrast, total phosphorus concentrations were greatest during the summer and least in the winter (fig. 14). The primary mechanisms causing this variation are seasonal fluctuations of base-flow discharge and dissolved oxygen concentrations in the stream. During the summer, when base flow is lowest, it is sustained primarily by the regional ground-water system, which has a lower dissolved nitrate concentration than does the shallow ground-water system near the stream.

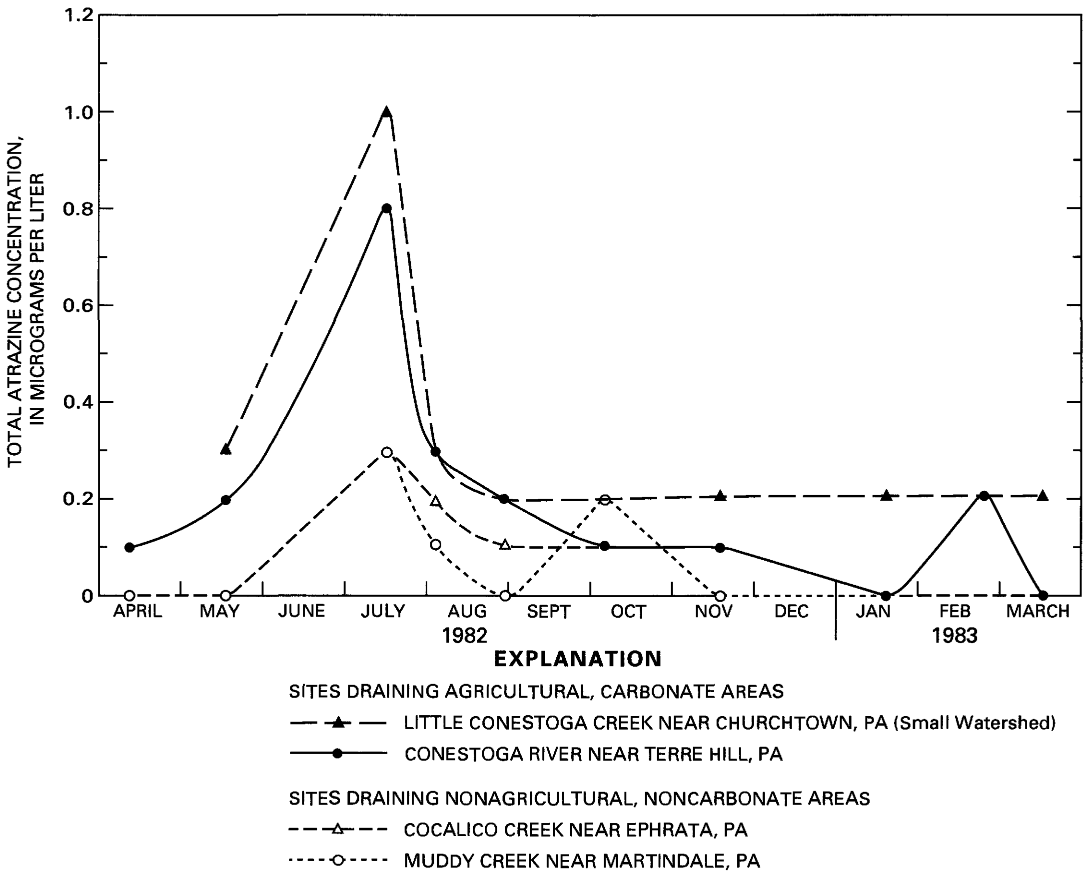


Figure 13. Total atrazine concentrations in base-flow samples from regional surface-water sites, Conestoga River Headwaters, Pennsylvania.

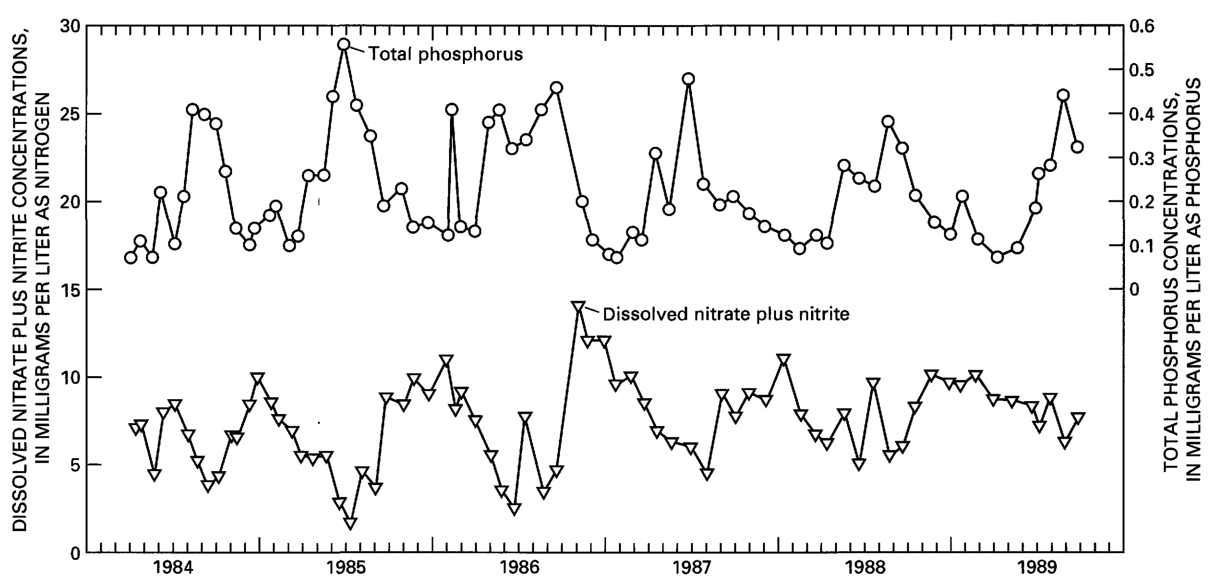


Figure 14. Time series of dissolved nitrate plus nitrite and total phosphorus concentrations in base flow from the Small Watershed, Conestoga River Headwaters, Pennsylvania, April 1984–October 1989. (Modified from Koerkle and others, 1996a.)

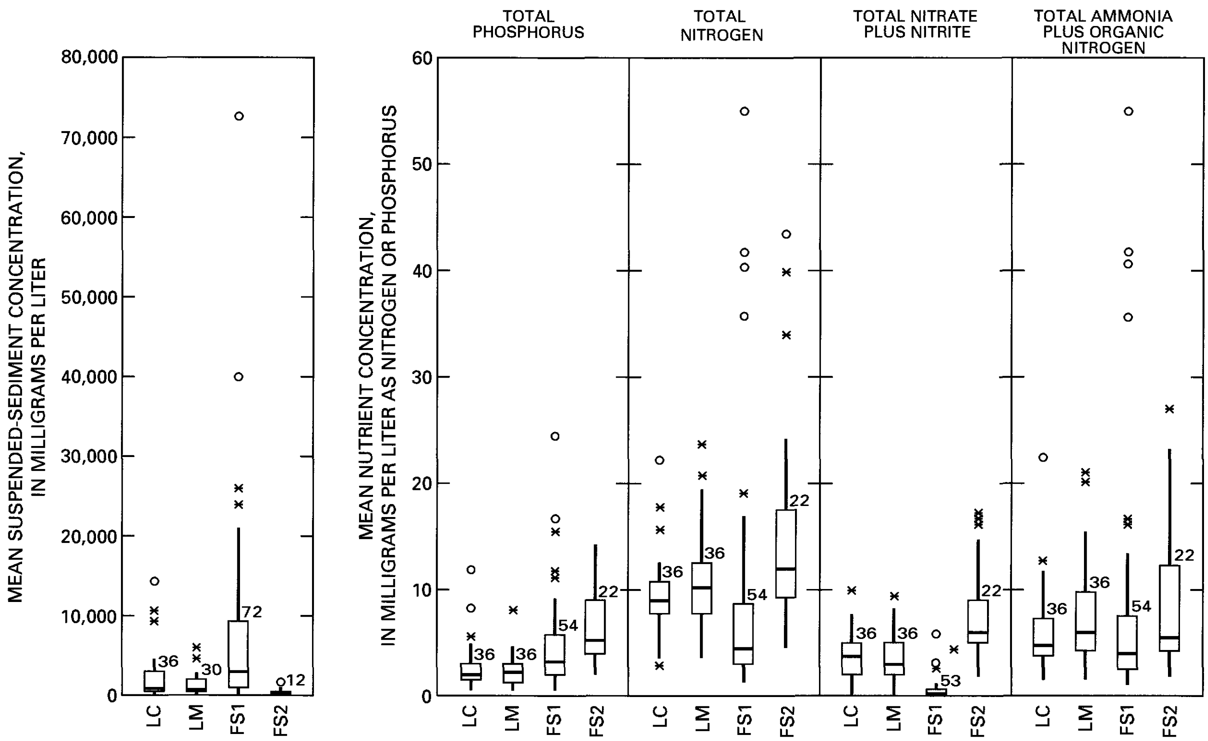
In addition, biological activity is greatest during the summer when much of the oxygen in the stream sediments is consumed, resulting in reducing conditions in the sediments. Under these conditions, nitrate can be reduced to nitrogen gas, which is lost to the atmosphere, and phosphorus can be released from streambed sediments to the water column (Wetzel, 1975). Low streamflows create less dilution of the released phosphorus than do higher flows. Flow dependency of dissolved nitrate plus nitrite and total phosphorus in base flow from the Small Watershed has been reported by Koerkle and others (1996a). At the outlet of the Small Watershed, dissolved nitrate plus nitrite concentrations increased with increased base-flow discharge to about 5 ft^3/s. Base-flow discharge greater than 5 ft^3/s did not affect nitrate concentrations. Conversely, total phosphorus concentrations decreased with increased base-flow discharge up to about 8 ft^3/s, at which point phosphorus concentrations were near the detection limit and similar to phosphorus concentrations in ground water.

The herbicides detected most frequently in base flow both for the Nutrient-Management Subbasin and the Small Watershed were atrazine and simazine; maximum concentrations were 0.8 and 2.8 µg/L, respectively. Cyanazine, metolachlor, and alachlor also were detected in base flow. The maximum concentrations of these compounds were recorded after early growing-season applications to the soil surface; concentrations did not correlate with base-flow discharge.

After the onset of stormflow, instantaneous concentrations of total nitrate plus nitrite in the stream decreased rapidly, and concentrations of total ammonia plus organic nitrogen, total phosphorus, and suspended sediment increased rapidly in the Small Watershed. For most storms, the maximum nutrient concentrations were slightly lower at the mouth of the Small Watershed than at the mouth of the Nutrient-Management Subbasin. The largest suspended-sediment and nutrient concentrations in the Small Watershed during the pre-BMP period were recorded in May, shortly after plowing and the largest annual application of crop fertilizers. Maximum instantaneous concentrations of suspended sediment, total nitrogen, and total phosphorus were 16,700 mg/L, 34 mg/L, and 20 mg/L, respectively, for the Nutrient-Management Subbasin and 34,300 mg/L, 28 mg/L, and 17 mg/L, respectively, for the Small Watershed. The type and amount of herbicides detected in stormflow were similar for the Nutrient-Management Subbasin and the Small Watershed. Maximum concentrations of total metolachlor (250 µg/L), total atrazine (210 µg/L), total alachlor (85 µg/L), and total cyanazine (200 µg/L) were detected in May soon after application; the maximum concentration of total simazine (21 µg/L) was detected in July 1984.

The maximum instantaneous concentrations of total nitrogen and phosphorus in runoff at the field sites were considerably higher than those detected during stormflow in the Small Watershed; maximum total nitrogen and total phosphorus concentrations were 79 and 30 mg/L, respectively, at Field-Site 1 and 64 and 44 mg/L, respectively, at Field-Site 2. Concentrations of these constituents varied widely in response to agricultural and climatic factors. The maximum suspended-sediment concentration in runoff samples from Field-Site 1 was 74,000 mg/L. At Field-Site 1, large sediment concentrations were common during peak discharges. Sparse ground cover, gully erosion on steep slopes, and conventional tillage across gullies in the spring provided large quantities of readily available sediment for transport with runoff. During one storm alone, edge-of-field losses amounting to 50 tons of sediment were measured at Field-Site 1. In contrast, at Field-Site 2, where no-till practices maintained ground cover throughout the year and pipe-outlet terraces were well established, the maximum suspended-sediment concentration was 2,800 mg/L. Herbicides applied to Field-Site 1 were present in runoff, and the largest concentrations were detected in runoff from the first sampled storms after application (73 µg/L of total atrazine and 84 µg/L of total metolachlor). Herbicide concentrations in runoff decreased through the growing season.

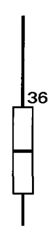
The distribution of mean concentrations of suspended sediment and nutrients discharged in stormflow from the Nutrient-Management Subbasin and the Small Watershed and of mean storm concentrations in runoff from the two field sites during the pre-BMP periods are shown in figure 15. Mean storm concentrations from the Nutrient-Management Subbasin and the Small Watershed were not significantly different. Because the pre-BMP periods are different for the field sites, no direct comparison of concentrations between sites was made; however, the data indicate that variation in mean storm concentrations of nutrients in edge-of-field runoff generally is greater than that of instream runoff concentrations (fig. 15). Because streamflow integrates runoff with base flow, concentrations of nutrients and suspended sediment are modified, especially for small storms. The data also indicate that conservation practices such as those at Field-Site 2 can dramatically reduce suspended-sediment concentrations in edge-of-field runoff.



EXPLANATION

o FAR-OUTSIDE VALUES—PLOTTED INDIVIDUALLY, ALL POINTS GREATER THAN 3 TIMES THE INTERQUARTILE RANGE

⁎ OUTSIDE VALUES—PLOTTED INDIVIDUALLY, POINTS 1.5 TO 3 TIMES GREATER THAN THE INTERQUARTILE RANGE



UPPER ADJACENT VALUE EQUALS LARGEST DATA POINT LESS THAN OR EQUAL TO THE UPPER QUARTILE PLUS 1.5 TIMES THE INTERQUARTILE RANGE

NUMBER OF SAMPLES
75TH PERCENTILE
UPPER QUARTILE
MEDIAN (50TH PERCENTILE)
LOWER QUARTILE
25TH PERCENTILE

LOWER ADJACENT VALUE EQUALS SMALLEST DATA POINT GREATER THAN OR EQUAL TO THE LOWER QUARTILE MINUS 1.5 TIMES THE INTERQUARTILE RANGE

LC MOUTH OF SMALL WATERSHED

LM MOUTH OF NUTRIENT-MANAGEMENT SUBBASIN

FS1 FIELD-SITE 1

FS2 FIELD-SITE 2

Figure 15. Distribution of mean suspended-sediment and nutrient concentrations in stormflow at the mouth of the Small Watershed, the mouth of the Nutrient-Management Subbasin, and in runoff at Field-Sites 1 and 2 before implementation of agricultural best-management practices, Conestoga River Headwaters, Pennsylvania.

Total annual flow and yields of suspended sediment, total phosphorus, and total nitrogen for all monitored sites within the Conestoga River Headwaters are shown in table 16. For comparison, data are presented for the Conestoga River at Conestoga (470 mi^2) (Lloyd A. Reed, U.S. Geological Survey, written commun., 1990), a downstream station draining areas of similar agricultural practices and about 50 percent underlain by carbonate rock, and for Pequea Creek at Martic Forge (Lietman and others, 1983), an adjacent basin similar in agricultural practices and about 50 percent underlain by carbonate rock. For reference, data are included for the Susquehanna River, the receiving stream for the Conestoga River, and for two forested, noncarbonate basins, Stony Creek near Dauphin, Pa., and Young Womans Creek near Renovo, Pa. (Lloyd A. Reed, U.S. Geological Survey, written commun., 1990) (fig. 16).

Estimates of annual yields in the Conestoga River near Terre Hill (which drains a 49-mi^2 agricultural area that is about 50 percent underlain by carbonate rock) from May 1982 through April 1983 indicated that (1) base flow was about 75 percent of the total streamflow; (2) about 94 percent of the suspended-sediment yield and 73 percent of the total phosphorus yield were discharged in stormflow; and (3) about 67 percent of the total nitrogen yield was discharged during base flow and was predominantly nitrate (table 16).

Similarly, estimates of annual yields in the Little Conestoga Creek near Churchtown at the mouth of the Small Watershed (5.8 mi^2, agricultural, 50 percent carbonate rock) and the Little Conestoga Creek near Morgantown at the mouth of the Nutrient-Management Subbasin (1.4 mi^2, agricultural, 50 percent carbonate rock) from April 1984 through March 1986 showed that at both sites (1) base flow was about 60 percent of the total streamflow; (2) more than 98 percent of the suspended-sediment yield and about 85 percent of the total phosphorus yield were discharged in stormflow; and (3) about 65 percent of the total nitrogen yield was discharged during base flow and was predominantly nitrate (table 16). For the Nutrient-Management Subbasin, about 5 percent of the phosphorus and 20 percent of the nitrogen applied to the fields were discharged in streamflow.

Estimates of annual runoff and ground-water yields for the pre-BMP periods were calculated for the field sites. At Field-Site 1, about (1) 82 percent of the water discharged from the site was ground water; (2) 100 percent of the suspended-sediment yield and 97 percent of the total phosphorus yield were discharged with runoff; and (3) 88 percent of the total nitrogen yield was from ground water, predominantly as nitrate (table 16). At Field-Site 2, about (1) 98 percent of the water discharged from the site was ground water; (2) 100 percent of the suspended-sediment yield and 70 percent of the total phosphorus yield were discharged with runoff; and (3) 99 percent of the total nitrogen yield was from ground water, predominantly as nitrate (table 16). In general, for the same years (1985–88 water years), runoff amounts were substantially higher and ground-water discharge was substantially lower at Field-Site 1 than at Field-Site 2. Total nutrient yields also were higher in runoff from Field-Site 1 than from Field-Site 2, whereas total nitrogen yields were higher in ground water from Field-Site 2. Dissolved phosphorus concentrations in ground water were not measured during the same years at both sites. The annual estimated suspended-sediment load from runoff during 1984 was 11 ton/acre at Field-Site 1, far exceeding the maximum erosion rate (T) of 4 ton/acre recommended by the NRCS. Mean event suspended-sediment concentrations in runoff were substantially lower for Field-Site 2 than for Field-Site 1 (fig. 15). Although suspended-sediment yields were not calculated for Field-Site 2 because of insufficient data, they would have been much lower than those from Field-Site 1, and well below T.

Runoff from storms on frozen ground produced the largest loads of nitrogen in runoff at both field sites. At Field-Site 1, runoff from four rain-on-snow or snowmelt storms made up 12 percent of the total runoff and contributed 31 percent of the estimated total nitrogen load for the 21-month pre-BMP period. At Field-Site 2, two storms on snow-covered, frozen ground in February 1985 accounted for 58 and 61 percent of the total nitrogen and total phosphorus loads in runoff, respectively, for the 2-year pre-BMP period.

Table 16. Streamflow, surface runoff, or ground-water flow, and yields of suspended sediment, phosphorus, and nitrogen for sites within and outside the Conestoga River Headwaters, Pennsylvania

[Mgal/acre, million gallons per acre; lb, pounds; lb/acre, pounds per acre; mi^2, square miles; --, no data]

Period	Flow		Suspended sediment		Total phosphorus		Total nitrogen	
	Total flow (Mgal/acre)	Percentage as base flow	Total yield (ton/acre)	Percentage in base flow	Total yield (lb/acre)	Percentage in base flow	Total yield[3] (lb/acre)	Percentage in base flow
Little Conestoga Creek near Churchtown (5.8 mi^2, 50 percent carbonate, 68 percent agricultural) (Small Watershed)								
April 1984–March 1985	0.48	58	1.7	2	2.9	12	31 (71)	65
April 1985–March 1986	.35	55	1.0	2	3.1	11	24 (69)	65
April 1986–March 1987	.35	63	.55	3	1.7	20	25 (81)	78
April 1987–March 1988	.47	55	1.4	2	4.5	9	31 (71)	64
April 1988–March 1989	.44	63	1.9	2	4.2	11	37 (65)	57
April 1989–September 1989	.37	59	1.8	2	3.9	9	34 (60)	51
Little Conestoga Creek near Morgantown (subbasin of the above site) (1.4 mi^2, 50 percent carbonate, 78 percent agricultural) (Nutrient-Management Subbasin)								
April 1984–March 1985	0.34	57	0.64	4	2.2	17	22 (72)	65
April 1985–March 1986	.32	66	.34	5	2.0	11	23 (71)	73
April 1986–March 1987	.21	62	.31	2	1.4	5	14 (79)	74
April 1987–March 1988	.34	57	1.1	1	3.0	10	22 (69)	64
April 1988–March 1989	.30	65	.64	5	2.5	20	22 (62)	63
April 1989–September 1989	.27	63	.36	8	1.7	13	18 (71)	64
Conestoga River near Terre Hill (49.2 mi^2, 50 percent carbonate, 50 percent agricultural)								
May 1982–April 1983	0.50	75	1.0	6	2.3	27	34 (--)	67
Conestoga River at Conestoga[1] (470 mi^2, 50 percent carbonate, 63 percent agricultural)								
January 1985–December 1985	0.34	--	0.24	--	1.5	--	26 (80)	--
January 1986–December 1986	.53	--	.61	--	2.9	--	38 (76)	--
January 1987–December 1987	.47	--	.66	--	2.5	--	33 (78)	--
January 1988–December 1988	.51	--	.84	--	2.6	--	36 (76)	--
January 1989–December 1989	.62	--	.78	--	2.6	--	45 (77)	--
Pequea Creek at Martic Forge[2] (148 mi^2, 50 percent carbonate, 68 percent agricultural)								
January 1978–December 1978	0.69	71	2.8	--	5.3	--	44 (63)	--
January 1979–December 1979	.80	66	3.6	--	7.7	--	53 (54)	--
January 1980–December 1980	.35	92	.13	25	.45	47	20 (91)	80
Stony Creek at Dauphin[1] (21.9 mi^2, 0 percent carbonate, 0 percent agricultural)								
January 1985–December 1985	0.42	--	0.02	--	0.06	--	2.0 (--)	--
January 1986–December 1986	.63	--	.05	--	.22	--	3.8 (--)	--
Young Womans Creek at Renovo[1] (46.2 mi^2, 0 percent carbonate, 0 percent agricultural)								
January 1985–December 1985	0.51	--	0.04	--	0.06	--	2.7 (--)	--
January 1986–December 1986	.64	--	.11	--	.07	--	3.4 (--)	--
January 1987–December 1987	.42	--	.03	--	.04	--	2.3 (--)	--
January 1988–December 1988	.36	--	.10	--	.03	--	2.1 (--)	--
January 1989–December 1989	.55	--	.13	--	.04	--	3.1 (--)	--
Susquehanna River at Harrisburg[1] (24,100 mi^2, 5 percent carbonate, 23 percent agricultural)								
January 1985–December 1985	0.40	--	0.07	--	0.23	--	6.0 (--)	--
January 1986–December 1986	.54	--	.18	--	.48	--	7.9 (--)	--
January 1987–December 1987	.43	--	.10	--	.36	--	5.6 (--)	--
January 1988–December 1988	.35	--	.07	--	.26	--	4.5 (--)	--
January 1989–December 1989	.51	--	.13	--	.35	--	6.8 (--)	--

Table 16. Streamflow, surface runoff, or ground-water flow, and yields of suspended sediment, phosphorus, and nitrogen for sites within and outside the Conestoga River Headwaters, Pennsylvania—Continued

[Mgal/acre, million gallons per acre; lb, pounds; lb/acre, pounds per acre; mi², square miles; --, no data]

Period	Flow		Suspended sediment [1]		Total phosphorus		Total nitrogen	
	Surface runoff (Mgal/acre)	Ground water (Mgal/acre)	Surface runoff (ton/acre)	Ground water (ton/acre)	Surface runoff (lb/acre)	Ground water (lb/acre)	Surface runoff[3] (lb/acre)	Ground water (lb/acre)
Field-Site 1 (23.1 acres, 100 percent carbonate, 100 percent agricultural)								
January 1983–September 1983	0.028	0.40	0.70	--	1.0	0.40	1.8 (9)	36
October 1983–September 1984	.21	.68	11	--	7.0	.47	12 (8)	63
October 1984–September 1985	.18	.32	3.4	--	3.1	--	8.0 (32)	32
October 1985–September 1986	.13	.30	.83	--	2.9	--	6.3 (32)	32
October 1986–September 1987	.14	.46	.54	--	4.0	--	4.6 (39)	48
October 1987–September 1988	.16	.41	1.0	--	3.8	--	9.3 (36)	41
October 1988–July 1989	.042	.44	.28	--	1.3	--	3.4 (22)	43
Field-Site 2 (runoff based on 27 terraced acres, ground water based on 55 acres; 100 percent carbonate, 100 percent agricultural)								
October 1984–September 1985	0.017	0.33	--	--	1.0	0.14	2.3 (42)	93
October 1985–September 1986	.008	.65	--	--	.34	.14	.93 (56)	200
October 1986–September 1987	.008	.70	--	--	.31	--	.52 (57)	190
October 1987–September 1988	.036	.63	--	--	1.6	--	3.4 (31)	129
October 1988–September 1989	--	.70	--	--	--	--	--	140
October 1989–September 1990	--	.57	--	--	--	--	--	116

[1]Lloyd A. Reed, U.S. Geological Survey, written commun., 1990.
[2]Lietman and others, 1983.
[3]Percentage as nitrate in parenthesis.

The long contact time of melting snow with surface-applied manure and nutrient-rich soils allowed time for the nutrients to be dissolved before melting produced runoff. Additionally, nearly all rain on frozen ground became runoff and carried surficially thawed manure and topsoils.

The hydrologic and nutrient inputs and outputs from the two field sites (which both drain entirely agricultural, carbonate areas) were estimated for the pre-BMP periods (Koerkle and others, 1996b; Lietman and others, 1996). At Field-Site 1, about 42 percent of the precipitation was infiltration to ground water, and 10 percent was surface runoff. At Field-Site 2, about 53 percent of the precipitation was infiltration to ground water, and only 4 percent was surface runoff. The remaining part of precipitation at both field sites was primarily evapotranspiration. At both field sites, long-term water-level data indicate that recharge to ground water equals discharge from the site during a typical year. About 95 percent of the total nitrogen input to each of the field sites was from manure. About 20 percent of the nitrogen input to Field-Site 1 was estimated to have left the site in ground water and 2.5 percent in surface runoff. About 27 percent of the nitrogen input to Field-Site 2 left the site with ground water and less than 1 percent left in surface runoff. Most of the remaining nitrogen was accounted for by crop uptake and volatilization. Inputs and outputs of phosphorus at the sites were not examined in detail; however, about 5.5 percent of the phosphorus applied to Field-Site 1 was discharged in runoff, and 0.5 percent of the phosphorus applied to Field-Site 2 was discharged in runoff.

Total annual yields of suspended sediment, total phosphorus, and total nitrogen from agricultural areas underlain about 50 percent by carbonate rock were significantly higher than yields from forested, noncarbonate basins, where the source of surface nutrients was much smaller and ground cover was more dense (table 16; figs. 16 and 17).

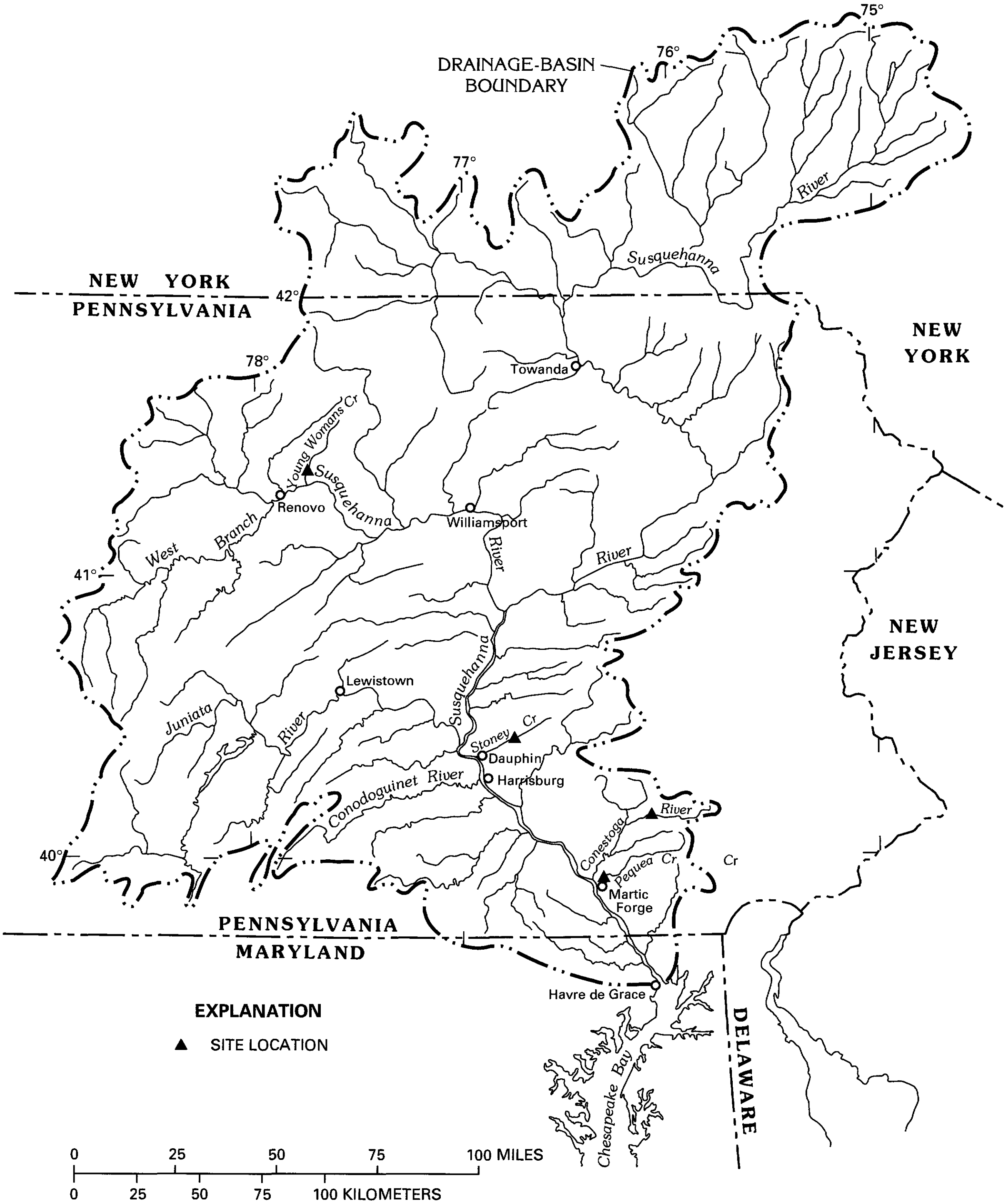


Figure 16. Location of selected sites in the Susquehanna River Basin where sediment- and nutrient-load data have been collected. (Modified from Fishel, 1984.)

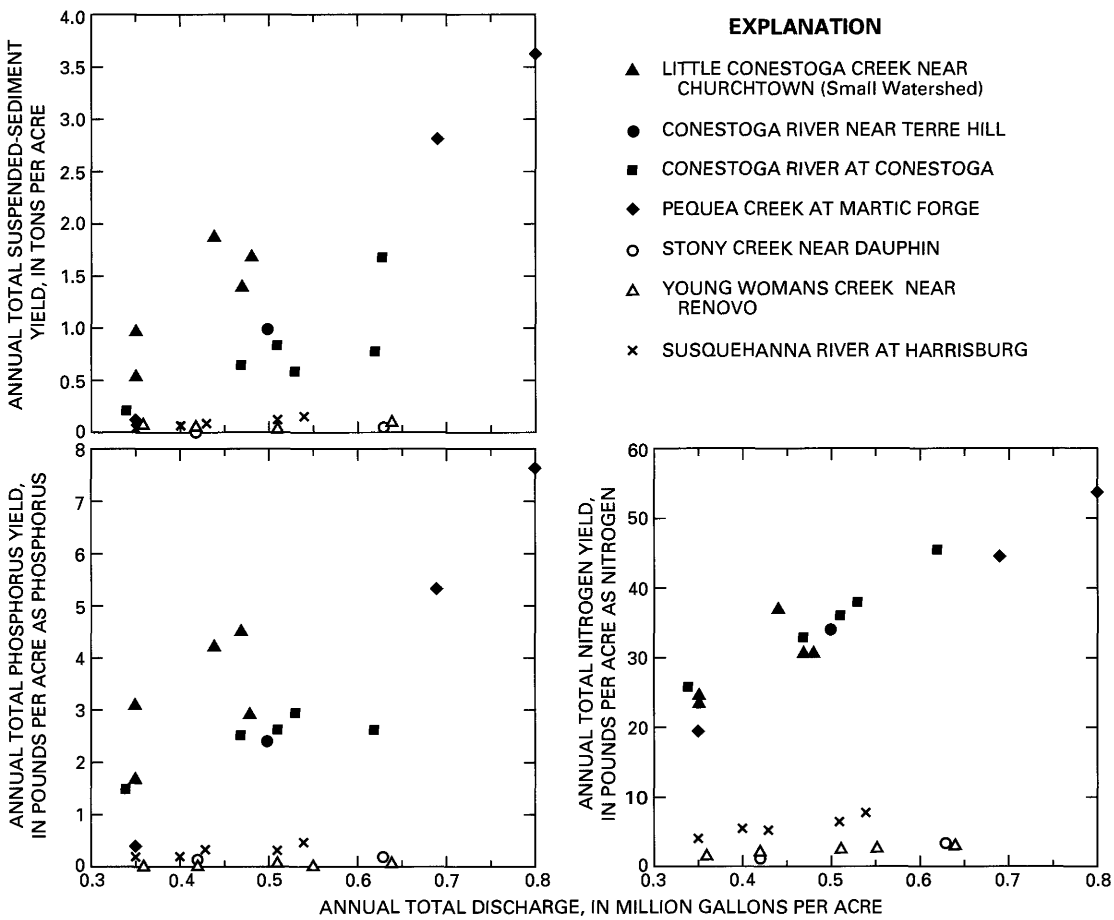


Figure 17. Relation of annual yields of suspended sediment, total phosphorus, and total nitrogen to annual discharge from selected sites in the Susquehanna River Basin, Pennsylvania.

Total sediment and nutrient yields from agricultural, carbonate basins also were substantially higher than yields in the receiving stream, as represented by data from the Susquehanna River at Harrisburg, about 40 mi upstream from the mouth of the Conestoga River (table 16; figs. 16 and 17).

Suspended-sediment yields per unit of discharge and, to a lesser extent, total phosphorus yields per unit of discharge from the agricultural, carbonate areas varied from basin to basin. In the Small Watershed, annual suspended-sediment yields per unit of discharge were higher than at any of the other stream sites. At the agricultural sites, suspended-sediment yields per unit of runoff increased as surface runoff became a larger part of total stormflow.

Nitrogen data are probably transferable from basin to basin within similar carbonate areas of the lower Susquehanna River Basin. Annual total nitrogen yields for comparable annual discharges were similar from site to site within the agricultural basins (table 16; fig. 17). Because most of the nitrogen load is in ground water, the surface features that control loads of suspended sediment and total phosphorus are not a predominant influence on nitrogen loads. Similar agricultural practices and soil and rock types throughout the area probably result in similar water quality.

The relation between annual total phosphorus and suspended-sediment yields is strong at the agricultural sites (fig. 18). This relation would be expected because phosphorus strongly sorbs to fine sediment particles readily transported with runoff. The relation between total nitrogen and suspended sediment also is strong for individual agricultural sites. However, there is less consistency in the relation between sites for nitrogen than phosphorus. Annual nitrogen yields were in the same range for all three agricultural sites, but sediment yields were substantially less for the Conestoga River at Conestoga (fig. 18; table 16). Because most of the total nitrogen load for all the sites is nitrate, which is highly soluble, changes in the sediment yield do not have as large an influence on the nitrogen yield as on the phosphorus yield.

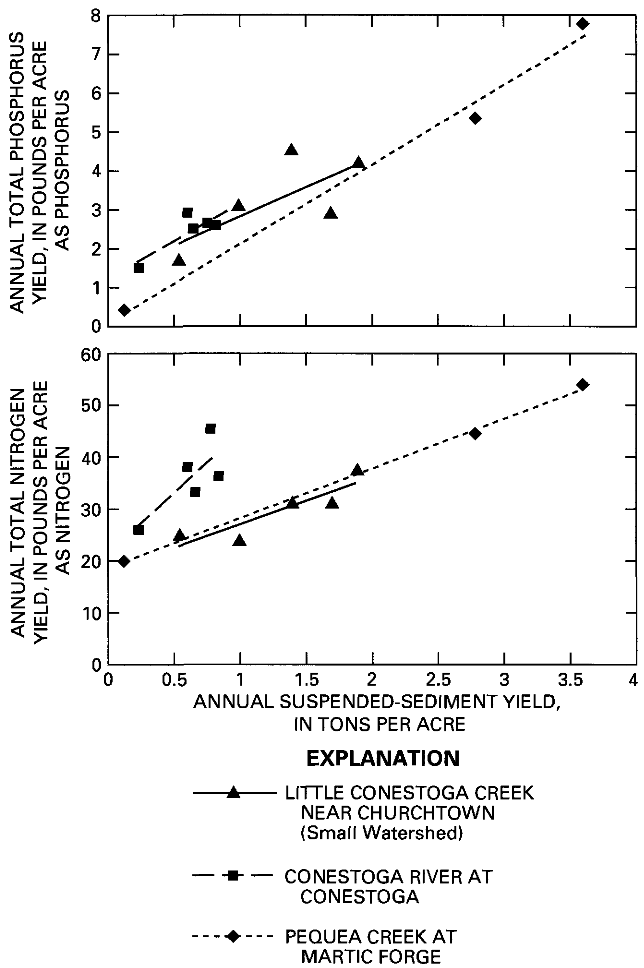


Figure 18. Relation and least-squares fit between annual yields of total phosphorus or total nitrogen and annual yield of suspended sediment from selected agricultural sites in the Susquehanna River Basin, Pennsylvania, predominantly underlain by carbonate rock.

EFFECTS OF SELECTED AGRICULTURAL BEST-MANAGEMENT PRACTICES ON WATER QUANTITY AND QUALITY

The effects of selected agricultural-management practices on surface- and ground-water quality were investigated at three locations. Quantitative analyses of the data and qualitative assessments were used to relate agricultural-activity data to water-quality data. Information presented in this section is based on detailed data analyses and interpretations from three intensive study areas—Field-Site 1, Field-Site 2, and the Small Watershed—reported in Lietman and others (1997), Hall and others (1997), and Koerkle and others (1996a), respectively.

Pipe-Outlet Terracing

Pipe-outlet terraces were constructed at Field-Site 1 to reduce soil erosion and to retain soil-associated nitrogen and phosphorus on the field. The objective was to prevent sediment and nutrients from being transported in runoff to nearby streams. Six pipe-outlet terraces, designed to accommodate a 5-in., 24-hour storm, were constructed in October and November 1984. Terraces were designed to trap runoff in ponds behind each terrace. The purpose of this design was to allow part of the suspended material in runoff to settle out in the temporary ponds and possibly to increase infiltration and decrease quantities of runoff leaving the site. The ponded runoff slowly drained into a perforated standpipe in each terrace and left the field through a solid outlet pipe, which extended from the most upgradient terrace to the base of the site.

Part of the terracing BMP planned for the site was the establishment of an alfalfa field on the steep slope downgradient from the first terrace. This alfalfa field became established 2 years after terrace construction (fig. 19).

Because the entire BMP plan was not fully implemented until 2 years after construction of the terraces, data from the third and fourth year after terrace construction (Period 3), and data from the 21-month pre-BMP period (Period 1) provided the best information for evaluation of the BMP. During the fifth and final year of the post-BMP monitoring, Period 4, the cropping pattern changed substantially (fig. 19).

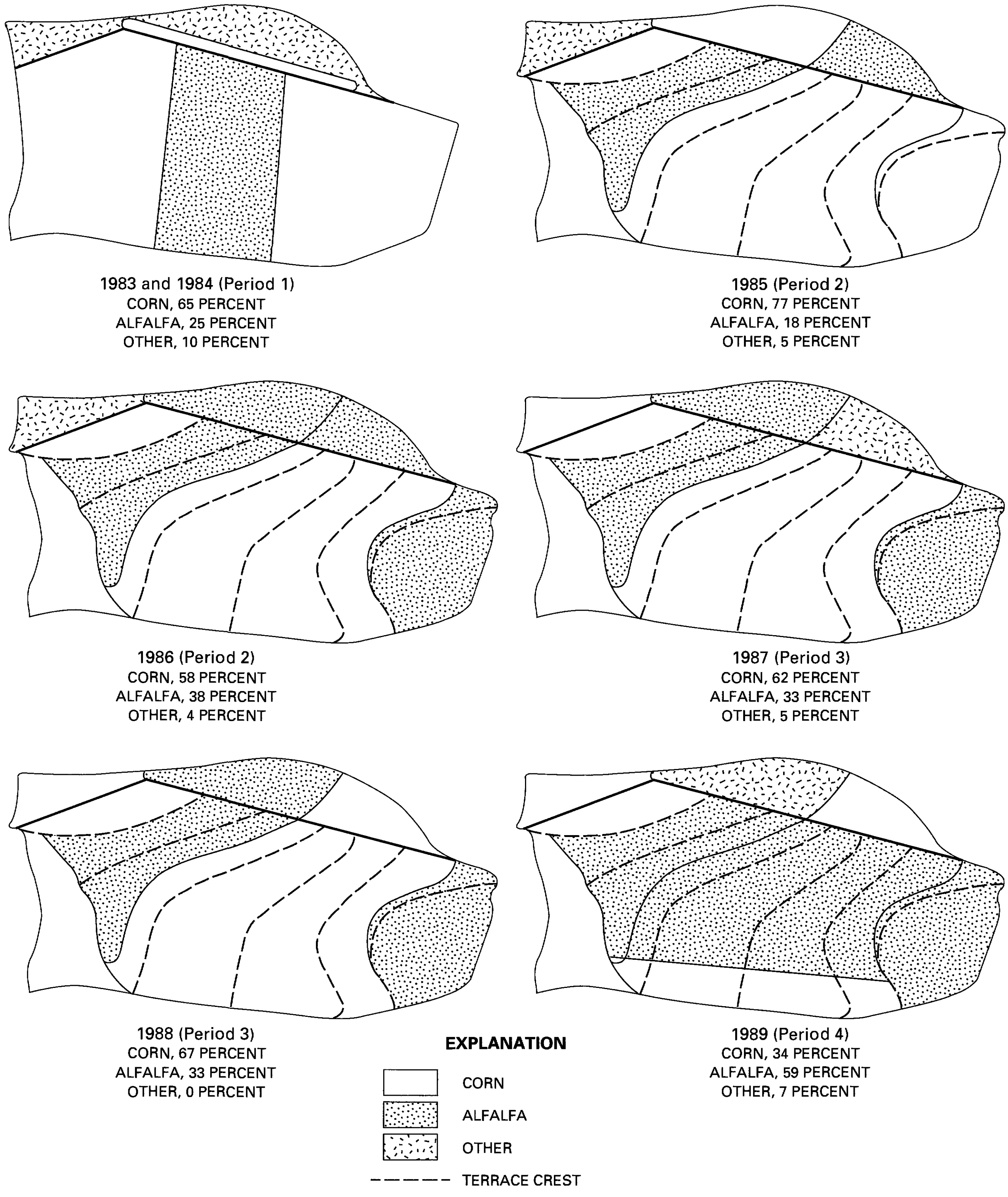


Figure 19. Cropping pattern at Field-Site 1, Conestoga River Headwaters, Pennsylvania. (From Lietman and others, 1997)

Period 3 was the post-BMP period most comparable to Period 1 (the pre-BMP period) with respect to precipitation (table 17), crops (fig. 19), and nutrient applications to the site (table 18). Periods 1 and 3 were climatologically similar; during each period, precipitation was about normal for 1 year of the 2 years and substantially above normal for the other year. The number of storms and the median quantity, duration, and intensities of precipitation were most similar between Periods 1 and 3. During each period, about 65 percent of the site was planted in corn. The corn planting and harvesting times were about the same for both periods, although a winter cover crop was planted during both years of Period 1 and little winter cover crop was planted during Period 3. The average annual application of nutrients to the site was about 270 lb/acre nitrogen and 70 lb/acre phosphorus during Period 1, and about 320 lb/acre nitrogen and 82 lb/acre phosphorus during Period 3.

No overall change in the partitioning of runoff and recharge quantities was measurable as a result of terracing, although the characteristics of runoff changed and the amount of precipitation required to produce runoff increased. Before terracing, surface runoff created small feeder gullies and larger receiving gullies throughout the field. The runoff hydrograph generally consisted of multiple sharp peaks reflecting varying storm intensities and traveltimes from various areas of the field. After terrace construction, runoff formed pools behind the six terraces, which slowly drained over periods of as much as 24 hours. The runoff hydrograph generally rose rapidly and then slowly decreased in a stepwise manner as each terrace drained. After terrace construction, the maximum instantaneous runoff discharges were controlled by restrictions of flow through the pipe-outlet system.

The relation between total storm runoff and total storm precipitation (fig. 20; table 19) did not significantly change for storms on thawed ground after terracing, according to results from an analysis of covariance test. (Data from storms on frozen ground were excluded in the data analysis because rainfall-runoff relations differed from those of other storms, and few data of this type were available for analysis.) Multiple regression analysis indicated that total storm runoff was primarily controlled by total storm precipitation and antecedent soil moisture before and after terraces were installed; however, storms with less than 0.4 in. of precipitation commonly produced runoff before terracing but rarely produced runoff

Table 17. Annual precipitation at Field-Site 1, Conestoga River Headwaters, Pennsylvania, and the 30-year mean from a nearby precipitation station at Morgantown, Pennsylvania

[From Lietman and others, 1997]

Period	Dates	Precipitation, in inches	
		Precipitation, Field-Site 1	30-year mean, Morgantown[1] (1951–80)
1	Jan. 1–Sept. 30, 1983	31.4	[2]31.9
	Oct. 1, 1983–Sept. 30, 1984	59.8	41.5
2	Oct. 1, 1984–Sept. 30, 1985	41.7	41.5
	Oct. 1, 1985–Sept. 30, 1986	35.6	41.5
3	Oct. 1, 1986–Sept. 30, 1987	46.2	41.5
	Oct. 1, 1987–Sept. 30, 1988	41.3	41.5
4	Oct. 1, 1988–July 31, 1989	40.2	[3]33.8

Period	Number of storms	Number of storms greater than 1.0 inch	Number of storms greater than 2.0 inches	Median quantity (inches)	Median duration (hours)	Median maximum 15-minute intensity	Median maximum 30-minute intensity
1	169	19	4	0.29	2.8	0.07	0.13
3	148	24	6	.33	3.4	.08	.10

[1]Data from the National Oceanic and Atmospheric Administration, 1985.
[2]Thirty-year mean for months of January through September.
[3]Thirty-year mean for months of October through July.

after terracing (fig. 20). Terracing (which changed the surface slopes) decreased runoff velocities, increased water-soil contact time, and increased surface storage. These factors promoted evaporation and soil wetting and delayed the onset of runoff; this delay was particularly apparent for small storms.

Table 18. Annual nutrient applications to Field-Site 1, Conestoga River Headwaters, Pennsylvania, by crop

[All values are in pounds per acre. From Lietman and others, 1997]

Period	Crop year	Corn		Alfalfa	
		Nitrogen	Phosphorus	Nitrogen	Phosphorus
1	1983	150	33	0	0
	1984	640	170	31	8
2	1985	230	61	9	15
	1986	290	72	7	12
3	1987	690	130	24	0
	1988	300	80	0	0
4	1989	540	160	290	84

Because many of the small storms did not produce runoff after terracing, use of all the storm data from each period could bias an analysis; therefore, the storms were additionally clustered by storm characteristics (amount, duration, and intensity), antecedent soil conditions, and crop cover for comparing storms before and after terracing. The data were divided into eight clusters (tables 20 and 21); however, only four clusters contained three or more storms each during Period 1 and Period 3, the minimum requirement for the statistical test (Mann-Whitney test) used for comparison. Large storms (generally greater than 0.6 in.) produced runoff during both periods. Total storm discharge was not significantly different between Periods 1 and 3.

Terracing did not measurably change the amount of recharge to the site. Double-mass curves of water-level residuals (obtained by subtracting the

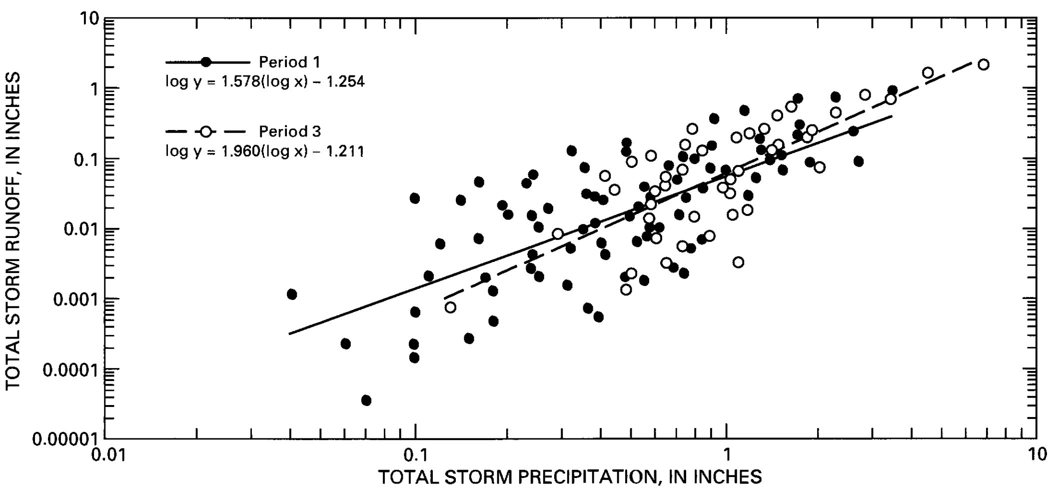


Figure 20. Regression of total storm runoff as a function of total storm precipitation at Field-Site 1, Conestoga River Headwaters, Pennsylvania, before implementation of best-management practices (Period 1) and after implementation (Period 3). (Modified from Lietman, 1992.)

Table 19. Regression statistics for the log of total storm runoff, in inches, as a function of the log of storm precipitation, in inches, for all storms in each period, except those on frozen ground, Field-Site 1, Conestoga River Headwaters, Pennsylvania

[<, less than. From Lietman, 1992]

Period[1]	Degrees of freedom	Coefficient of the log of total precipitation	Intercept	t-statistic	p-value	Coefficient of determination (Adjusted R^2)[3]	Standard error		
							Log units	Percent[2] Plus	Percent[2] Minus
1	84	1.578	−1.254	8.47	<0.001	0.46	0.70	401	80
3	43	1.960	−1.211	7.41	<.001	.46	.54	247	71

[1]Period 1, January 1983–September 1984; Period 3, October 1986–September 1988.

[2]Method of computation from G.D. Tasker, U.S. Geological Survey, written commun., 1978.

[3]Coefficient of determination (R^2) adjusted for degrees of freedom.

Table 20. General storm characteristics, by cluster, and percentage of total precipitation by cluster and period for Period 1 (January 1983–September 1984) and Period 3 (October 1986–September 1988) at Field-Site 1, Conestoga River Headwaters, Pennsylvania

[All storms that occurred during January 1983–July 1989, except those on frozen ground, were included in the dataset when clustered. --, insufficient number of storms to calculate percentiles. Modified from Lietman, 1992]

Cluster	Characteristics	Rainfall quantity, in inches		Period	Number of storms	Percentage of total precipitation[1]
		25 percent	75 percent			
1	Summer showers, generally 0.2 to 0.4 inches of rain on moist soil with crop cover			1	31	11
		0.2	0.4	3	21	10
2	Three large storms in December 1983, September 1985, and June 1987, 3.4 to 5.1 inches of rain			1	1	3.8
		--	--	3	1	3.9
3	Spring and fall all-day rains, generally on soil with little crop cover			1	22	9.4
		.2	.6	3	2	1.7
4	One large September 1987 storm, 6.7 inches of rain			1	0	0
		--	--	3	1	7.7
5	Three large summer storms, one in May 1985 and two in July 1988, 2.8 to 4.5 inches of rain			1	0	0
		--	--	3	2	8.3
6	Thunderstorms, predominantly in the summer, on soil with crop cover			1	18	18
		.6	1.4	3	10	14
7	Small storms throughout the year on dry soil, most storms on soil with little crop cover			1	67	22
		.2	.4	3	73	24
8	Spring and fall all-day rains on soil with little crop cover			1	15	21
		.8	1.6	3	12	16

[1]Total precipitation at the site includes precipitation on frozen ground.

minimum water-table altitude for the period of record at a well from the monthly mean water levels for that well) are shown in figure 21. Water-level data from 1984, before terracing, and 1989, after terracing, were available for well LN 1659, upgradient from the terraced area of Field-Site 1. Water-level data from well LN 1659 were compared with water-level data from well LN 1643, a well for which complete water-level data were available and which was downgradient from the terraces (fig. 4). Because no significant change (according to analysis of covariance) was evident in the slope of the double-mass curves of water-level data from wells LN 1659 and LN 1643 from the pre- to the post-BMP periods, water-level data from well LN 1643 were used for double-mass analysis of water-level data from the other wells within the terraced area of Field-Site 1 (fig. 21). The changes in slope from the pre- to post-BMP periods for water-level data for wells LN 1645, LN 1646, LN 1650, and LN 1651, relative to well LN 1643, were not significantly different, according to analysis of covariance (Hall, 1992b).

A comparison of suspended-sediment concentrations and loads before and after terrace construction indicated that soil erosion was reduced by installation of pipe-outlet terracing at the site. The terraces reduced runoff energy and, thus, the ability of runoff to transport sediment. Also, pooling in terraces allowed time for deposition of suspended material before the runoff discharged through the pipe outlet. During 1984, before terracing, the annual suspended-sediment yield exceeded the T value (erosion rate) of 4 ton/acre recommended for the site by the USDA, NRCS. The suspended-sediment yield was substantially less than T for all the years after terrace installation and stabilization (1986–89 water years) (table 16). Suspended-sediment yields as a function of runoff were significantly lower during Period 3

Table 21. Mann-Whitney test results for within-cluster mean storm total discharges, mean storm nutrient concentrations, and total storm yields between Period 1 (1983–84) and Period 3 (1987–88) at Field-Site 1, Conestoga River Headwaters, Pennsylvania, except storms on frozen ground

[↑, statistically significant increase; ↓, statistically significant decrease; ↔, no statistically significant change; (90), significant at the 90-percent confidence interval; (95), significant at the 95-percent confidence interval; n, number of storms; ft^3/acre, cubic feet per acre; mg/L, milligrams per liter. Clusters described in table 20. From Lietman, 1992]

		Cluster 1	Cluster 6	Cluster 7	Cluster 8
		Period 1/Period 3	Period 1/Period 3	Period 1/Period 3	Period 1/Period 3
		All storms[1]			
Total discharge (ft^3/acre)	Change	↓(90)	↔	↓(95)	↔
	Median	84/0	52/400	0/0	205/260
	n	31/21	18/10	67/73	15/12
		Storms that produced runoff			
Total discharge (ft^3/acre)	Change	↑(90)	↔	↔	↔
	Median	120/240	102/740	24/80	260/260
	n	21/7	13/9	26/10	13/12
Mean suspended-sediment concentrations (mg/L)	Change	↔	↓(95)	↓(95)	↓(95)
	Median	2,870/2,030	9,040/1,850	3,530/725	1,930/470
	n	19/7	9/8	22/6	7/10
Mean total phosphorus concentration (mg/L as P)	Change	↔	↔	↔	↔
	Median	2.6/2.7	4.1/3.4	3.1/3.4	3.1/4.3
	n	12/7	8/7	17/3	6/7
Mean total nitrogen concentration (mg/L as N)	Change	↑(90)	↔	↔	↑(90)
	Median	3.4/6.1	5.4/6.2	5.2/7.4	4.1/7.2
	n	12/7	8/7	17/3	6/7
Mean total ammonia plus organic nitrogen concentration (mg/L as N)	Change	↔	↔	↔	↔
	Median	2.7/4.2	4.6/4.2	4.1/4.2	3.6/4.8
	n	12/7	8/7	17/3	6/7
Mean total nitrate plus nitrite concentration (mg/L as N)	Change	↑(95)	↑(95)	↑(95)	↑(95)
	Median	0.56/1.7	0.54/1.8	0.59/4.1	0.43/3.0
	n	12/7	8/7	17/3	6/7

[1]Total and mean discharge set equal to zero if no measurable runoff occurred.

than during Period 1 (fig. 22; table 22). Moderate storms carried about the same amount of sediment relative to total storm runoff before and after terracing, but large storms carried much less sediment relative to runoff after terracing than before terracing. The clustered storm data indicated that suspended-sediment concentrations decreased significantly from Periods 1 to 3, except during small summer storms when there was a crop cover (cluster 1). The median concentration of suspended sediment decreased about fourfold to fivefold for storms in the other clusters.

Reduced soil erosion after terracing did not result in reduced total phosphorus losses from the field (fig. 22; table 22). No change in mean storm concentration of total phosphorus in runoff was detected from Period 1 to Period 3. Total phosphorus concentrations did not decrease proportionately with suspended-sediment concentrations throughout most of the storm groupings. Most phosphorus is sorbed to and transported by fine particles (Sharpley and others, 1981). Observation of runoff at the site and limited particle-size data analysis of suspended-sediment samples indicate that many fine sediment particles

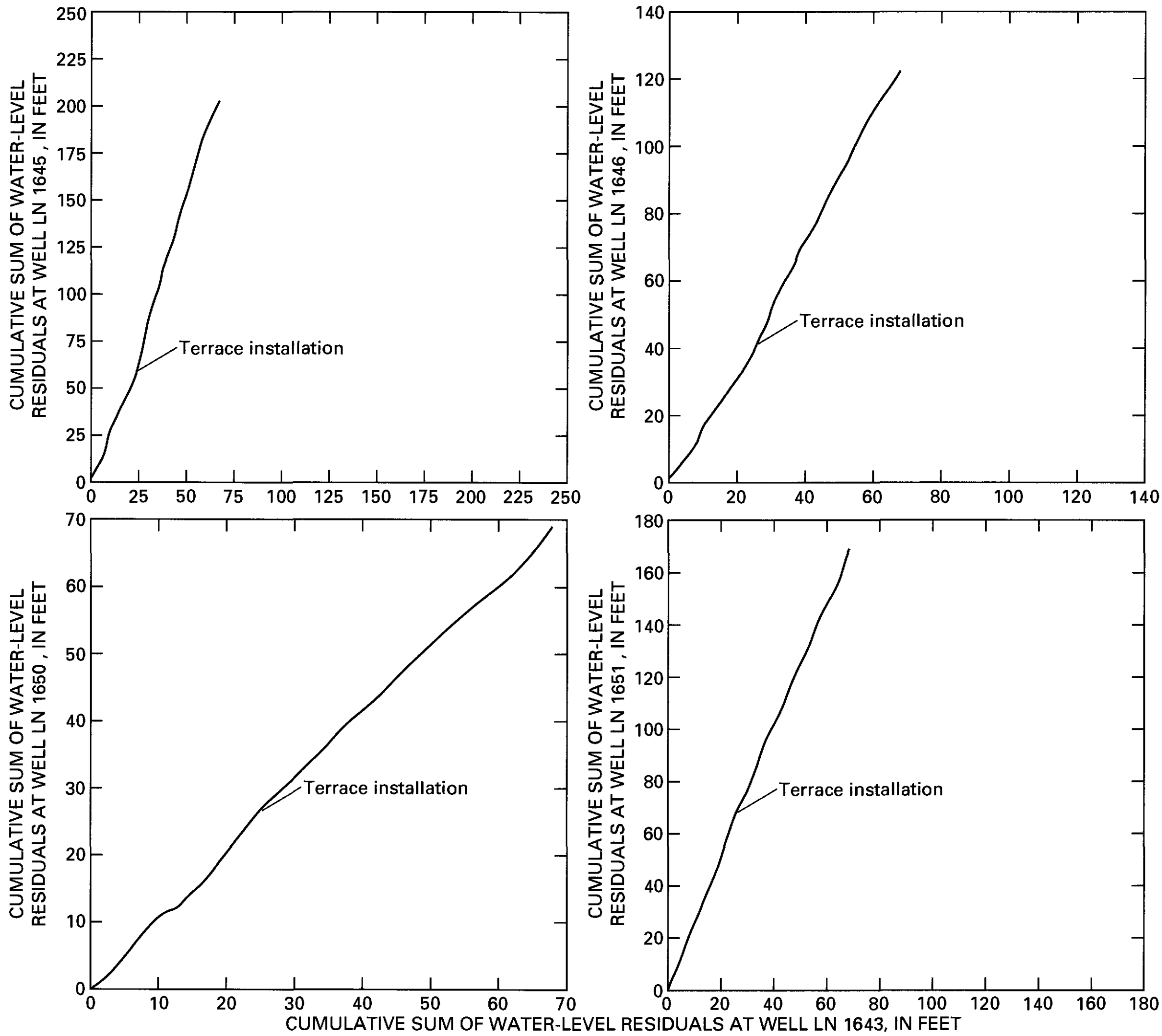


Figure 21. Double-mass comparisons of cumulative water-level residuals from January 1983 through September 1989 at Field-Site 1 wells, Conestoga River Headwaters, Pennsylvania. (From Hall, 1992b.)

(less than 0.62 μm in diameter) continued to be discharged from the sites after terracing, whereas heavier particles (sands) were retained on the field. The small amount of phosphorus-concentration data (125 instantaneous runoff samples during the pre-BMP period and 52 samples during the post-BMP period) indicate that there was a small but statistically significant increase in dissolved phosphorus concentration in runoff after terracing but that total and suspended phosphorus concentrations did not change significantly. Small increases in dissolved phosphorus concentrations in runoff may have offset any decrease in suspended phosphorus concentration.

Yields of total ammonia plus organic nitrogen relative to runoff were not significantly different after terracing than they were before terracing (fig. 23; table 22). No changes in total ammonia plus organic nitrogen concentration were detected within any of the storm clusters from Period 1 to Period 3.

Yields of total nitrate plus nitrite relative to runoff increased significantly after terracing (fig. 23; tables 21 and 22). Within each storm cluster, the mean storm concentration of total nitrate plus nitrite in runoff also increased significantly from Period 1 to Period 3; the median concentration increased by threefold to sevenfold (table 21). Therefore,

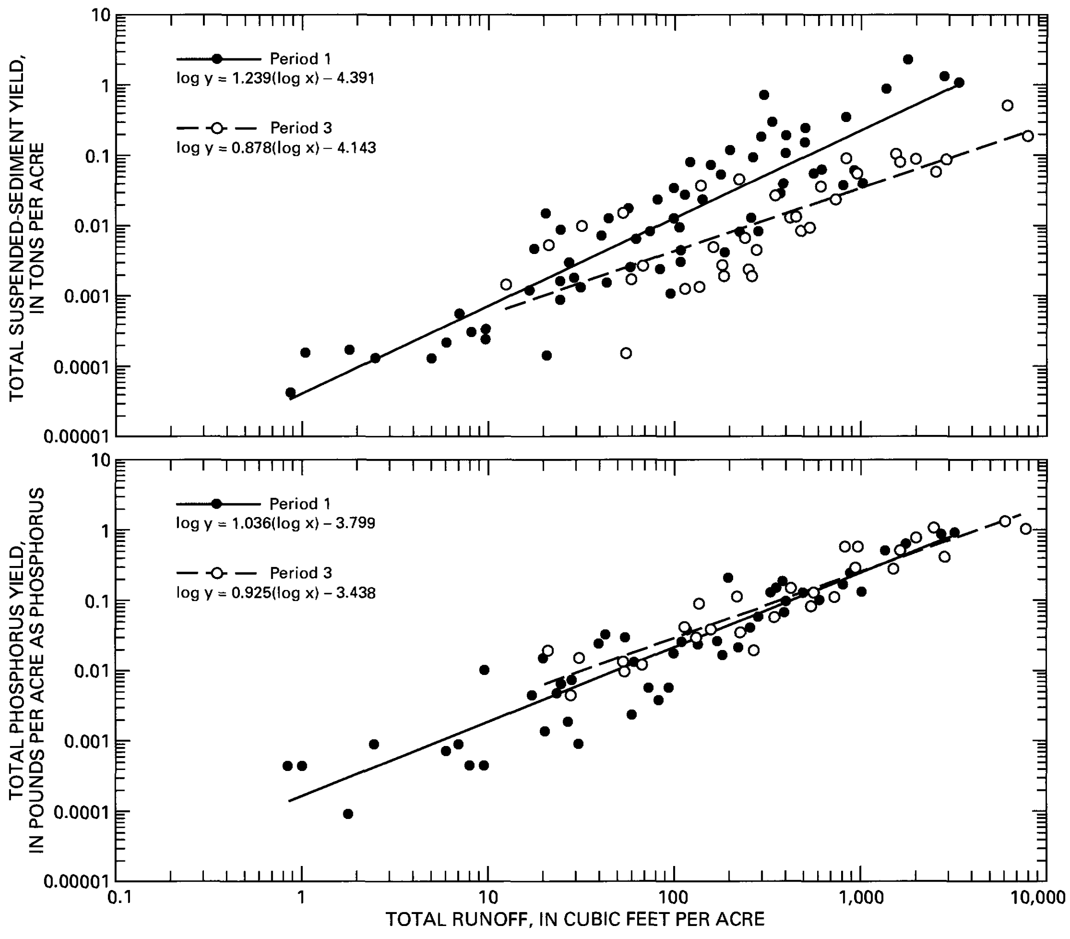


Figure 22. Regression of total suspended-sediment and total phosphorus yields as a function of total runoff at Field-Site 1, Conestoga River Headwaters, Pennsylvania, before implementation of best-management practices (Period 1) and after implementation (Period 3). (Modified from Lietman, 1992.)

regardless of the type of storm, nitrate transport by runoff increased after terracing. During small storms that produced no runoff after terrace construction, an overall increase in soil moisture may have allowed an increase in nitrification and, therefore, an increase in the amount of nitrate available for transport by runoff. Also, the soil-wetting area probably increased because of an increase in sheet runoff and a decrease in gully runoff. Thus, the increased contact time and the possibly increased contact area of the runoff water with the nutrient-rich soils may have allowed an increase in the conversion to, and dissolution of, nitrate. During many storms, runoff that pooled in the terraces resulted in increased contact time of runoff and soil, which could result in increased dissolution of nitrate.

During Period 1, about 8 percent of the annual total nitrogen yield was total nitrate plus nitrite (the remainder was total ammonia plus organic nitrogen); during Period 3, about 37 percent of the annual total nitrogen yield was total nitrate plus nitrite (table 16). The increase in nitrate concentrations did not substantially affect the overall total nitrogen yields with respect to runoff (fig. 23; table 22) but probably resulted in the statistically significant increase in total nitrogen concentration from Period 1 to 3 in one of the storm clusters (cluster 8, table 21).
No changes within clusters were detected in mean storm concentrations of total ammonia plus organic nitrogen in runoff between Periods 1 and 3. The mean storm concentrations of total ammonia plus organic nitrogen in runoff were much more variable than the

Table 22. Regression statistics of log of suspended-sediment and log of total nutrient yields, as a function of log of total runoff, for all storms in Periods 1 and 3 at Field-Site 1, Conestoga River Headwaters, Pennsylvania, except storms on frozen ground

[Suspended-sediment yield is expressed as tons per acre; nutrient yields are expressed as pounds per acre as nitrogen or phosphorus; total runoff is expressed as cubic feet per acre; all variables were log transformed; <, less than. From Lietman and others, 1997]

Period[1]	Dependent variable	Degrees of freedom	Regression coefficient	Intercept	t-statistic	p-value	Coefficient of determination (Adjusted R^2)[3]	Standard error		
								Log units	Percent[2]	
									Plus	Minus
1	Suspended sediment	65	1.239	–4.391	15.47	<0.001	0.82	0.495	213	68
3	Suspended sediment	34	.878	–4.143	7.13	<.001	.60	.491	210	681
1	Total nitrogen	49	.942	–3.379	16.85	<.001	.85	.341	119	54
3	Total nitrogen	27	.866	–3.063	12.21	<.001	.85	.259	82	45
1	Total ammonia plus organic nitrogen	49	.948	–3.470	15.77	<.001	.83	.367	133	57
3	Total ammonia plus organic nitrogen	27	.876	–3.295	11.60	<.001	.83	.276	89	47
1	Total nitrate plus nitrite	49	1.006	–4.528	14.23	<.001	.80	.431	170	63
3	Total nitrate plus nitrite	27	.869	–3.553	10.59	<.001	.80	.300	100	50
1	Total phosphorus	49	1.036	–3.799	16.65	<.001	.85	.379	139	58
3	Total phosphorus	27	.925	–3.438	12.90	<.001	.86	.262	83	45

[1]Period 1, January 1983–September 1984; Period 3, October 1986–September 1988.
[2]Method of computation from G.D. Tasker, U.S. Geological Survey, written commun., 1978.
[3]R^2 adjusted for degrees of freedom to allow more valid comparison between seasons.

mean storm concentrations of total nitrate plus nitrite in runoff. Total nitrogen concentrations, which are the sum of total ammonia plus organic nitrogen and total nitrate plus nitrite concentrations, also are more variable than total nitrate plus nitrite concentrations. Therefore, significant changes could be detected in the total nitrate plus nitrite concentrations without detecting corresponding significant changes in total nitrogen concentrations.

If nitrate concentrations in runoff increased as a result of terracing, then nitrate concentrations in recharge water, which has a larger contact area and more contact time with the nutrient-rich soils than runoff has, would probably also have higher nitrate concentrations and thus would increase nitrate concentrations in ground water. Dissolved nitrate concentrations in ground water did increase significantly after terracing at four of the six ground-water sites monitored (fig. 24; table 23). This increase, based on a qualitative evaluation of surface-runoff, ground-water, and nutrient-application data, is probably attributable to terracing. The same mechanisms that increased nitrate availability to surface runoff also would increase the amount of available nitrate to ground water. Additionally, the small storms that no longer produced runoff after terracing may have resulted in higher soil-moisture levels, which, in turn, may have (1) promoted nitrification, thus increasing the amount of nitrate available to recharge; and (2) led to increased infiltration through micropore flow, although the quantity of this infiltration would probably not be substantial enough to be observable by analysis of water-level hydrographs, particularly in carbonate rocks.

Dissolved nitrate concentration did not change significantly in one well (LN 1650) and decreased in another (LN 1646). The area upgradient from both of these wells was planted in corn prior to terracing and in alfalfa after terracing. Because nearly all the nutrient applications were to corn (table 18), applications upgradient from these two wells decreased dramatically as a result of the change in cropping pattern. The response of the ground water to the large decrease in available nitrogen upgradient from the wells probably masked any effects of terracing on nitrate concentration in ground water.

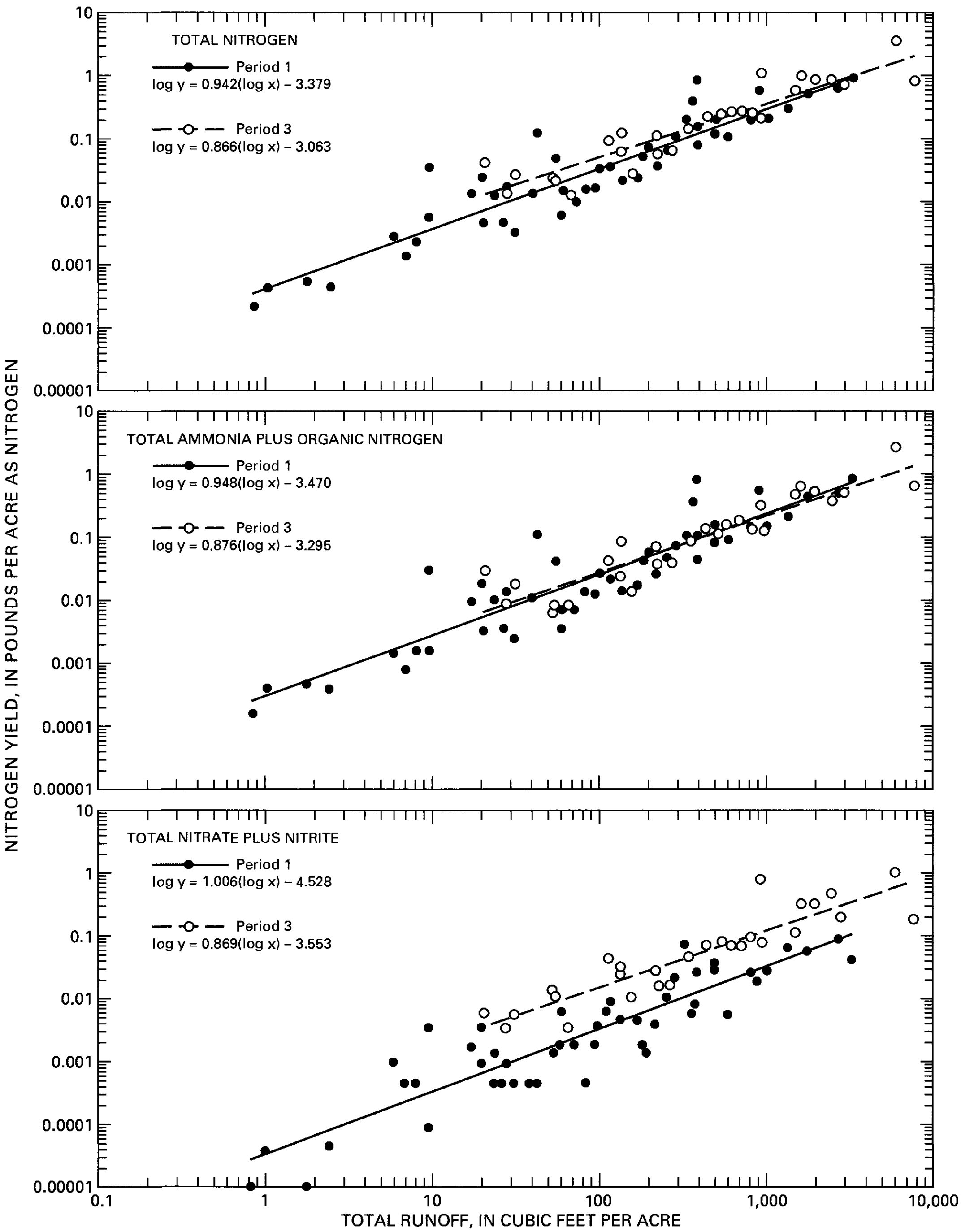
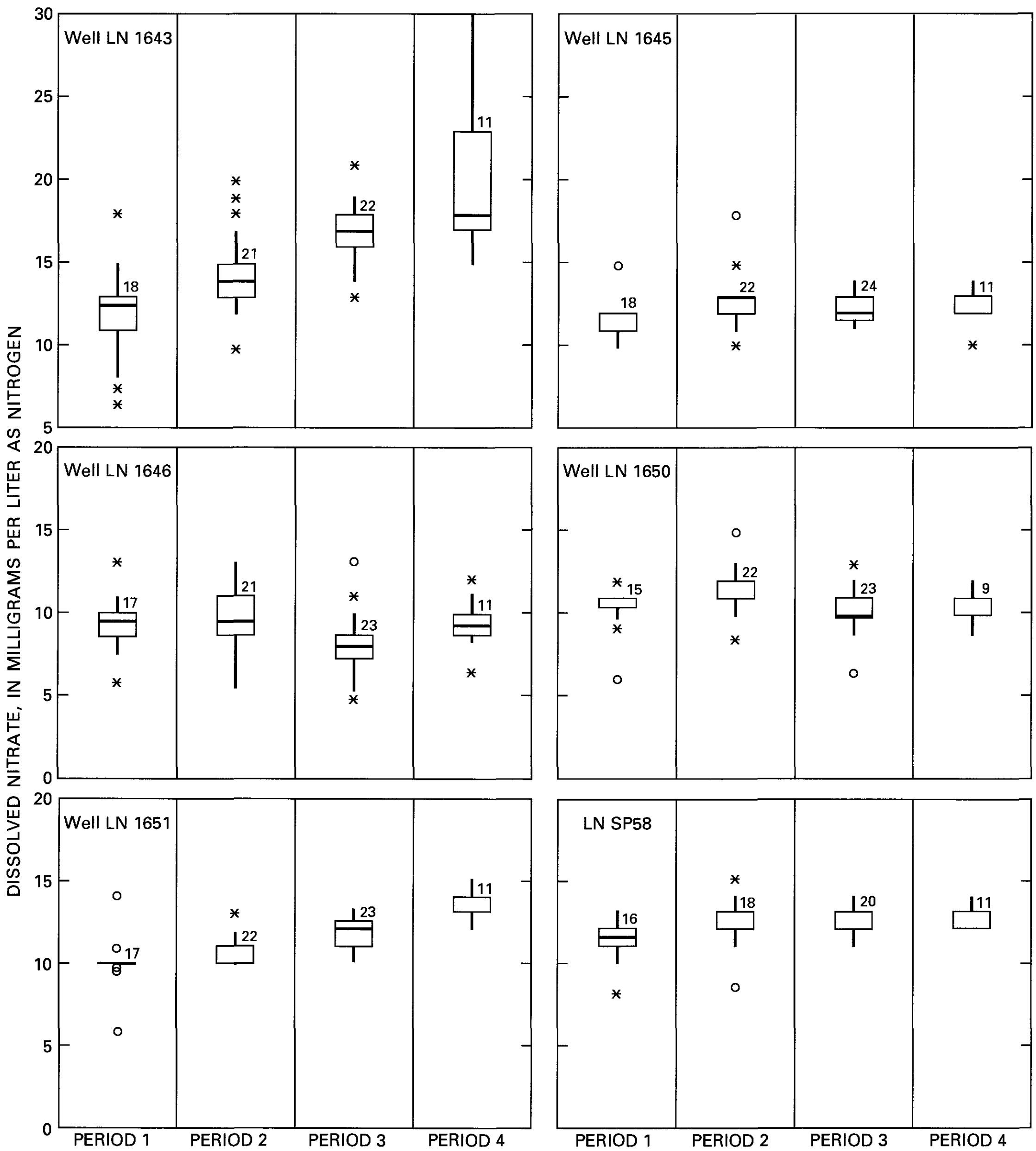


Figure 23. Regression of total nitrogen, total ammonia plus organic nitrogen, and total nitrate plus nitrite yields as a function of total runoff at Field-Site 1, Conestoga River Headwaters, Pennsylvania, before implementation of best-management practices (Period 1) and after implementation (Period 3). (Modified from Lietman, 1992.)



EXPLANATION

o FAR-OUTSIDE VALUES—PLOTTED INDIVIDUALLY, ALL POINTS GREATER THAN 3 TIMES THE INTERQUARTILE RANGE

* OUTSIDE VALUES—PLOTTED INDIVIDUALLY, POINTS 1.5 TO 3 TIMES GREATER THAN THE INTERQUARTILE RANGE

UPPER ADJACENT VALUE EQUALS LARGEST DATA POINT LESS THAN OR EQUAL TO THE UPPER QUARTILE PLUS 1.5 TIMES THE INTERQUARTILE RANGE

17 NUMBER OF SAMPLES

75TH PERCENTILE
UPPER QUARTILE

MEDIAN (50TH PERCENTILE)

LOWER QUARTILE
25TH PERCENTILE

LOWER ADJACENT VALUE EQUALS SMALLEST DATA POINT GREATER THAN OR EQUAL TO THE LOWER QUARTILE MINUS 1.5 TIMES THE INTERQUARTILE RANGE

PERIOD 1 (Pre-best-management practices) Jan. 1983 – Sept. 1984

PERIOD 2 (Post-best-management practices) Oct. 1984 – Sept. 1986

PERIOD 3 (Post-best-management practices) Oct. 1986 – Sept. 1988

PERIOD 4 (Post-best-management practices) Oct. 1988 – July 1989

Figure 24. Distribution of dissolved nitrate concentrations in ground water from wells and the spring at Field-Site 1, Conestoga River Headwaters, Pennsylvania. (From Lietman and others, 1997.)

Table 23. Median dissolved nitrate concentrations in ground water at Field-Site 1 and results of Mann-Whitney testing between Period 1 and Period 3, Conestoga River Headwaters, Pennsylvania

[Period 1, 1983–84 (before best-management practices); Period 3, 1987–88 (after best-management practices); mg/L, milligrams per liter ↑, statistically significant increase at the 95-percent confidence interval; ↓, statistically significant decrease at the 95-percent confidence interval; ↔, no statistically significant change. Modified from Lietman and others, 1997]

Well or spring number	Period 1		Period 3		Period 1–Period 3
	n[1]	Median concentration (mg/L)	n	Median concentration (mg/L)	
LN 1643	18	12.5	22	17.0	↑
LN 1645	18	11.0	24	12.0	↑
LN 1646	17	9.4	23	7.9	↓
LN 1650	15	11.0	23	10.0	↔
LN 1651	17	10.0	23	12.0	↑
LN SP58	16	11.5	20	13.0	↑

[1]Number of samples; excludes samples collected when water levels were rapidly responding to recharge.

Dissolved nitrate concentrations in ground water at Field-Site 2, where terraces had been in place for almost 20 years before this study, were high compared to concentrations in other agricultural, carbonate areas sampled as part of the regional network (figs. 2 and 8; table 13; fig. 25). Although excessive nutrient applications would be expected to be one of the primary factors affecting nitrate concentrations in ground water, terraces also may have affected nitrate concentrations at Field-Site 2. Total nitrate was 31 to 57 percent of the annual total nitrogen load in runoff from the terraces at Field-Site 2. This range of percentages is comparable to data from Field-Site 1 after terracing, when total nitrate was 22 to 39 percent of the total annual nitrogen load in runoff at Field-Site 1. The 32- to 39-percent range was a dramatic increase from the pre-terracing range of 8 to 9 percent (table 16).

Nutrient Management

Nutrient-management plans were developed for farms within Field-Site 1, Field-Site 2, and the Nutrient-Management Subbasin of the Small Watershed. The nutrient-management BMP was the primary BMP implemented in the Conestoga River Headwaters and was developed in response to the documented water-quality problem of nitrate concentrations in drinking-water samples that commonly exceeded the MCL of 10 mg/L as N. Discharges of nitrate-enriched ground water to streams resulted in elevated nitrate concentrations in base streamflow and contributed about 75 percent of the total nitrogen

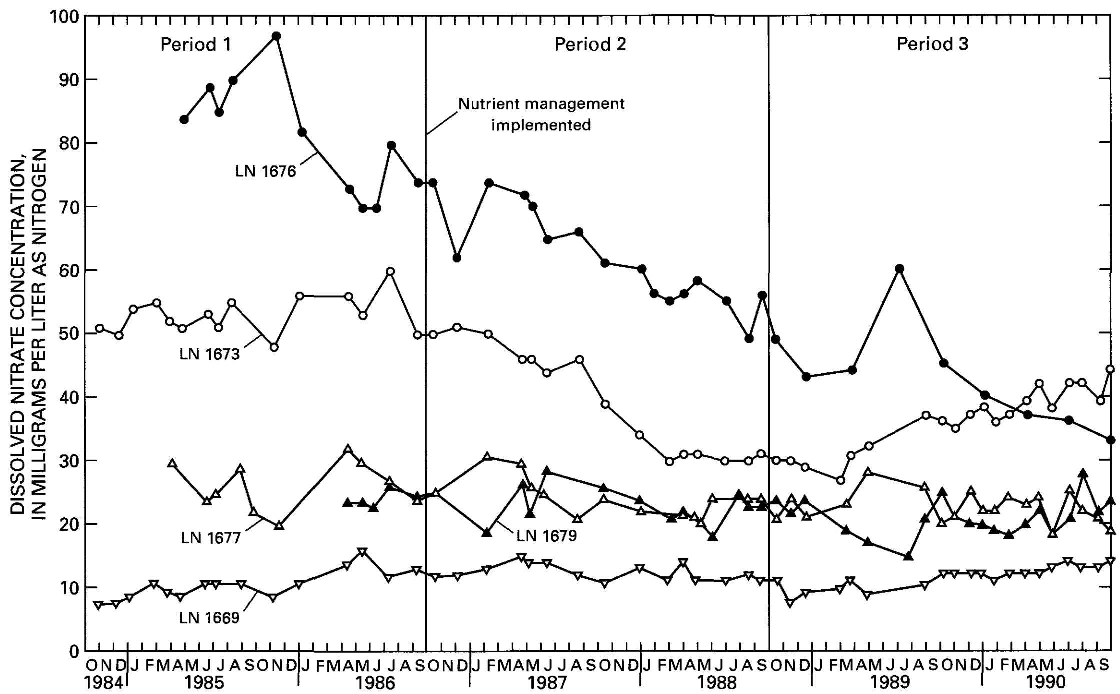


Figure 25. Dissolved nitrate concentrations in water from wells at Field-Site 2, Conestoga River Headwaters, Pennsylvania. (From Hall, 1992a.)

load in streamflow. The elevated nitrogen concentrations were thought to be the result of overapplication of nutrients to the cropland. High livestock densities in the watershed resulted in more manure nutrients being produced on the farm than were needed to fertilize the crops being produced. This, in turn, resulted in overapplication of nutrients through disposal of manure. In addition, the nutrients in manure were often underaccounted for; as a result, commercial fertilizer as well as manure was applied to the cropland.

Nutrient management was generally defined as limiting the application of nitrogen to match expected crop requirements for nitrogen. Because nitrogen was a primary ground-water contaminant in the watershed, the nutrient-management recommendations were based on the nitrogen content of manure. Nutrient-management plans took into account nutrients available from manure (on the basis of manure analysis), history of manure applications (for estimation of residual nitrogen), and estimated crop yields. Although reduction in manure applications commonly resulted in reduced inputs of phosphorus to the cropland, the phosphorus inputs generally continued to exceed crop requirements.

At Field-Site 2 and at farms in the Nutrient-Management Subbasin, nutrient management resulted in decreased nutrient applications. At Field-Site 2, the average annual nitrogen applications decreased 22 percent, and phosphorus application decreased 29 percent from the pre- to the post-BMP period. In the Nutrient-Management Subbasin, an average of 32 percent less nitrogen and 35 percent less phosphorus was applied annually during the post-BMP period than during the pre-BMP period. At Field-Site 1, the nutrient-management plan was not fully implemented; thus, the amounts of nutrients applied to the site did not change substantially.

The effects of nutrient management were evaluated in ground water and surface runoff at Field-Site 2 and in streamflow in the Nutrient-Management Subbasin and the Small Watershed.

At Field-Site 2, changes in nitrate concentrations in ground water were quantitatively compared to changes in applications of nitrogen to the land surface (Hall, 1992a). Amounts of nitrogen applied upgradient from the wells (on the basis of contributing areas defined for each well) were calculated in 4-month increments and were plotted in figure 26 on the date of the highest application in the period. In order to estimate the relative monthly nitrogen mass available for transport with recharge, a curve was drawn between the nitrogen-application data points by use of a smoothing technique (Tellagraf, 1984; fig. 26). The dissolved nitrate concentrations in ground-water samples collected monthly when the water level was not rapidly changing because of recharge also were plotted in figure 25. Dissolved nitrate concentrations for the months where no samples of this type were collected were estimated from the graph. Monthly dissolved nitrate concentrations were then correlated with monthly nitrogen applications by applying a lag function to the dissolved nitrate-concentration data. The lag time that produced the correlation within the highest confidence interval was determined by use of a cross-correlation lag function (Wilkinson, 1987); Spearman's rho was used to select the lag with the strongest correlation. The lag times represent the approximate delay in response of nitrate concentrations in ground water to surface-applied nutrients. Significant correlations between the dissolved nitrate concentrations in ground water and the nitrogen quantities applied to the land surface indicate that as nitrogen applications decrease, dissolved nitrate concentrations in ground water also decrease. Additionally, the analysis indicates that dissolved nitrate concentrations in ground-water samples from the site respond to changes in surface applications within 4 to 19 months (fig. 26). Although the lag times between changes in dissolved nitrate concentrations in ground water and reduced surface application of nitrogen may vary from those determined by this particular analysis, dissolved nitrate concentrations did appear to respond to reduced surface applications within 2 years at all the wells. Nitrate-concentration data from the wells (fig. 25) were compared by dividing the data into 2-year periods: Period 1, the pre-BMP period; Period 2, the 2 years immediately after implementation of nutrient management; and Period 3, the third and fourth years after implementation of the BMP. At one well, LN 1679, pre-BMP data were insufficient for analysis. Dissolved nitrate concentrations at three of the other four wells decreased from Period 1 to Period 3 (table 24). Changes in dissolved nitrate concentration in the fourth well were not significant. These analyses indicate that implementation of nutrient management generally resulted in decreased concentrations of dissolved nitrate in ground water.

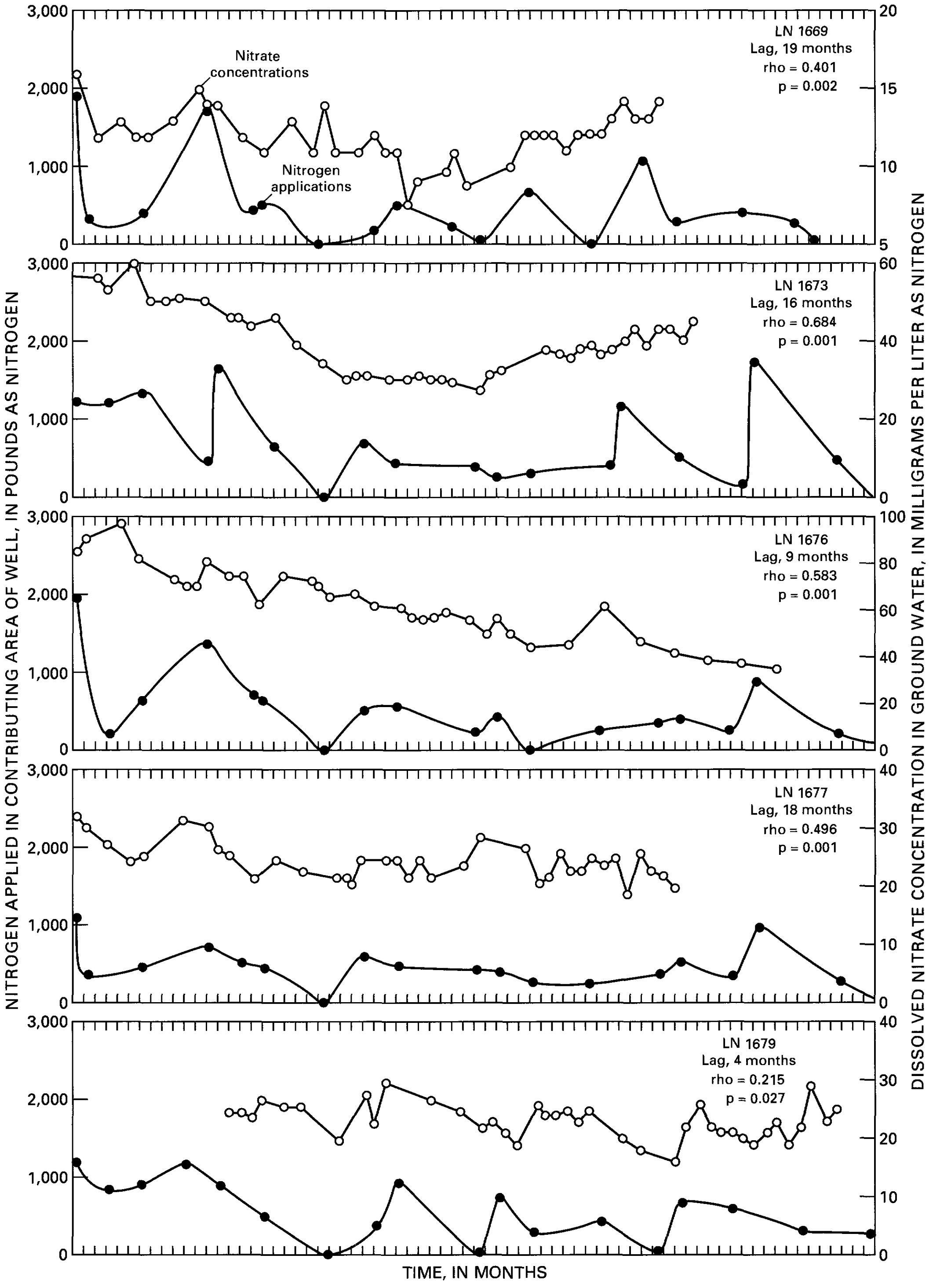


Figure 26. Amount of nitrogen applied in contributing areas of wells at Field-Site 2, Conestoga River Headwaters, Pennsylvania; dissolved nitrate concentration in water from those wells; and statistics from Spearman rank correlations between monthly application data and lagged monthly concentration data. (The nitrogen-application curves have been shifted to the right by the amount of the indicated lagtime in the above graphs to highlight correlations with nitrate concentrations.) (From Hall, 1992a.)

Table 24. Median dissolved nitrate concentrations in ground water at Field-Site 2 and results of Mann-Whitney testing between Period 1 and Period 3, Conestoga River Headwaters, Pennsylvania

[Period 1, 1984–86 (before best-management practices); Period 3, 1988–90 (after best-management practices); mg/L, milligrams per liter; ↓, statistically significant decrease at the 95-percent confidence interval; ↔, no statistically significant change at the 95-percent confidence interval]

Well number	Period 1		Period 3		Period 1–Period 3
	n[1]	Median concentration (mg/L)	n	Median concentration (mg/L)	
LN 1676	11	82	9	43	↓
LN 1673	15	53	20	37	↓
LN 1677	10	26	19	22	↓
LN 1669	15	11	20	12	↔

[1]Number of samples; excludes samples collected when water levels were rapidly responding to recharge.

Mean storm concentrations of total nitrogen and total phosphorus in runoff from the terraced areas of Field-Site 2 did not change significantly after implementation of nutrient management (Hall and others, 1997). Although mean storm concentrations of total nitrate plus nitrite decreased significantly from the pre- to the post-BMP periods, the decrease was probably caused by a change in tillage practices (from no-till to minimum-till) and in crop cover (from continuous crop cover to none in winter) rather than nutrient management. The change in total nitrate plus nitrite concentration, however, was not large enough to result in a significant change in the mean storm concentrations of total nitrogen from the pre- to the post-BMP periods. Runoff accounted for only about 5 percent of the water discharged from Field-Site 2 and carried only about 1 percent of the nitrogen discharged from the site; therefore, any effects of nutrient management on ground water are far more critical than effects on surface runoff at this terraced site.

For the Small Watershed study, a qualitative assessment of the effects of nutrient management on surface-water quality indicated that nutrient management was beneficial in preventing increased concentrations of dissolved nitrate plus nitrite in base streamflow (Koerkle and others, 1996a). Nitrate was selected as the best indicator of the effects of nutrient management because nitrate is the primary form of nitrogen in ground water and base flow in the Small Watershed. The total nitrate plus nitrite load accounted for about 70 percent of the total nitrogen load in streamflow in the watershed, and dissolved nitrate accounted for about 98 percent of the total nitrate plus nitrite concentration. Base flow integrates ground-water inputs throughout the drainage basin rather than just nearstream inputs, and the water quality of base flow fluctuates less than that of stormflow. Therefore, much of the data analysis to determine the effects of nutrient management on water quality was based on dissolved nitrate concentrations in base flow.

A seasonally grouped Wilcoxon Mann-Whitney Rank-Sum test was used to determine whether a step trend in median nutrient concentrations in base flow had occurred from the pre- to the post-BMP periods. The test results indicate a significant increase ($p = 0.06$) of 0.7 mg/L in flow-adjusted dissolved nitrate plus nitrite concentration in base flow from the entire Small Watershed, whereas no significant change was detected in flow-adjusted dissolved nitrate plus nitrite concentration in base flow from the Nutrient-Management Subbasin. Significant trends in concentrations of other nutrients in base flow were observed at some sites; however, the changes in concentration were probably a result of factors such as changes in climate or nearstream or instream conditions rather than nutrient management (Koerkle and others, 1996a).

Similar procedures were used to analyze the mean stormflow-concentration data from the Nutrient-Management Subbasin and Small Watershed sites. For fall storms only, mean total nitrate plus nitrite concentrations in stormflow increased significantly ($p = 0.06$) at the mouth of the Small Watershed site from the pre- to post-BMP periods, whereas no significant change was detected ($p = 0.60$) in mean total nitrate plus nitrite concentration for the Nutrient-Management Subbasin. This trend is similar to the trends in base-flow concentrations of dissolved nitrate plus nitrite at both sites. Also, a decrease ($p = 0.02$) in total phosphorus was detected for the Small Watershed (no significant change for the Nutrient-Management Subbasin). The only other changes from the pre- to the post-BMP periods with a high probability of significance were a decrease ($p = 0.07$) in mean stormflow concentrations of total ammonia plus organic nitrogen at the Nutrient-Management Subbasin site for spring storms (no significant change for the Small Watershed). Stormflow characteristics, such as rate of rise in discharge, peak discharge, and amount of nutrient transported with runoff, varied considerably from season to season and from storm to storm. Because of this large variability, significant differences in nutrient concentrations were less likely to be detected. Additionally, changes in nutrient applications in the Nutrient-Management Subbasin were moderate, varied from year to year, and were primarily in fields away from the stream. Changes in nutrient application near the stream would be expected to affect runoff quality more than changes in applications to distant fields.

A paired-subbasin analysis indicated that dissolved nitrate plus nitrite concentrations in base flow in the Nutrient-Management Subbasin (1.4 mi^2) did not change significantly from the pre- to the post-BMP period, but concentrations increased in the Nonnutrient-Management Subbasin (1.4 mi^2) (fig. 3) from the pre- to the post-BMP period. Analysis of covariance showed change in the relation between concurrent concentrations of dissolved nitrate plus nitrite in base flow from the paired subbasins (fig. 27). Time-series plots and LOWESS smooths (Helsel and Hirsch, 1992) showed the change to be due to increases in dissolved nitrate plus nitrite in the Nonnutrient-Management Subbasin rather than to decreases in the Nutrient-Management Subbasin (fig. 28). A LOWESS smooth of dissolved nitrate plus nitrite data in base flow from the entire Small Watershed (5.8 mi^2) also indicated increasing concentrations overall (fig. 28).

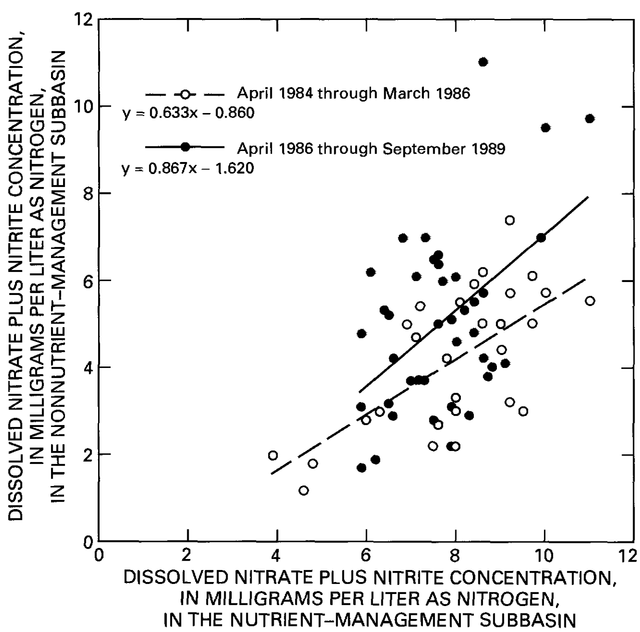


Figure 27. Relation between dissolved nitrate plus nitrite concentrations in base flow from the Nutrient-Management Subbasin and base flow from the Nonnutrient-Management Subbasin, Conestoga River Headwaters, Pennsylvania. (From Koerkle and others, 1996a.)

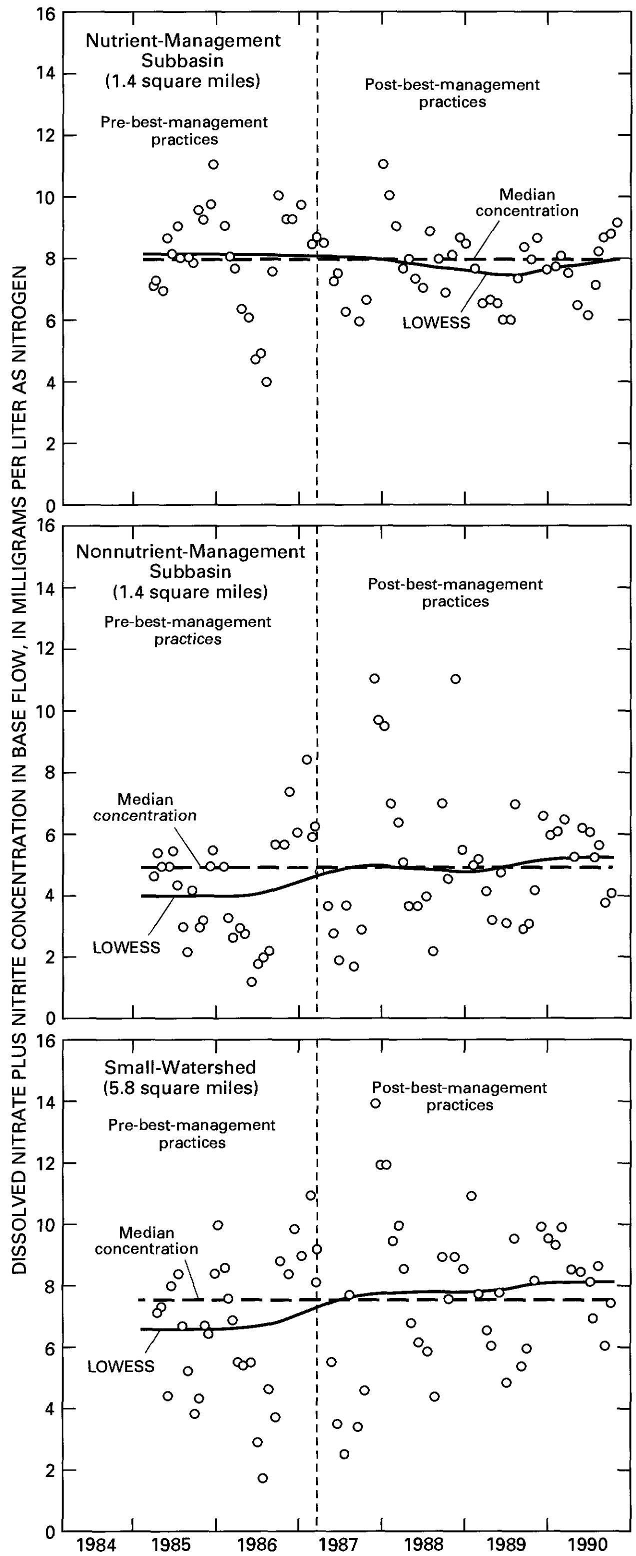


Figure 28. Time series of dissolved nitrate plus nitrite concentrations in base flow from the Nutrient-Management Subbasin, the Nonnutrient-Management Subbasin, and the Small Watershed, Conestoga River Headwaters, Pennsylvania. (From Koerkle and others, 1996a.)

Although significant reductions in concentrations of nitrate in ground water were documented after implementation of nutrient management at Field-Site 2, substantial reductions in nitrate concentration after nutrient-management implementation were not found in base flow from the Nutrient-Management Subbasin. The Small Watershed study did show that nutrient management prevented increases in dissolved nitrate plus nitrite concentrations in base flow, and data from Field-Site 2 and the Nutrient-Management Subbasin indicated that, practiced according to plan, nutrient management could eventually lead to reductions in dissolved nitrate concentrations in base flow and, therefore, reductions in total nitrogen discharged by the stream. The LOWESS trend of dissolved nitrate plus nitrite concentrations in base flow from the Nutrient-Management Subbasin (fig. 28) indicates that nitrate plus nitrite concentrations decreased slightly during 1987 and 1988. This slight decrease follows the time period of the smallest nutrient applications to the subbasin. As shown in figure 29, nitrogen applications to the subbasin decreased substantially starting in April 1986, after implementation of nutrient-management plans. However, after 2 years of nutrient management, applications of nitrogen increased. Dissolved nitrate plus nitrite concentrations in base flow also increased in the subbasin after applications of nitrogen increased, as indicated by the LOWESS trend line (fig. 28). Despite the absence of a strong correlation between applications and concentrations of nitrogen in base flow in the Nutrient-Management Subbasin, a statistical correlation between nitrogen application and nitrogen concentrations in ground water was detected for Field-Site 2. The large variability in the base-flow nitrogen data for the Nutrient-Management Subbasin, partly due to streambed processes, makes significant changes in the concentrations more difficult to detect than in the less variable nitrogen data for ground water from Field-Site 2. Additionally, the complications associated with the varied degrees to which the nutrient-management BMP was adopted by the 16 farmers within the Nutrient-Management Subbasin compromised the possibility of linking any water-quality changes to changes in application.

In summary, reductions in nutrient application after nutrient-management implementation appear to be effective in reducing concentrations of dissolved nitrate in ground water; therefore, nutrient management, practiced according to plan, may eventually be effective in reducing nitrogen loads in streamflow.

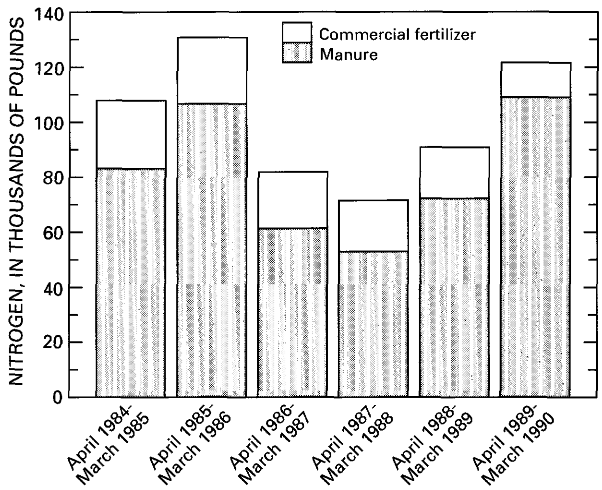


Figure 29. Nitrogen applications to Nutrient-Management Subbasin of the Small Watershed, Conestoga River Headwaters, Pennsylvania, before and after implementation of nutrient management.

SUMMARY AND CONCLUSIONS

A 9-year (1982–90) study to determine the effects of selected agricultural best-management practices (BMP's) on surface- and ground-water quality in the Conestoga River Headwaters, Pa., was done by the USGS in cooperation with the Pennsylvania Department of Environmental Protection and the U.S. Department of Agriculture, Consolidated Farm Service Agency. This study was part of the experimental Rural Clean Water Program (RCWP) sponsored by the U.S. Department of Agriculture. The objectives of the RCWP were to accelerate voluntary implementation of agricultural BMP's for improvement of water quality and to monitor changes in water quality associated with implementation of BMP's.

This report describes and evaluates the project monitoring design, characterizes the water quality of the Conestoga River Headwaters, and describes the effects of pipe-outlet terracing and nutrient management on surface- and ground-water quality in three intensive-monitoring areas of the basin.

Project Design

Water quality was monitored at three scales—regional, small watershed, and field—before implementation of BMP's (pre-BMP) and at two scales—small watershed and field—after implementation (post-BMP). Surface-water quantity and ground-water-level data were collected. Surface- and ground-water samples were analyzed for concentrations of suspended sediment, nutrients, and selected herbicides. Land-use and agricultural-activity data, as well as other pertinent data that may relate to water quality (precipitation, soil, and manure) were collected to aid in evaluation of the water-quality data.

The 188-mi^2 regional study area was monitored from April 1982 through September 1983. Four surface-water sites and 43 ground-water sites (domestic water wells) were used to characterize the basin. Because of the low level of farmer participation in the RCWP, implementation of BMP's was not expected to be widespread throughout the regional study area. Therefore, monitoring of the regional study area was discontinued earlier than planned.

Field-Site 1 (23.1 acres of agricultural cropland) was monitored from January of 1983 through July 1989 to determine the effects of pipe-outlet terracing on surface- and ground-water quality. Terraces constructed in October 1984 were designed to reduce erosion, thereby retaining sediment and associated nutrients onsite. One runoff site, which drains the entire field site, and five wells and a spring were monitored throughout the study period.

Field-Site 2 (47.5 acres of agricultural cropland) was monitored from October 1984 through September 1990 to determine the effects of nutrient management on surface- and ground-water quality. Nutrient management, implemented in October 1986, was the BMP selected to decrease the amount of nutrients available for runoff and leaching to the ground water. Nutrient management involved decreasing manure applications to the rate of crop requirements. One runoff site and five wells and a spring were monitored throughout the study period.

The Small Watershed drains 5.6 mi^2 and is 68 percent agricultural and 24 percent forested. Surface-water quantity and quality were monitored at five stream sites from April 1984 through September 1989 to determine the effects of nutrient management in the upper part of the basin and the overall effects of all BMP's implemented in the entire basin. Nutrient management was implemented on 11 farms in a 1.4-mi^2 subbasin, the Nutrient-Management Subbasin, in April 1986.

Pre-BMP data from all components of the project were used for a general characterization of the Conestoga River Headwaters watershed and for a detailed characterization of the intensive BMP-monitoring sites—the two field sites and the Small Watershed. For the two field sites and the Small Watershed, pre-BMP data were compared with post-BMP data to determine changes in water quality and changes in agricultural activities, as well as to associate these changes and evaluate the effects of the BMP's. Additionally, inputs and outputs of water and nutrients were estimated for the two field sites.

Although the final overall monitoring design did not differ greatly from the original design, the scope of the project was reduced. The project design was modified throughout the project to increase the probability of successfully determining the effects of BMP's and to improve the efficiency of the project. Changes from the detailed monitoring design planned at the onset of the project to the final monitoring design included discontinuing the regional network after the initial characterization period, monitoring only two of the three BMP's planned, decreasing the number of soil and soil-water components of the study, and decreasing the number of constituents for which water-quality samples were analyzed. However, one of the two BMP's was monitored at the field and small watershed scales with an added paired-watershed component, and post-BMP monitoring was continued longer than planned to allow time for changes in land practices to be reflected in the water quality.

Through participation in this particular project and in the national RCWP, project personnel learned valuable lessons about monitoring design for studies involving evaluation of water quality in response to implementation of BMP's. This information could be applied to any study evaluating water-quality changes in response to changes in land use or human activities. The lessons include the following:

- Surface- and ground-water systems should be evaluated over a full range of hydrologic conditions before and after implementation of a BMP to fully assess the effects of the BMP.
- The project should last long enough for changes made at the land surface to affect water quality.
- Controls on study designs, such as paired watersheds (one with treatment and one without) or sites upgradient and downgradient from the area affected by a BMP, facilitate attempts to associate changes in water quality with the specific factors that may have produced the changes; for example, climatic variability or BMP implementation.

- Agricultural-activity data, as well as ancillary data such as precipitation, are needed to relate changes in water quantity or quality to changes resulting from adoption of a BMP.
- For increased transferability of data on the water-quality effects of BMP's, only one BMP should be implemented and evaluated at a site, and the same BMP should be evaluated at more than one site.
- Statistical methods of data analysis should be selected during project planning to ensure that the types of data and the frequency of collection will meet the requirements for data analysis.
- The monitoring design should be flexible enough to accommodate non-ideal site logistics or changes indicated by preliminary data analysis.
- Constituents selected for analysis should be reevaluated throughout the study to determine whether they are useful indicators for meeting the project objectives.
- Agricultural-activity information is most accurate if farmers are interviewed frequently and if the data are verified by field inspection; however, agricultural-activity information is generally less accurate than water-quality data and, therefore, limits data analysis.
- Cooperation among all participants in the study is necessary. The Conestoga River Headwaters project involved farmers and Federal, State, and local scientific and agricultural agencies.

Characterization of Study Areas and Water

Data collected from the regional study area and the intensive-monitoring sites during the pre-BMP periods were used to characterize the Conestoga River Headwaters. The northern two-thirds of the Conestoga River Headwaters is underlain by conglomerate, shale, sandstone, and diabase. The intensively agricultural southern one-third of the basin, which contains the two field sites and the southern half of the Small Watershed, is underlain by carbonate rock. High livestock densities predominate on small farms in the basin; animal waste from these farms and commercial fertilizer are the primary nutrient sources to surface water and ground water. Conventional tillage methods are used in producing corn and alfalfa, the primary crops. The silt-clay loam soils in the carbonate areas of the basin are deep and well drained. Soil samples from cropland in the field sites and the Small Watershed were rich in nutrients. After fall crop harvest, nitrate concentrations in the 0- to 4-ft-deep crop root zone ranged from 30 to 400 lb/acre and in the 4- to 8-ft-deep zone ranged from 40 to 500 lb/acre. Most phosphorus was in the top 8 in. of soil.

The unconfined aquifer underlying the Conestoga River Headwaters is a complex fractured-bedrock system that is recharged by an average of 42 in. of precipitation annually. Most ground water discharges to numerous local streams. In general, the water table is a subdued image of surface topography. Water levels in wells when samples were collected in the regional study area ranged from 7 to 126 ft below land surface. During the study period, the water table ranged from 34 to 74 ft below land surface at Field-Site 1 and from 3 to 32 ft below land surface at Field-Site 2. Recharge to the ground water occurs rapidly through soil macropores and near-surface fractures and sinkholes but also gradually through soil micropores.

In the Conestoga River Headwaters, base flow was highest in the spring during ground-water recharge periods and lowest in the late summer and early fall. Heavy spring rains, intense summer thunderstorms, and rain on frozen ground generally produced the largest amounts of runoff. In the Small Watershed, streamflow commonly reached maximum discharges within 1 hour of the maximum precipitation intensity, and generally returned to near base flow within 1 to 2 days after precipitation ended. Peak stormflows generally exceeded base flows by one to three orders of magnitude. Runoff from Field-Site 1, which is conventionally tilled cropland on a 6-percent slope, was frequent and extremely flashy. Rainfalls of only 0.1 to 0.4 in. often produced runoff through gullies. In contrast, little runoff was discharged from the pipe-outlet terrace system at Field-Site 2, which is no-till cropland on an average 5-percent slope. During the pre-BMP period at Field-Site 2, only rainfalls greater than 0.5 in. produced runoff and most of it during winter rainfall on frozen ground.

The concentrations of nitrate in ground water from wells in agricultural areas underlain by carbonate rock in the regional study area often exceeded the USEPA drinking-water MCL of 10 mg/L as N. Atrazine was detected in many samples. During the pre-BMP period, nitrate concentrations at Field-Site 1 ranged from 5.6 to 34 mg/L as N and, at Field-Site 2, ranged from 7.4 to 130 mg/L as N. At Field-Site 1, atrazine, metolachlor, and cyanazine were detected in ground water soon after application of the herbicides in spring; atrazine was persistent in the ground water throughout most of the year.

Concentrations of nitrate were higher and herbicide concentrations were detected more frequently in base flow from streams flowing through the agricultural, carbonate areas of the Conestoga River Headwaters Basin than from streams draining the nonagricultural, noncarbonate areas of the basin. For the pre-BMP period in the Small Watershed study, the median concentrations of nitrate and phosphorus in base flow increased from 2.7 mg/L as N and 0.04 mg/L as P in the nonagricultural, noncarbonate area of the basin to 8.1 mg/L as N and 0.14 mg/L as P as the stream flowed through the agricultural, carbonate areas of the basin. In addition to ground-water discharge, manure from cows in streamside pastures and nutrient-rich streambank sediments from trampled streambanks are major sources of nutrients to base flow. In base flow in the Small Watershed, dissolved-nitrate concentrations were greatest in the winter months and least in the summer months, and total phosphorus concentrations were greatest during the summer months and least in the winter months. The primary mechanism for this variation is the amount of base-flow discharge and the associated dissolved-oxygen concentration in the stream. The maximum concentrations of nutrients, except nitrate, and suspended sediment in streamflow in the Small Watershed were measured in samples collected during storms after spring plowing and crop fertilization. Maximum concentrations of nitrogen, phosphorus, and suspended sediment measured at the mouth of the Small Watershed during the pre-BMP period were 28 mg/L as N, 17 mg/L as P, and 34,300 mg/L, respectively. The maximum instantaneous concentrations of total nitrogen and total phosphorus in runoff from the field sites, without moderation by base flow, were substantially higher than those in stormflow from the Small Watershed—79 mg/L as N and 30 mg/L as P at Field-Site 1 and 64 mg/L as N and 44 mg/L as P at Field-Site 2. The maximum suspended-sediment concentration in runoff samples from Field-Site 1, where the soil was conventionally tilled across gullies in the spring and crop cover was plowed under, was 74,000 mg/L. In contrast, at Field-Site 2, where no-till practices resulted in continuous crop cover and pipe-outlet terraces were in place, the maximum suspended-sediment concentration was 2,800 mg/L.

Partitioning of annual discharge and constituent yields between ground-water and surface-runoff components was similar for two streamflow sites (Conestoga River at Terre Hill, 49.2 mi^2; and at the mouth of the Small Watershed, 5.8 mi^2) in the Conestoga River Headwaters Basin. The streamflow sites drained agricultural areas that are about 50 percent underlain by carbonate rock. Field-Sites 1 and 2 were more dominated by ground water than the stream sites. The two field sites drained agricultural areas completely underlain by carbonate rock. Base flow was 60 to 75 percent of the total streamflow at the two streamflow sites, and ground water was 82 and 98 percent of the water discharged from Field-Site 1 and Field-Site 2, respectively. About 65 percent of the nitrogen load in streamflow was discharged during base flow, and 88 and 99 percent of the total nitrogen load discharged with water from Field-Site 1 and Field-Site 2, respectively, was transported by the ground-water system. Nitrate was the predominant form of nitrogen discharged from all sites. About 73 to 85 percent of the phosphorus load in streamflow was discharged during stormflow from the stream sites, and 97 and 70 percent of the total phosphorus load discharged from Field-Site 1 and Field-Site 2, respectively, were transported with runoff. Between 95 and 100 percent of the suspended-sediment load was discharged with stormflow or runoff from all sites.

Estimates of water and nitrogen inputs and outputs from the field sites were made. At Field-Site 1, 41 to 42 percent of the precipitation infiltrated to the ground water, and 10 percent of the precipitation became runoff. At Field-Site 2, 53 percent of the precipitation infiltrated, and 4 percent of the precipitation became runoff. About 95 percent of the total nitrogen input to the field sites was from manure. At Field-Site 1, about 20 percent of the nitrogen input was discharged with ground water and 2.5 percent with surface runoff. At Field-Site 2, about 35 percent of the nitrogen input was discharged with ground water and 0.4 percent with surface runoff. Most of the remaining nitrogen was accounted for in crop uptake and volatilization. About 5.5 percent of the phosphorus applied to Field-Site 1 and 0.5 percent of the phosphorus applied to Field-Site 2 was discharged with runoff.

Effects of Best-Management Practices

Pipe-outlet terraces were constructed at Field-Site 1 to reduce soil erosion and to retain soil-associated nutrients on the field. There was no measurable overall change in the partitioning of runoff and recharge quantities as a result of terracing, although the characteristics of runoff changed, and the runoff threshold increased. After terrace construction, runoff formed pools behind each terrace, which drained slowly over periods of as much as 24 hours. Flashy runoff peaks before terracing were replaced by a rapid rise in runoff, and then runoff slowed in a stepwise manner as each terrace drained. Storms of less than 0.4 in. of precipitation commonly produced runoff before terracing but rarely produced runoff after terracing. A double-mass comparison of water-level data from wells within and outside the terraced area of the field site indicated no measurable changes in recharge as a result of terracing. Pre- and post-BMP runoff data were compared using regression and analysis of covariance techniques and by Mann-Whitney testing of runoff data clustered by storm characteristics. The results of these analyses indicate that soil erosion was reduced after terracing, but total nitrogen and total phosphorus losses to runoff were not significantly different before and after terracing. The terraces reduced runoff energy and, thus, the ability of runoff to transport sediment; pooling in the terraces allowed time for deposition of suspended material before discharge through the pipe-outlet system. Although the suspended-sediment yield substantially exceeded the NRCS T value (erosion rate) in 1984 (before terracing), suspended-sediment yields were substantially less than the T value for all years after terrace installation and stabilization. Moderate storms carried about the same amount of sediment relative to total storm runoff before and after terracing, but large storms carried much less sediment relative to runoff after terracing. Reduced soil erosion did not result in reduced phosphorus losses from the field, as had been anticipated in selecting the BMP. The small set of available particle-size data indicates that much of the fine sediment, with which the phosphorus is primarily associated, continued to be discharged after terracing and that dissolved phosphorus concentrations in runoff may have increased. After terracing, the highly variable ammonia plus organic nitrogen yields, which made up most of the total nitrogen yield, did not significantly change relative to runoff. Total nitrate plus nitrite transported by runoff increased after terracing, regardless of the type of storm. Increased soil moisture, as well as increased contact time and area of the runoff water with the soils as a result of terracing, probably led to the increased availability of nitrate to runoff. Before terracing, about 8 percent of the annual total nitrogen yield was nitrate plus nitrite; after terracing, this increased to about 37 percent. However, the increase in concentrations of nitrate plus nitrite in runoff did not produce a significant change in the overall total nitrogen yields with respect to runoff after terracing. After terracing, concentrations of nitrate in ground water increased significantly at four of the six wells monitored, did not change at one well, and decreased significantly at one well. A qualitative assessment based on ground-water, surface-runoff, and agricultural-activity data indicated that terracing probably led to increased concentrations of nitrate in ground water. The same mechanisms that resulted in increased concentrations of nitrate in surface runoff could have led to increased concentrations in infiltrating water. The areas upgradient from the two wells in which nitrate concentrations did not increase received substantially reduced nitrogen applications after terracing than before as a result of crop changes upgradient from these wells after terracing.

Nutrient management was implemented at Field-Site 2 and in the Nutrient-Management Subbasin of the Small Watershed in an effort to reduce nitrate concentrations in ground water and streamwater, respectively. Nutrient-management plans recommended limiting nitrogen application to the amount required to meet crop requirements. Nutrient-management plans were based on nutrient content of manure, residual manure nutrients from applications in previous years, and estimated crop yields. As a result of nutrient-management implementation, 22 percent less nitrogen and 29 percent less phosphorus, on average, were applied annually during the post-BMP period at Field-Site 2, and 32 percent less nitrogen and 35 percent less phosphorus, on average, were applied annually during the post-BMP period in the Nutrient-Management Subbasin.

At Field-Site 2, median concentrations of nitrate decreased significantly from the pre- to the post-BMP period in water samples from three of four monitored wells. A quantitative evaluation of the ground-water and agricultural-activity data from Field-Site 2 indicated that the decrease in nitrate concentrations was due to a decrease in surface-applied nutrients and, therefore, a result of implementation of the nutrient-management practice. The analysis further indicated that ground-water quality responded to changes in surface-applied nitrogen at the site in less than 2 years. Mean concentrations of total nitrogen and total phosphorus in storm runoff from the terraced areas of Field-Site 2 did not change significantly after the implementation of nutrient management. Runoff quantities and nitrogen loads were a very small part of water and nitrogen discharged from the site.

In the Small Watershed study, a qualitative assessment of the effects of nutrient management on surface-water quality indicates that nutrient management was beneficial in preventing increased concentrations of nitrate plus nitrite in stream base flow. Nitrate plus nitrite makes up about 70 percent of the total nitrogen load in streamflow from the Small Watershed. Step-trend tests of flow-adjusted concentrations of nitrate plus nitrite showed no significant change in the Nutrient-Management Subbasin after implementation of nutrient management but indicated a significant increase in concentrations for the entire Small Watershed. Analysis of covariance and time-series analysis of paired-watershed data indicated that dissolved nitrate plus nitrite concentrations in base flow in the Nutrient-Management Subbasin did not change significantly after implementation of nutrient management, but concentrations increased in the Nonnutrient-Management Subbasin after implementation. Further qualitative analysis of data from Field-Site 2 and the Nutrient-Management Subbasin indicated that nutrient management, practiced according to plan and given sufficient time, may be effective in reducing nitrogen loads in streamflow.

The findings of this study indicate that agricultural-management practices selected with consideration of their overall effect on both surface- and ground-water systems are most likely to result in improved water quality. Where sediment and phosphorus are contaminating water supplies, management practices targeted to control surface runoff are desirable. However, particularly in carbonate-rock areas, surface control of transport of soluble agricultural chemicals, such as nitrates and some herbicides, is essential for protecting ground-water quality. Where soluble chemicals are contaminating water supplies in carbonate-rock areas, BMP's selected to reduce transport to the ground-water system are desirable. In addition, data from this study indicate that (1) use of nutrient-management practices on a continuing basis would allow the maximum water-quality benefits of nutrient management to be achieved, and (2) elimination of nutrient applications on frozen soils would be a beneficial component of nutrient-management programs.

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APPENDIX

APPENDIX: BIBLIOGRAPHY OF CONESTOGA RIVER HEADWATERS PROJECT REPORTS

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