EFFECTS OF RECLAMATION ON WATER QUALITY AND GEOCHEMICAL PROCESSES IN LAKES IN AN ABANDONED SURFACE COAL MINE IN HENRY COUNTY, MISSOURI--AUGUST 1988-MAY 1990

By Dale W. Blevins and Andrew C. Ziegler

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	**By**	**To obtain**
acre	0.4047	hectare
cubic foot per second	0.02832	cubic meter per second
foot	0.3048	meter
gallon per minute	0.06308	liter per second
inch	25.4	millimeter
mile	1.609	kilometer
square mile	2.590	square kilometer
tons per acre	2,242	kilograms per hectare

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) by using the following equation:

$$^{\circ}F = 1.8\ ^{\circ}C + 32$$

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.

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ABSTRACT

Almost 1,000 of 2,400 acres of coal-mine spoil near Montrose in Henry County, Missouri, were partially regraded, limed, and revegetated by 1988. Hydrochemical data were collected to determine the effects of reclamation on water quality.

Ground-water samples from most wells had pH values greater than 6.0 before reclamation. However, acidic water (pH 3.9 to 5.3) in two wells increased about one unit after reclamation. Shallow ground water had pH values that were 0.2 to 0.5 unit less, bicarbonate concentrations that were 130 to 297 milligrams per liter less, and iron concentrations that were 14 to 91 milligrams per liter more than ground water near the bottom of the spoil. Siderite precipitation may control iron concentrations at depth. Runoff remained acidic (pH less than 4.5) during at least one storm after reclamation at 8 of 12 sites.

Most lakes that were acidic before reclamation (pH less than 4.5) remained acidic after reclamation. However, the pH of six formerly acidic lakes, including lake LS, increased from less than 4.5 to more than 6.0 after reclamation. Lake LS outflow substantially increased pH values downstream during low flow. The deeper ground-water-supplied lakes (pH 6.2 to 8.5) were more basic than shallow ground-water-supplied lakes primarily because of the more acid-neutralizing ability of deep ground water as indicated by lower ferrous iron to bicarbonate ratios. Seasonal stratification of deep lakes assisted in maintaining the neutral pH values of deep lakes because ferrous iron in anaerobic hypolimnions precipitated as siderite and iron sulfides and was buried in lake bottom sediments inhibiting acid-producing reactions, such as the oxidation of ferrous iron.

Generally, the pH of laboratory mixtures of samples from shallow acidic lakes and deep neutral lakes was greater than 6.0 if the mixtures contained less than one-third acidic lake water. Discharges from shallow acidic lakes were substantially less than one-half of the discharge from nearby deep neutral lakes. Therefore, mixtures resulting from the drainage of the shallow acidic lakes into nearby deep neutral lakes could be expected to have pH values greater than 6.0.

INTRODUCTION

Surface coal mining near Montrose, Missouri, supplied fuel for the Montrose Power Plant from 1956 (Kansas City Power and Light, written commun., 1954) through 1988. Major reclamation of surface mines began about 1972, but most of the mined lands northwest of Montrose were unreclaimed as of 1986. The mined area of 2,400 acres northwest of Montrose contained more than 100 lakes and several streams. Many of these lakes and streams had pH values between 3.0 and 6.0. A previous study by the U.S. Geological Survey characterized the hydrology and water quality of the mine spoil before reclamation (Blevins, 1991). The Missouri Department of Natural Resources, Land Reclamation Commission, began leveling the tops of spoil ridges and revegetation of barren mine spoil in the fall of 1986 and completed most reclamation activities during 1987. This study to determine the effects of reclamation and lake chemistry on water quality was conducted by the U.S. Geological Survey, in cooperation with the Missouri Department of Natural Resources, Land Reclamation Commission.

Purpose and Scope

The purpose of this report is to present the results of a hydrologic study made in west-central Missouri near Montrose at an abandoned surface coal mine from August 1988 to May 1990. Objectives of the study were to determine changes in surface- and ground-water chemistry since mine-reclamation activities were completed during 1987; determine the reasons for differences in water chemistry between shallow and deep lakes; and determine probable changes in pH values caused by draining shallow lakes in which pH values were less than 4.5 into deep lakes in which pH values were greater than 6.

Description of Study Area

The study area consists of about 3,000 acres in west-central Missouri (fig. 1) underlain by Pennsylvanian shale, sandstone, limestone, and coal of the Cherokee Group[1] (fig. 2). The hydrology, geology, and water chemistry of the study area have been described by Ziegler (1989) and Blevins (1991). The underclays, shales, and coals of the Tebo[1] and Scammon[1] Formations contribute most of the acidity, iron (Fe), and other trace elements to mine waters (Ziegler, 1989). Between 1956 and 1973, 2,400 acres of the study area were surface mined. In most places, only coals in the Weir[1] and Tebo[1] Formations were mined; however, coals in the Fleming[1] and Croweburg[1] Formations also were recovered where they had not been eroded and were thick enough to be mined economically (Peabody Coal Company maps of the Power Mine, Montrose, Missouri).

Thirty-three percent of the mined area had been reclaimed by regrading and revegetation before 1986. Reclaimed areas have smooth topography and usually are covered with grass. Topsoil had been applied to about 20 percent of the reclaimed area (fig. 1). By 1988, almost 1,000 acres of the remainder of the study area were partially regraded and revegetated by the Missouri Department of Natural Resources, Land Reclamation Commission (fig. 1). Reclamation activities during 1986 through 1988 included leveling the tops of spoil ridges and revegetating the tops of the ridges with grasses and trees. About 40 acres between lakes LM and LEE (fig. 1) were covered with fly ash from the power plant. This area was regraded, intensely limed, and revegetated during 1987 (fig. 1). About 450 acres of ungraded spoil is covered with trees and was not included in the most recent reclamation activities.

The study area has more than 25 lakes caused by last-cut and haul-road excavations that have become filled with water. Many more smaller bodies of water are present between ridges of spoil. These ridges cause a large part of the mined area to have internal drainage. The western 1,200 acres of the study area are drained by Horn Branch, and the eastern part is drained by six smaller streams (fig. 1). This study concentrated on areas that were partially regraded and revegetated from 1986 through 1988, approximately corresponding to the Horn Branch basin (fig. 1).

Study Methods

Data were collected at several sites to determine the water quality of the study area after reclamation. Water levels in 21 wells were measured quarterly, using a steel tape, to determine seasonal and spatial variations in ground-water levels. Wells were cased with 2-in.- (inch), 3-in.-, or 4-in.-diameter plastic pipe that was slotted in the bottom 5 ft (feet). Water levels in 28 lakes were monitored with quarterly staff gage readings to determine seasonal and temporal variations in lake levels. Altitudes of lake staff gages and water-level measuring points were determined by land survey from benchmarks set by a contractor for the Missouri Land Reclamation Commission during reclamation activities. Streamflow was continuously monitored at two sites on Horn Branch (sites Q1 and Q3, fig. 1) and one major tributary (site Q2). Weirs with 90 degree notches at sites Q1 and Q3, and a 12-in. diameter plastic pipe at site Q2 were rated with discharge measurements, to monitor discharge

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[1] Unit follows the usage of the Missouri Division of Geology and Land Survey.

at these lake outflow sites. Stage-discharge relations were determined with volumetric and pygmy current-meter discharge measurements. Rainfall was continuously monitored at one site in the study area (site RG, fig. 1). Daily precipitation data from the National Weather Service Station (National Oceanic and Atmospheric Administration, 1988-90) near Appleton City (fig. 1), 7 mi (miles) from the study area were used during periods of missing record.

Surface- and ground-water samples were collected to determine water-quality characteristics after reclamation and identify hydrochemical processes. Specific conductance, pH, Eh (oxidation-reduction potential), temperature, and dissolved oxygen were measured at stream, lake, and ground-water sites. Samples were analyzed for hydrogen sulfide (H_2S) at selected lake and ground-water sites. Stream sites Q1, Q2, Q3, and Q4 (fig. 1) were equipped with minimonitors to continuously monitor fluctuations in specific conductance, pH, and temperature caused by runoff and seasonal changes. Specific conductance was measured onsite with a portable meter with manual temperature compensation and reported in microsiemens per centimeter at 25 °C (degrees Celsius). The specific conductance meter was calibrated in a range bracketing the sampled waters. The pH was measured electrometrically, and the pH meter was calibrated with a pair of buffered standards that bracketed each water sample. The Eh was measured with a platinum-silver silver-chloride electrode and reported relative to the standard hydrogen electrode. Between each measurement the electrode was cleaned and checked against standard Zobell solution with a potential of 0.43 volt. Temperature was measured with a mercury thermometer and reported to the nearest 0.5 °C. Dissolved oxygen concentrations in all samples were measured electrometrically, and the meter was calibrated in an air chamber saturated with water and checked in a solution of sodium thiosulfate containing less than 0.1 mg/L (milligram per liter) dissolved oxygen. Dissolved oxygen concentrations for selected ground-water and lake-hypolimnion samples also were measured using a Chemetrics[1] low dissolved-oxygen kit containing Rhodazine D and a spectrophotometer set at a wavelength of 555 nanometers. The Chemetrics method had a lower detection limit (0.01 mg/L) than the electrometric method (0.1 mg/L).

Selected lake and ground-water samples were analyzed for H_2S with a semiquantitative test using the procedures outlined by the Hach Company[1] The H_2S and sulfide in the water were evolved as H_2S gas by adding sodium bicarbonate tablets. As the H_2S evolved from the water, it reacted with a lead acetate indicator paper to form lead sulfide. Concentrations of H_2S were determined by visual comparison to a chart. The detection limit for the test was 0.1 mg/L.

Total and dissolved concentrations of Fe in water samples were determined at the time of sample collection and by laboratory analysis. Onsite determinations of Fe were measured colorimetrically with a spectrophotometer set at a wavelength of 510 nanometers. Methods were adapted from those described by the Hach Company, with Hach reagents containing 1,10 phenanthroline and hydroxylamine-hydrochloric acid.

Six lakes were selected for detailed sampling to determine possible causes for differences in lake chemistries between the shallow and deep lakes that were identified by Blevins (1991). Lakes LN (north and south), LP (north and south), LQ, LS, LX, and LEE (fig. 1) were sampled after the onset of lake stratification, maximum lake stratification, and after destratification. Location of the thermocline (layer of lake where temperature decreases markedly with depth) and chemocline (layer of lake where chemical concentrations grade from concentrations in epilimnion to concentrations in hypolimnion) in each lake was determined by measuring the specific conductance, pH, temperature, and dissolved oxygen with increasing depth using a minimonitor or by analysis of samples collected using a Van Dorn sampler. Water samples were collected in the epilimnion (upper layer of lake where

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

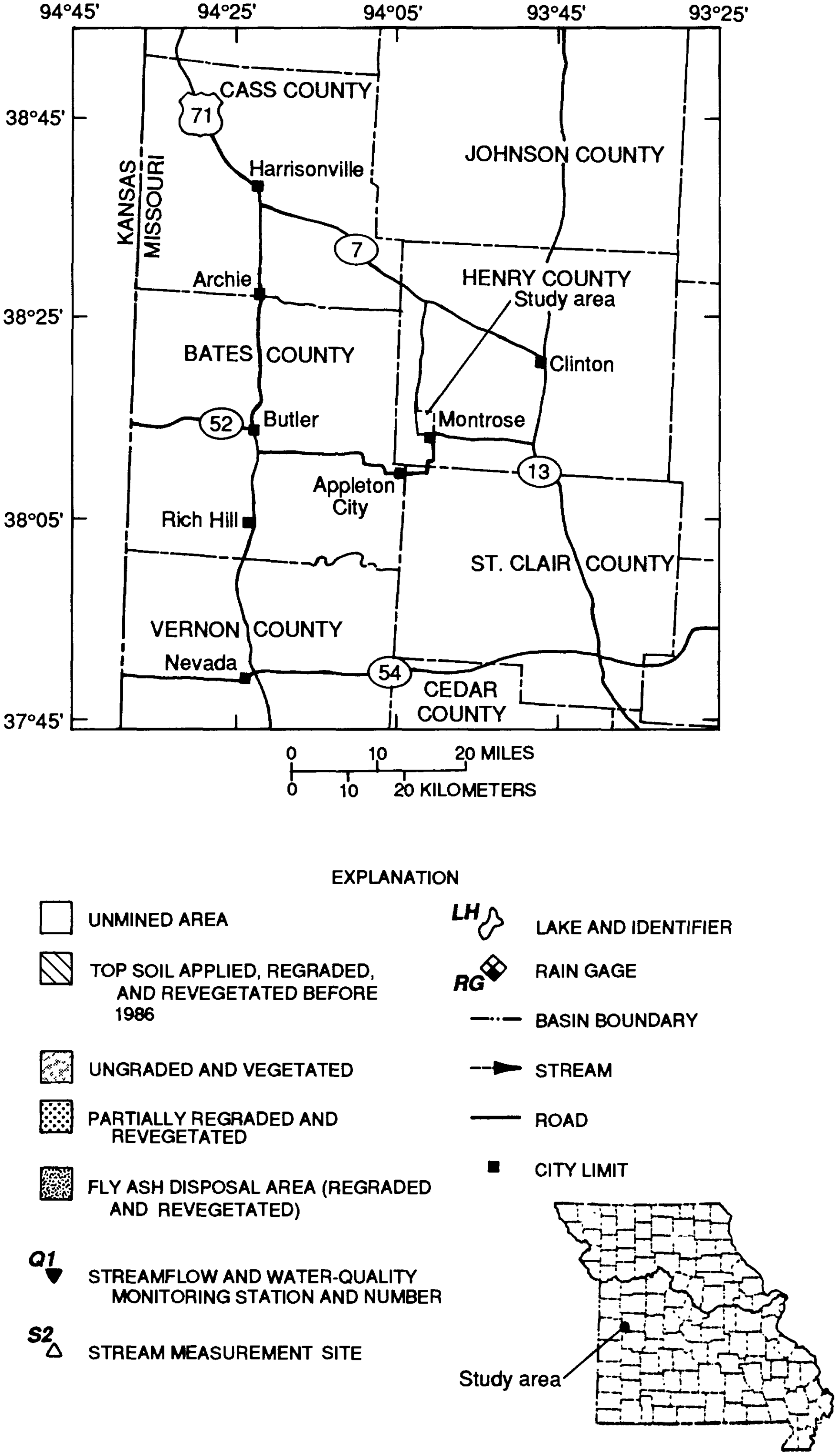


Figure 1.--Location of study area, surface features, and surface-water-data collection sites.

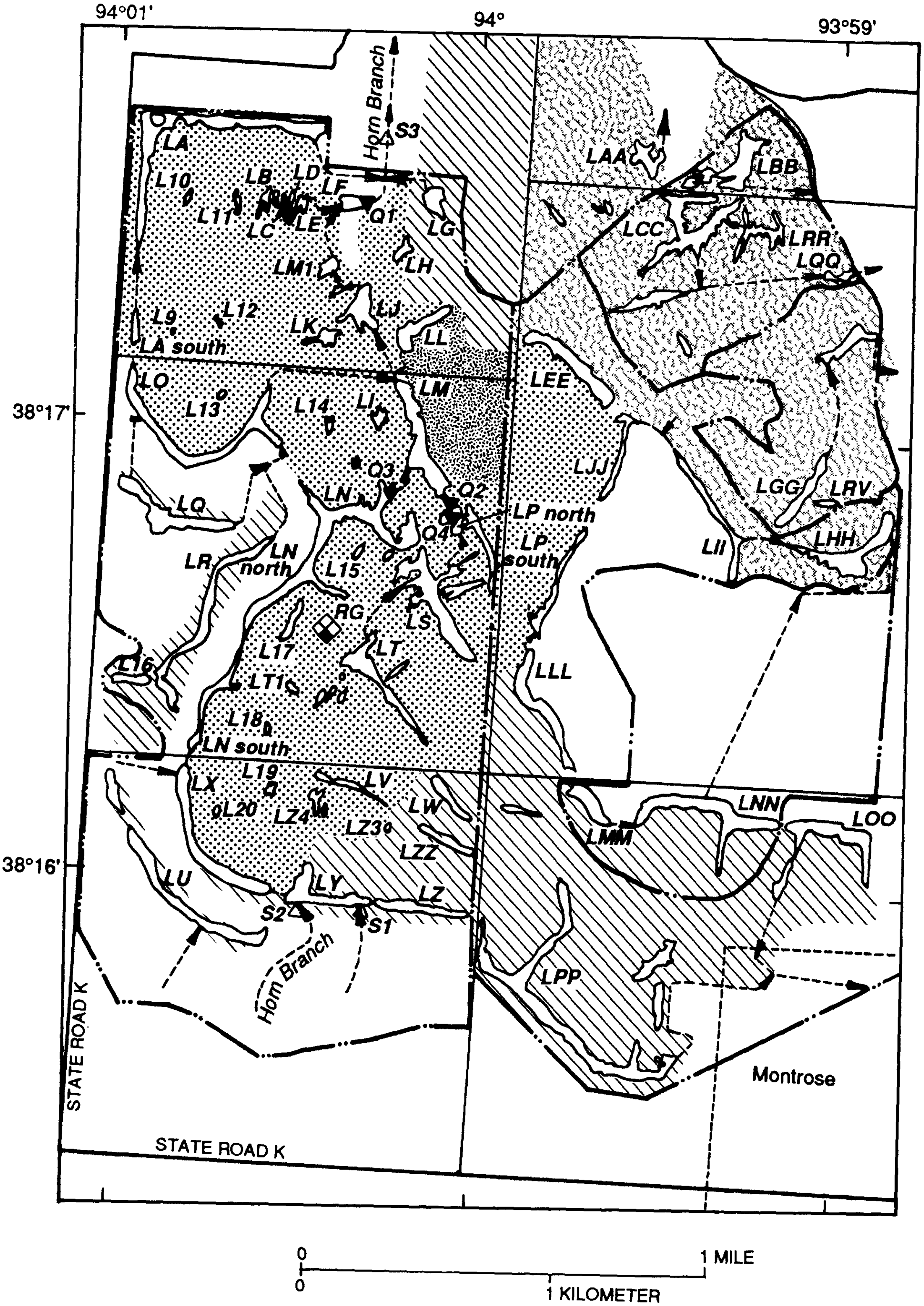
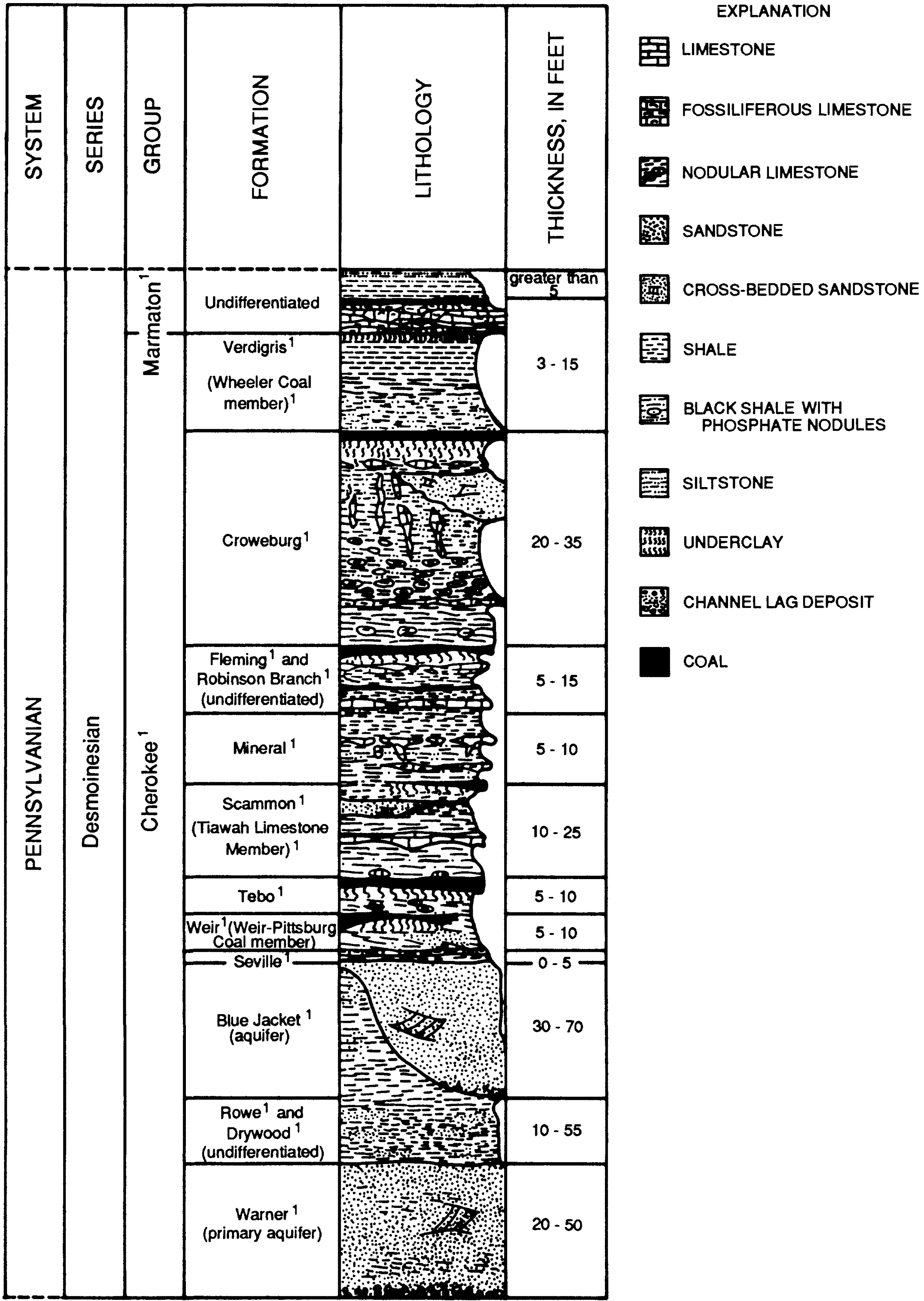


Figure 1.--Location of study area, surface features, and surface-water-data collection sites--Continued.



[1] Unit follows the usage of Missouri Division of Geology and Land Survey. Unit thicknesses and lithologies below the Seville Formation were obtained from well logs on file at the Missouri Division of Geology and Land Survey at Rolla, Missouri.

Figure 2.--Generalized stratigraphy of the study area.

temperature is virtually uniform), metalimnion (middle layer of lake where temperature decreases markedly with depth), and hypolimnion (lowermost layer of lake where temperatures are nearly uniform) to determine differences in chemistries of the lake layers.

From 1988 through 1990, surface-water samples were collected at 47 sites during low flow and 13 sites during runoff to identify possible changes in water chemistry caused by reclamation activities. Stream samples were collected from the midpoint of the stream cross section in polyethylene bottles.

Ground-water samples were collected from 13 wells to determine possible changes in water chemistry caused by reclamation activities. Ground water from wells that would not sustain pumpage of about 0.5 gal/min (gallon per minute) was sampled with a bailer several minutes after removing one well volume by pumping. Larger-yielding wells were sampled several minutes after the specific conductance and temperature of water pumped from the well had stabilized. Ground-water samples were collected in a polyethylene churn splitter before filtering and preservation.

Laboratory analyses of water samples were made by the U.S. Geological Survey, in accordance with procedures described by Fishman and Friedman (1989). All constituents analyzed in the dissolved phase were determined from water samples filtered at the time of sampling through a 0.10 µm (micrometer) cellulose nitrate filter in a polyvinyl chloride chamber using a peristaltic pump as the pressure source. Samples analyzed for anions (except dissolved nitrogen species) were filtered but otherwise unpreserved. Samples analyzed for dissolved nitrogen species were preserved with 1 mL (milliliter) of mercuric chloride, chilled, and maintained near 4 °C until analysis. Water samples analyzed for total organic carbon were collected directly from a stream, pump outflow, or Van Dorn sampler into a glass bottle, chilled, and maintained near 4 °C until analysis. Water samples analyzed for trace elements were acidified onsite with double-distilled, laboratory-grade nitric acid to a pH less than 2.

Acidity is defined in this report as the capacity of a solution to react with hydroxyl ions and was determined by endpoint titration with sodium hydroxide to a pH of 8.3. Alkalinity is defined similarly as the capacity of a solution to react with hydrogen ions (H^+) and was determined, at the time of sample collection, by incremental titrations with 0.16 normal sulfuric acid made to the inflection point of the titration curve at a pH of about 4.5, where nearly all the carbon dioxide (CO_2) species are in the form of carbonic acid (H_2CO_3; method described by Brown and others, 1970).

Bottom-sediment samples were collected from lakes LN north, LN south, LQ, LS, and LEE with a 2-in. polyvinyl chloride sampling tube. The tube and sample were then frozen and the top 6 in. were sawed off. The ends of the tube were then sealed and sent to the laboratory. Mineralogic and total Fe analyses were used to determine solid phases and possible sinks for selected elements. Analyses were done by the U.S. Geological Survey in Lakewood, Colorado. Bottom-sediment samples were collected when lakes were stratified and after destratification, if it occurred. Total Fe was determined using inductively coupled plasma and atomic-emission spectrometry. Mineralogy of the bulk samples was determined using X-ray diffraction and optical microscopy. An aliquot of the bulk sample was panned, dried, and floated in bromoform to separate minerals with specific gravities greater than 2.85. X-ray diffraction and optical microscopy also were used to determine the mineralogy of the heavy-mineral separates. Analyses for total organic carbon were done using infrared spectrometry.

Computations of saturation indices were done using the chemical equations and equilibrium constants in a computer algorithm called WATEQ4F (Plummer and others, 1976; Ball and others 1987). WATEQ4F computes saturation indices for several minerals commonly associated with mine drainage and was used to identify geochemical reactions that could explain lake and ground-water chemistry.

Acknowledgments

Appreciation is extended to the Peabody Coal Company staff at the Power Mine for access to their property and to various types of data from their files. Also, land owners near the mine were cooperative in permitting access to their land and wells. Support of this study by the U.S. Department of Interior, Office of Surface Mining Reclamation and Enforcement also is acknowledged. However, the contents of this publication do not necessarily reflect the views and policies of the Office of Surface Mining Reclamation and Enforcement.

EFFECTS OF RECLAMATION ACTIVITIES ON WATER QUALITY

Water samples from runoff, ground-water, lake, and stream sites were analyzed to document changes in water quality that have occurred since partial regrading and partial revegetation of spoil. Changes in water quality were determined by comparing the chemical analyses from 1984 to 1986 (Blevins, 1991) to analyses of samples collected during this study at the same or similar sites.

Runoff

Blevins (1991) concluded that 20 percent of the Horn Branch drainage basin did not contribute runoff to streams because runoff was trapped between spoil ridges. The flattening of spoil ridge tops and revegetation would be expected to increase ponding behind spoil ridges and increase evapotranspiration, thereby decreasing the percentage of rainfall leaving Horn Branch basin as runoff. The percentage of rainfall leaving the Horn Branch basin as runoff decreased slightly from 32 percent from 1984 to 1986 to 28 percent from November 1988 to May 1990 (table 1) using methods used by Blevins (1991). However, this small decrease may be because of differences in total rainfall and evaporative demand during the study.

Table 1.--*Rainfall and volume of surface outflow in the Horn Branch basin before and after reclamation*

[Stream gaging station at site Q1 (fig. 1) with a drainage area of 1.88 square miles]

State of reclamation activities	Period	Rainfall (inches)	Surface outflow[a]		Approximate percentage lost to evapotranspiration[b]
			Inches	Percentage of rainfall	
Before	September 7, 1984, to September 6, 1986	99.0	31.5	32	68
After	November 29, 1988, to May 15, 1990	50.4	14.2	28	72

[a] Volume expressed as equivalent depth over the 1,200-acre basin.

[b] Assuming negligible gains or losses to the regional ground-water system and ground-water storage.

Blevins (1991) analyzed samples of runoff collected May 13, 1985, from six unreclaimed and unvegetated sites in the study area; the pH values for runoff were between 2.9 and 3.5. Rapid acidification of rainwater probably was because of dissolution and subsequent hydrolysis of ferric iron (Fe^{+3}) sulfates. This process is described by Nordstrom (1982). Miller (1979) suggested that when jarosite and ferric hydroxide are present, pH values of acidic spoil water are buffered between 3.0 and 3.4, which was similar to pH values of runoff before reclamation (Blevins, 1991).

During 1987, large quantities of agricultural lime were applied to spoil while regrading and revegetation operations were in progress (fig. 3). Lime was applied to most of the area at the rate of 30 tons/acre (tons per acre) in the spring of 1987. Additional lime was added in the fall of 1987 according to the quantities determined by soil analyses. Runoff samples were collected about 2 years after the initial lime application.

Results of runoff sampling during four storms and the rainfall totals for the 48-hour period preceding sampling are listed in table 2, at the back of this report. The pH of runoff remained less than 5.0 throughout the sampling period at four of the six mined sites sampled before reclamation (fig. 4). However, pH values of runoff increased from two to three pH units at two of the six sites (near lakes LM and LS). Lime applications probably caused the increase in pH values at these sites. Additionally, runoff from four of six mined sites not sampled before reclamation had runoff from at least one storm with a pH less than 4.5. Altogether, 8 of the 12 sites had runoff from at least one storm after reclamation with the pH less than 4.5. The decrease in the pH values at the site near lake LJJ, after the first sampling, was probably caused by acid dissolution and removal of lime in the drainage area by runoff.

Ground Water

Examination of nearby active mining pits indicates that spoil in the study area forms a water-table aquifer bounded on the sides and bottom by unmined and unsaturated Pennsylvanian rocks of low permeability that allow only small quantities of water to flow from the spoil into adjacent and underlying rocks. Water-table contours in spoil during 1984 to 1986 are illustrated in figure 5. Generally, ground-water mounds (recharge areas) overlie ridges and domes of unmined rock below the spoil and underlie shallow between-spoil-pile lakes (Blevins, 1991). Water levels averaged about 10 ft below land surface and the spoil thickness averaged about 30 ft. Generally, water levels near lakes formed in last-cut excavations have hydraulic gradients toward the lakes. Consequently, water levels in these deep lakes were a primary control of water levels in the spoil. Shallow lakes recharged ground water in topographically high areas and deep lakes received ground-water discharge in topographically low areas. Highest water levels occurred in late spring and early summer and the lowest levels were in late summer and early fall. Fluctuations in spoil-water levels closely followed monthly precipitation with a 1- to 2-week lag time (Blevins, 1991).

From 1988 through 1990, five new deeper wells were drilled near existing shallow wells and seven more wells were drilled in four new nests (wells with numbers of 40 or more were drilled during this study). Altogether water levels in 21 wells completed in spoil were measured seasonally. Mean water levels at these wells and in ground-water-supplied lakes were used to develop a water-table map of the spoil (fig. 6). Water levels were similar to those measured before reclamation. Adjacent wells screened near the top and bottom of the spoil had small or no substantial water-level differences (for examples, see water-level data for wells 13, 53, and 54; wells 30 and 50; and wells 40 and 41 in table 3, at the back of this report), indicating minimal downward gradients.

Before reclamation began, the pH values of ground water from all wells and springs, except wells W18 and W24, were from 5.7 to 7.0 (Blevins, 1991). Most of these wells were completed in the upper one-half of the spoil. Well W18 (fig. 5) was near a shallow acidic lake (L19, pH less than 4.5, fig. 1). Water from well W24 (pH 5.2 to 5.3) probably was made acidic by reaction with several feet of fly ash from a nearby power plant. Acid production in the ground-water system was limited by small dissolved-oxygen concentrations that decreased the oxidation rate of pyrite (Blevins, 1991). Also, the large bicarbonate (HCO_3) concentrations in ground water from most areas of the spoil indicated that substantial quantities of carbonate (CO_3) minerals remained in the spoil and neutralized recharge from acidic lakes similar to lake L19.

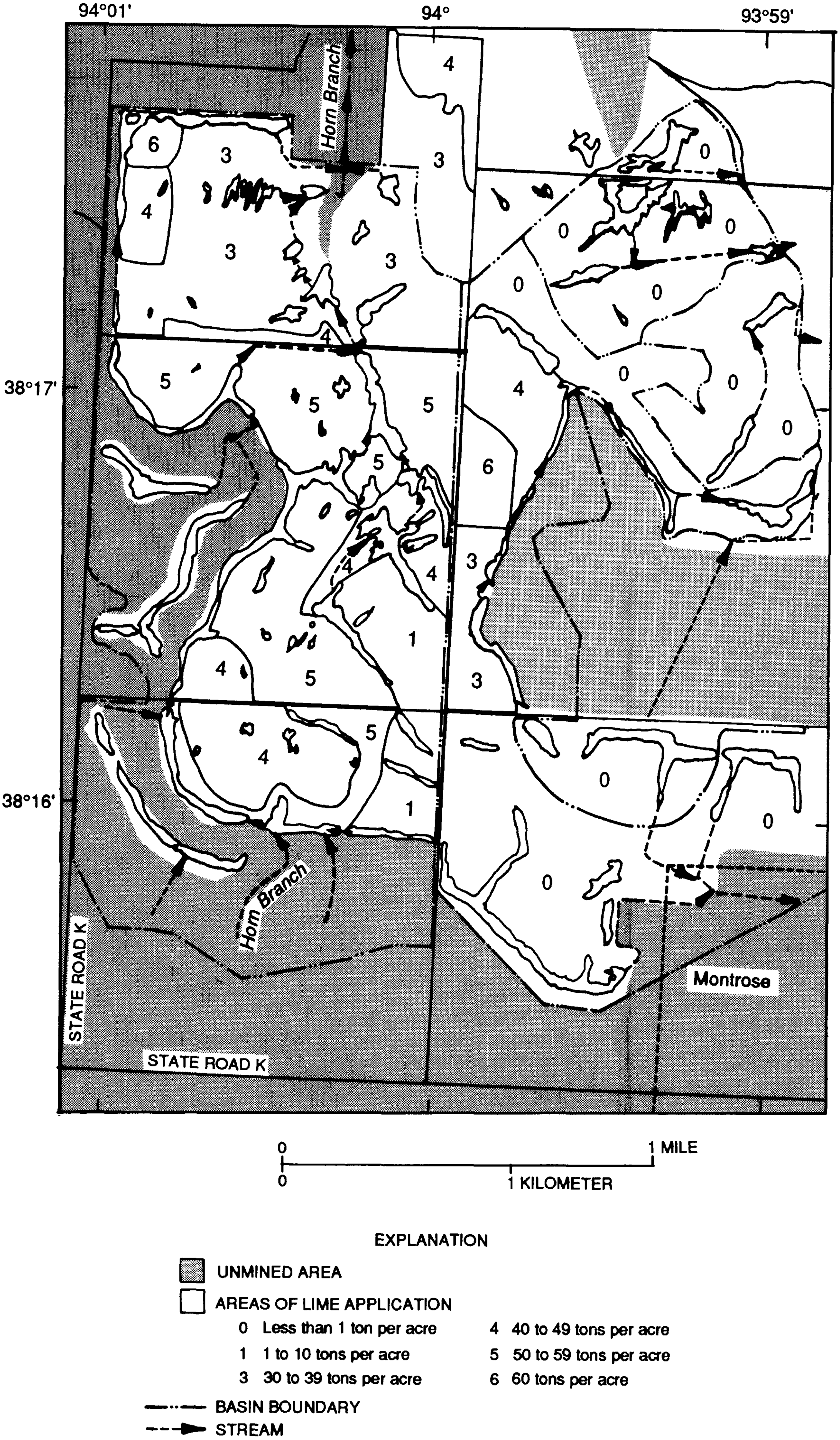
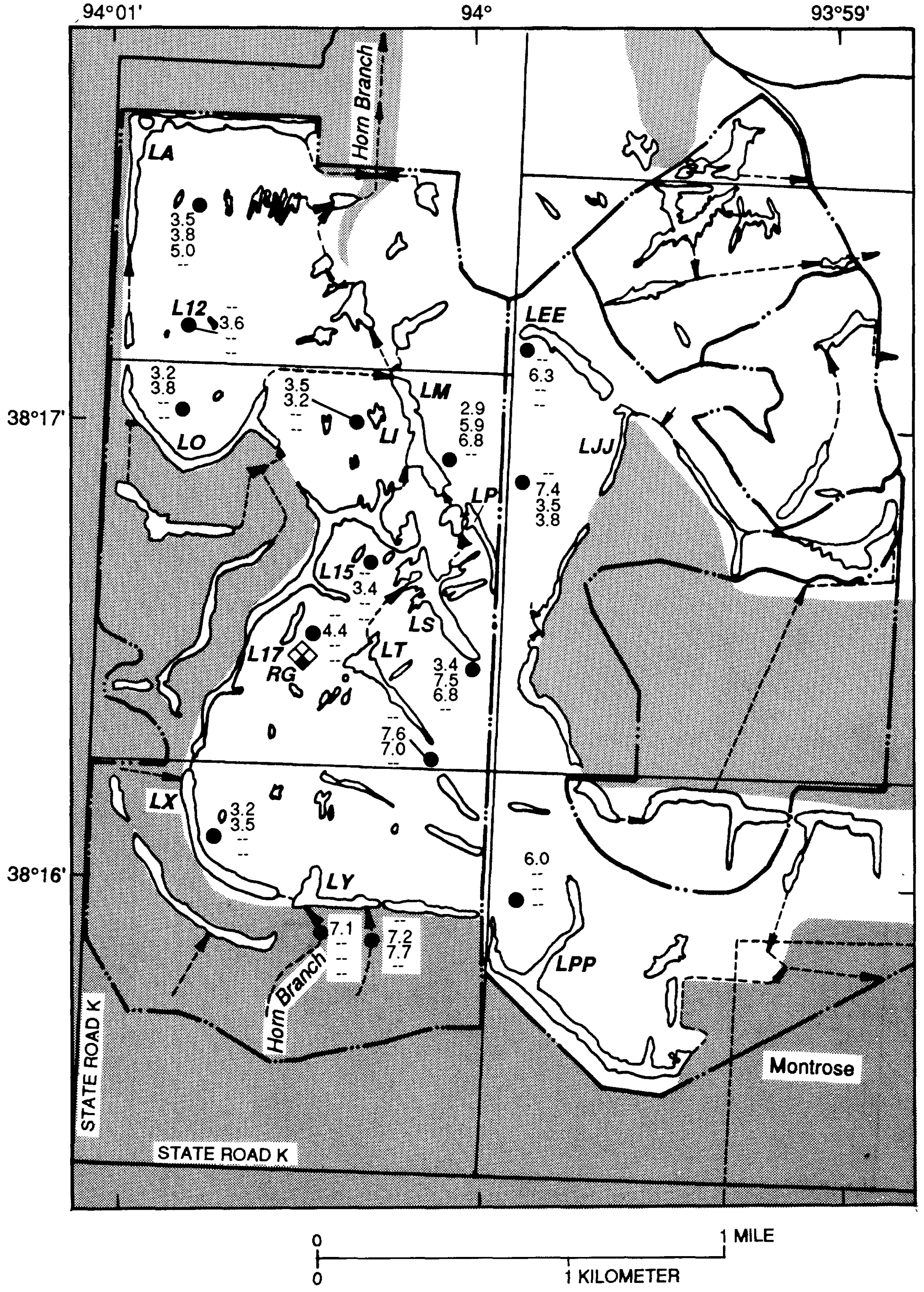


Figure 3.--Lime applications to the spoil.



EXPLANATION

☐ MINED AREA

▨ UNMINED AREA

LI LAKE AND IDENTIFIER

—··— BASIN BOUNDARY

---► STREAM

● LOCATION OF pH MEASUREMENT OF RUNOFF

2.9 5.9 6.8 --	Top number is pH value of runoff measured before reclamation (Blevins, 1991). All other numbers are pH values measured after reclamation in chronological order (table 2); --, missing value

RG ◈ RAIN GAGE

Figure 4.--pH values of runoff.

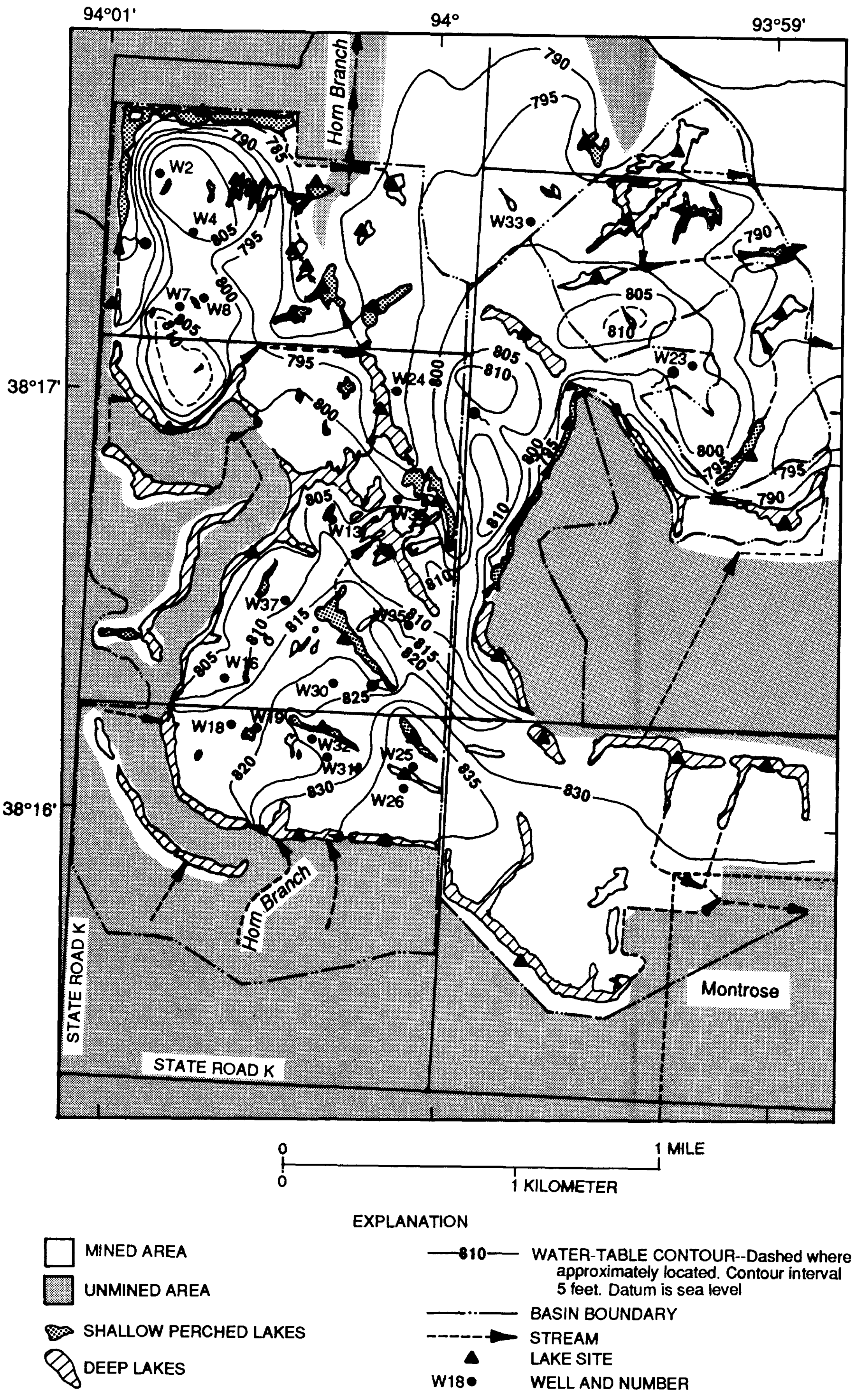


Figure 5.--Altitude of the water table in the spoil, 1984-86.

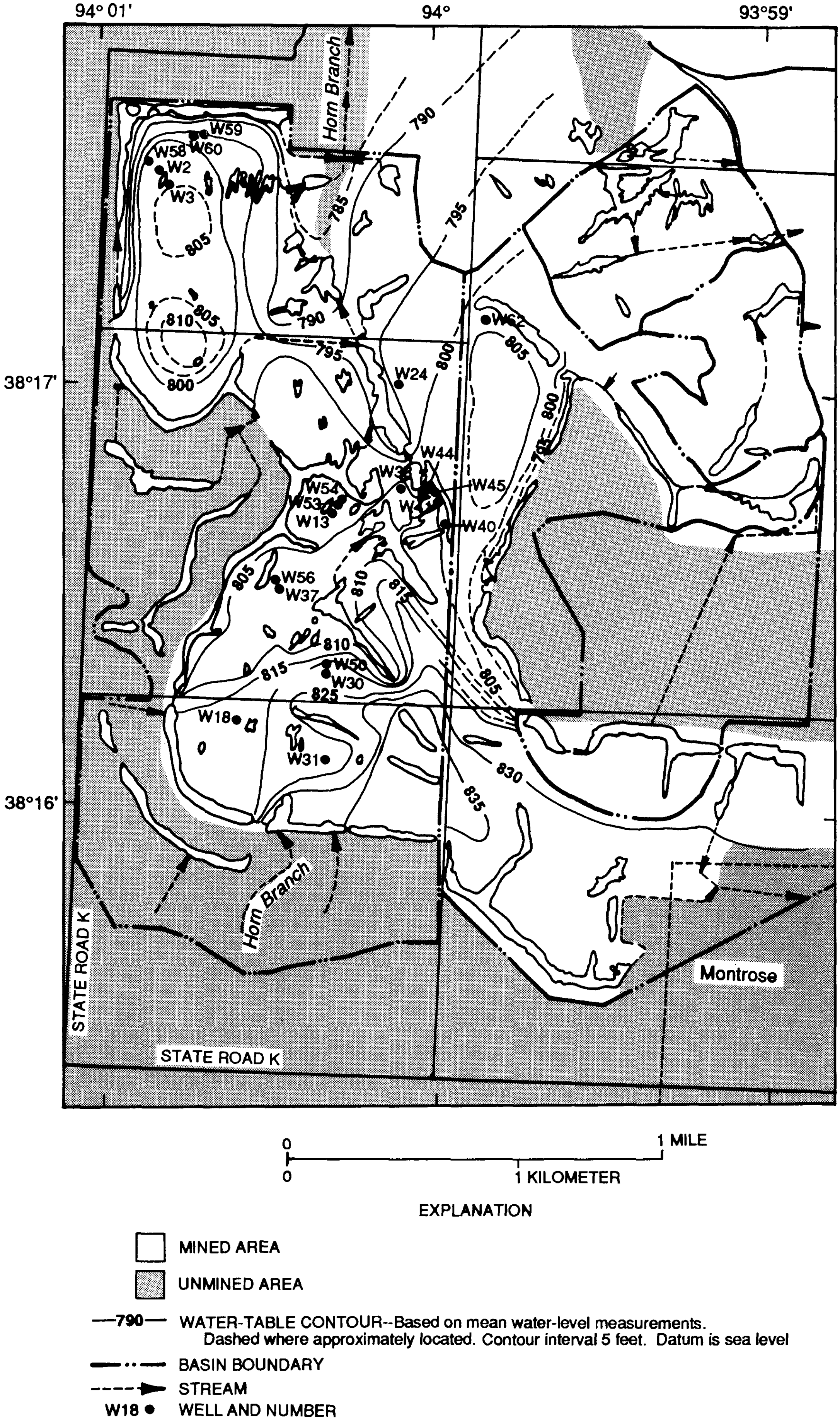


Figure 6.--Altitude of the water table in the spoil, 1988-90.

Before reclamation, water from well W18 had a pH less than 4.0 after intense rains, but the pH increased to about 6.0 during dry weather (Blevins, 1991). Well W24 had a pH of 5.2 and an Fe concentration of 220 mg/L. Changes in surface drainage caused by reclamation activities greatly decreased the quantity of acidic recharge near well W18. After completion of these and other reclamation activities, the pH of water from well W18 was 5.6 and the pH of water from W24 increased to 6.3 (table 3). Increases in the pH value of ground water may be related to quantities of lime added during reclamation activities. The spoil near well W18 had an average lime application of 45 tons/acre and spoil near well W24 had an average of 50 tons/acre (fig. 3). Small increases in pH values were noted in wells W13, W30, and W37 (table 3) where similar quantities of lime were added to the spoil.

The pH for all wells sampled during 1989, except W18 and W62, ranged from 6.1 to 6.6. Wells W18 and W62 are shallow wells, were completed in the upper 15 ft of the saturated zone, and are near small acidic lakes that recharge the spoil aquifer. Well W62 was not sampled before reclamation, but samples collected after reclamation had the lowest pH value (4.8) and largest Fe concentration (490 mg/L) of any ground water sampled in the study area.

The increase of pH values in wells W18 and W24 was accompanied by a substantial decrease in Fe concentrations. Fe concentrations in water from well W18 decreased from 310 to 190 mg/L and Fe concentrations in water from well W24 decreased from 220 to 44 mg/L. Large decreases in sulfate (SO_4) also occurred (table 3). The concurrent decrease of H^+, Fe, and SO_4 indicates decreased pyrite oxidation and acidification at the spoil surface. Blevins (1991) showed that if the mole ratio of ferrous iron (Fe^{+2}) to HCO_3 is greater than 0.5, then water has the potential to acidify. This is because HCO_3 concentrations are not sufficient to buffer the acidity produced by hydrolysis of Fe^{+3} below a pH of about 5.0. The mole ratio of Fe^{+2} to HCO_3 for water from well W18 was 2.8 and from W24 was 2.3 (table 3). Therefore, even though there have been increases in pH values of water from these wells, the potential for acidification of water from these wells remains when this water is exposed to the atmosphere.

Saturation indices [log (activity product/equilibrium constant)] for selected minerals were calculated by WATEQ4F (table 4) based on data from water analyses and onsite temperatures. Various geochemical processes not accounted for by WATEQ4F and imprecise thermodynamic data for some minerals preclude precise interpretations of the saturation indices. While a substantially negative saturation index indicates that a pure phase of that mineral cannot precipitate, it does not preclude precipitation of impure phases that WATEQ4F does not consider. Conversely, a substantially positive saturation index indicates a mineral is not thermodynamically prevented from precipitating, but may be prevented from precipitating by other physiochemical properties. A saturation index that is consistently close to zero from several samples of the same water body indicates, but does not prove, that mineral solubility limits further dissolution of that mineral. Minerals were selected for table 4 that are possible sources or sinks of calcium (Ca), CO_3, SO_4, aluminum (Al), Fe, or manganese (Mn). Most of the minerals in table 4 are commonly associated with mine drainage or were qualitatively identified by optical mineralogy, X-ray diffraction, or physical onsite tests.

The Eh values were required to speciate multivalent ions, such as Fe and Mn. Measured values of Eh in ground water were used for WATEQ4F. These values ranged from 126 to 362 mV (millivolts). The dissolved-oxygen concentrations were less than the detection limit of 0.1 mg/L and no H_2S odor was detected in any well. To determine the sensitivity of model results to errors in estimates of the Eh value, the models were run at various Eh values ranging from 100 and 400 mV. There was little change in dominant aqueous species or saturation indices of manganese minerals. However, saturation indices of Fe^{+3} minerals, such as ferrihydrite and jarosite, were sensitive to even 50 mV charges in Eh (table 5).

Changes in the saturation indices of samples collected since 1986 indicate that the liming of the spoil affected the speciation of aqueous phases and precipitation of Fe minerals from the ground water at only a few sites. Generally, saturation indices for minerals in water samples from wells W18, W30,

Table 4.--*Saturation indices of selected minerals dissolved in ground-water samples as calculated by the computer program WATEQ4F*

[Wells are grouped by well nest; saturation index is log (activity product/equilibrium constant); saturation indices were calculated by WATEQ4F (Ball and others, 1987); data from Ziegler (1989) and Blevins (1991)]

				Saturation indices									
Well number (fig. 6)	Date	Depth of well (feet)	pH	Gypsum ($CaSO_4 \cdot 2H_2O$)	Calcite ($CaCO_3$)	Rhodochrosite ($MnCO_3$)	Siderite ($FeCO_3$)	Ferrihydrite [$Fe(OH)_3$]	Potassium jarosite [$KFe_3(SO_4)_2(OH)_6$]	Alunite [$KAl_3(OH)_6(SO_4)_2$]	$Al_4(OH)_{10}SO_4$	Crystalline gibbsite [$Al(OH)_3$]	Kaolinite [$Al_4(Si_4O_{10})(OH)_8$]
W13	9-25-87	27.6	5.9	0.00	-1.0	-0.79	0.36	2.71	10.39	1.77	0.70	0.13	1.29
	10-11-89		6.1	.00	-.77	-.65	.54	.27	3.89	5.11	3.80	.90	2.96
W54	10-11-89	47.2	6.3	.02	-.33	-.31	.80	-.17	1.69	1.87	.10	.11	3.38
[a]W18	9-13-85	23.4	5.9	-.02	-1.60	[b]-1.20	[b].25	[b]1.20	[b]7.70	3.80	.84	.30	[c]
	4-24-86		5.3	-.04	-2.30	[b]-2.00	[b]-.61	[b]-.67	[b]3.30	3.40	.07	-.40	.27
	10-24-89		5.6	-.07	-1.88	-1.87	-.38	-.28	3.40	2.50	-.31	-.37	.80
[d]W24	9-13-85	36.6	5.3	.00	-2.50	[b]-1.90	[b]-.80	[b]-.72	[b]3.30	6.20	3.70	.48	2.50
	4-24-86		5.2	.00	-2.20	[b]-1.70	[b]-.68	[b]-1.10	[b]2.50	3.40	-.65	-.46	.06
	10-20-89		6.3	.04	-1.61	-1.98	-.86	.46	4.03	1.57	-.83	-.15	.40
W30	4-24-86	18.0	5.8	.02	-1.30	[b]-1.10	[b].16	[b].61	[b]6.00	3.20	.71	-.13	.13
	9-25-87		6.0	.02	-.80	-.56	.48	.68	5.52	5.57	3.94	.99	3.02
	5-13-88		6.0	.00	-.82	-.61	.40	-.63	1.24	3.94	2.36	.48	1.98
	10-16-89		6.3	.01	-.54	-.36	.68	.68	4.60	6.10	5.44	1.41	3.90
W50	10-16-89	34.4	6.6	.02	-.00	.14	.53	.99	4.25	1.81	.77	.40	2.04
W31	4-24-86	17.5	6.1	.00	-.64	[b]-.31	[b].72	[b]1.30	[b]7.70	1.40	-2.30	-.34	-.38
	10-24-89		6.1	.01	-.61	-.40	.75	.37	4.30	3.50	1.48	.31	1.70
W37	4-25-86	26.4	6.0	-.05	-.85	[b]-.80	[b].03	[b].63	[b]5.30	2.90	.43	.10	.93
	5-13-88		6.6	-.02	-.24	-.14	.66	1.24	4.92	2.75	2.02	.76	2.94
	10-12-89		6.1	-.04	-.79	-.73	.08	-.28	2.12	1.47	-.99	-.29	.80
W56	10-12-89	33.7	6.3	.01	-.37	-.39	.57	-.48	.85	1.59	-.32	-.01	1.22
W40	10-10-89	8.5	6.1	.01	-.76	-.48	.42	-.87	.40	2.45	.35	.02	1.36
W41	10-10-89	46.9	6.6	.00	-.03	.14	.09	.12	2.18	1.58	-.22	.17	1.63
W62	10-19-89	23.2	4.8	.01	-3.09	-2.79	-1.17	-.20	6.54	7.66	4.53	.38	3.16

[a] Well affected by adjacent acidic recharge lake L19.

[b] Eh value estimated with pH and iron concentrations using method described by Barnes and Clark (1964).

[c] The saturation index for kaolinite was not calculated because of no available concentration for dissolved silica.

[d] Well in fly ash.

Table 5.--*Change of saturation indices of manganese and iron minerals in water from well W24 in April 1986 with change in oxidation-reduction potential*

Oxidation-reduction potential (millivolts)	Saturation indices			
	Rhodochrosite ($MnCO_3$)	Siderite ($FeCO_3$)	Ferrihydrite [$Fe(OH)_3$]	Potassium jarosite [$KFe_3(SO_4)_2(OH)_6$]
100	-1.72	-0.68	-3.69	-5.24
150	-1.72	-.68	-2.82	-2.66
200	-1.72	-.68	-1.96	-.07
250	-1.72	-.68	-1.10	2.52
300	-1.72	-.68	-.24	5.11
350	-1.72	-.68	.63	7.69
400	-1.72	-.69	1.48	10.3

and W31 were unchanged after partial regrading and revegetation, but wells W24 and W37 had substantial changes in the saturation index for ferrihydrite. The saturation index of ferrihydrite for water from well W24 changed from -1.96 (Blevins, 1991) to 0.46 from 1986 to 1989. This change from undersaturation to slight oversaturation for ferrihydrite corresponds to an increase in pH value and a large decrease in Fe concentrations in water from the well (table 3) and indicates that ferrihydrite precipitation, resulting from an increase in pH value, may be the cause of the decrease in the Fe concentrations. The saturation index of ferrihydrite for water from well W37 changed from an oversaturated value during 1988 (1.24) to an undersaturated value (-0.28) during 1989 because of decreased concentrations of Fe^{+3}. In this case, lower concentrations of Fe^{+3} may have been caused by lime additions at the acidic spoil surface, increasing the pH value of the spoil and decreasing the downward mobility of Fe^{+3} at the surface.

During 1988 to 1990, deep wells were drilled near existing shallow wells to determine differences in water quality in the spoil with depth. Regression analyses of constituent concentrations in water from all nested wells indicated substantial differences in water chemistry depending on the depth of the well below the water table. The pH ($r^2 = 0.57$) values and HCO_3 ($r^2 = 0.66$) concentrations increased and Fe ($r^2 = 0.43$) concentrations decreased significantly with depth below the water table (fig. 7), which is not unexpected. Deeper ground water generally has higher pH values and higher concentrations of HCO_3 because CO_3 minerals are dissolved at depth and H^+ bonds to the CO_3. The Fe concentrations might be expected to be larger near the surface of the spoil because most of the Fe is dissolved near the surface in acidic recharge where pyrite is rapidly oxidizing. Decreases in Fe concentrations with depth may be attributed to precipitation of siderite or ferrihydrite as the pH value increases with depth. Most recharge to the spoil comes from the acidic spoil surface or shallow acidic lakes. The increase in pH values and HCO_3 concentrations and decrease in Fe concentrations also would be expected based on the results of Soxhlet leaching (Ziegler, 1989) because rock types with near-neutral pH values and that are capable of leaching only small trace-element concentrations usually were placed near the bottom of the spoil during mining.

Lakes and Streams

Blevins (1991) determined that the study area contained three lake types; shallow perched lakes, shallow ground-water-supplied lakes, and deep lakes. The shallow perched lakes (average depth less than 8 ft) were filled by runoff from the spoil ridges. Perched lakes received little or no ground-water inflow and had pH values less than 4.0. Shallow ground-water-supplied lakes (average depth less than 8 ft) received substantial quantities of ground water containing large Fe^{+2} concentrations and also had pH values less than 4.0. Shallow ground-water-supplied lakes were the primary source of acidic water

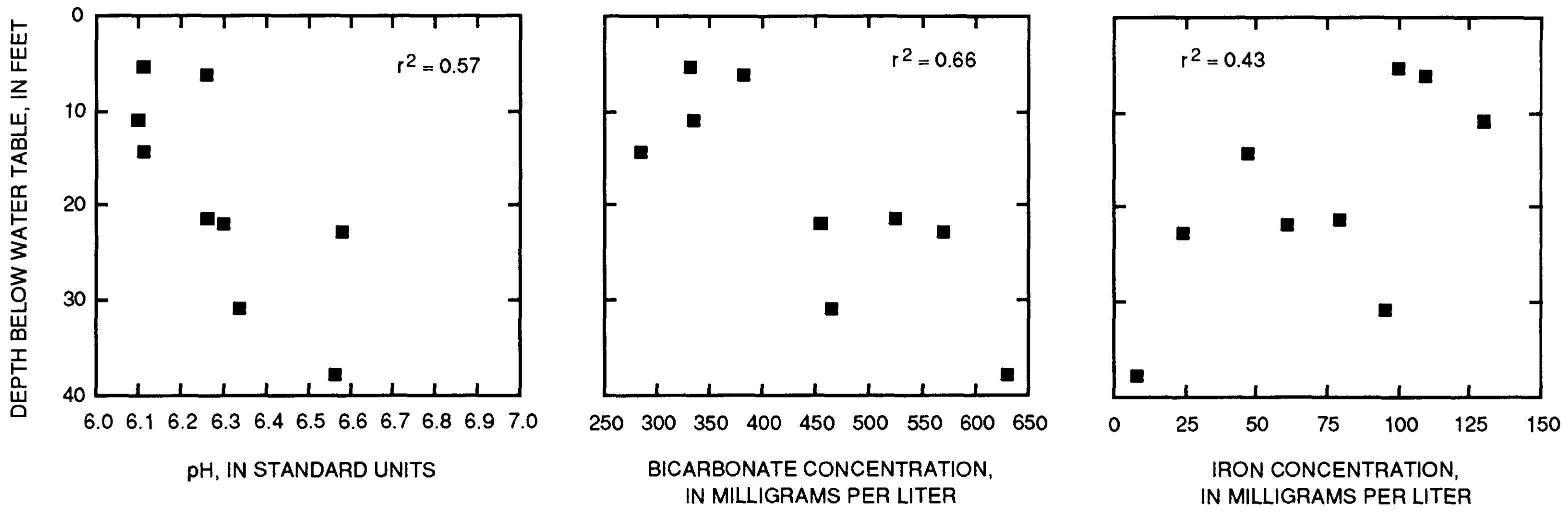


Figure 7.--Changes in pH values and selected constituent concentrations with depth in the spoil.

to streams in the study area. Deep lakes (average depths more than 9 ft) had near-neutral pH values (6.5 to 8.5) and small concentrations of trace elements. Deep lakes received substantial quantities of ground water and were the primary source of neutral-pH water to streams. Lake type is depicted in figure 8 and the pH value of most lakes is shown in figure 9.

The specific conductance, pH, and temperature of most of the lakes in the Horn Branch basin were measured near the beginning of the study in December 1988 and at the end of the study in March 1990 to determine the effects of reclamation on the water quality of acidic lakes (table 6). Between 1986 and December 1988, the pH of lakes LF, LH, and LS increased from less than 4.5 to greater than 6.5 and increased to more than 7.0 in 1990 (figs. 9 and 10; table 6; Blevins, 1991). Also, the pH of three additional lakes (lakes L15, LP, and LZ4) increased from less than 4.5 to greater than 6.0 from 1988 to 1990 (fig. 11). The increased pH values of all six of these lakes occurred after completion of reclamation activities during 1987. The increased pH values of water from shallow, perched lakes L15, LH, and LZ4 probably were because of the addition of lime and reclamation activities in the drainage areas of these lakes. The spoil areas near all of these lakes had at least 30 tons/acre of lime added (fig. 3). The pH of lakes L9, L10, L11, L12, L13, L14, L17, L19, L20, LA, LB, LC, LG, LGG, LI, LT, LT1, LV, and LZ3 remained less than 4.5 despite reclamation and lime additions.

Blevins (1991) determined that the pH values of Horn Branch downstream from lake LN were controlled by the acidities of the two main tributaries of Horn Branch. Before reclamation during 1986, water from the tributary that included deep lakes LX and LN was near neutral and had small trace-element concentrations. Water from the tributary flowing from lake LT to lake LS to lake LP had pH values less than 4.0 and had large concentrations of Fe and other trace elements. Outflows from acidic lake LP and neutral lake LN mixed in lake LM. If the flow from lake LP was greater than the flow from lake LN, then water in lake LM and the entire reach from lake LM downstream to lake LF usually had a pH less than 4.0. If flow from lake LN was greater than flow from lake LP, water in Horn Branch was near neutral, except during periods of runoff from the spoil. Before reclamation during 1986, runoff from spoil would decrease the pH values of lake water, unless the pH of a lake already was less than 4.0. If the stream had a pH less than 3.5, runoff tended to increase the pH to about 3.5 (the approximate pH value of spoil runoff).

The pH values of lake LN remained near neutral after reclamation. Runoff decreased the pH of lake LN slightly during May 1989 to 6.8, but this was the smallest pH value detected during this study (fig. 12). Outflow from lake LN was the main neutralizing effect on occasionally acidic (pH less than 4.5) outflows from lake LP (fig. 12). The pH of lake LM (just downstream from lakes LN and LP) was larger than 6.0 after reclamation (table 6). In fact, the large quantity of discharge from lake LN helped neutralize acidic runoff and acidic seepage and kept the pH of Horn Branch greater than 6.0 downstream to the point where it left the mined area.

The pH of water in lake LT remained less than 4.0 after reclamation, but Fe and trace-element concentrations were smaller than those detected before reclamation (table 6; table 7, at the back of this report; Blevins, 1991). Revegetation and lime applied near the lake may be responsible for immobilizing Fe and trace elements on the spoil surface and helped decrease trace-element concentrations in lake LT. After reclamation, the pH of runoff in the vicinity of lakes LS and LT increased to greater than 6.0 (table 2; fig. 4). Reclamation activities during 1987 caused surface flow from lake LT into lake LS to cease. This lack of acidic discharge from lake LT has helped the pH of lake LS to increase to near 7, thereby increasing the pH values of Horn Branch as far downstream as site Q1 (fig. 1).

Before reclamation during 1986, the pH of lake LS usually was less than 4.5 (fig. 9). However, after reclamation, the pH of lake LS outflow was not less than 6.3 (fig. 12). The pH value of runoff into lake LS was near neutral and was similar to pH values of the outflow from lake LS after reclamation (fig. 12). The increase in the pH values of lake LS probably was the result of a decrease of acidic flow from lake LT (table 6) and the application of lime to nearby spoil that increased the pH value of runoff and

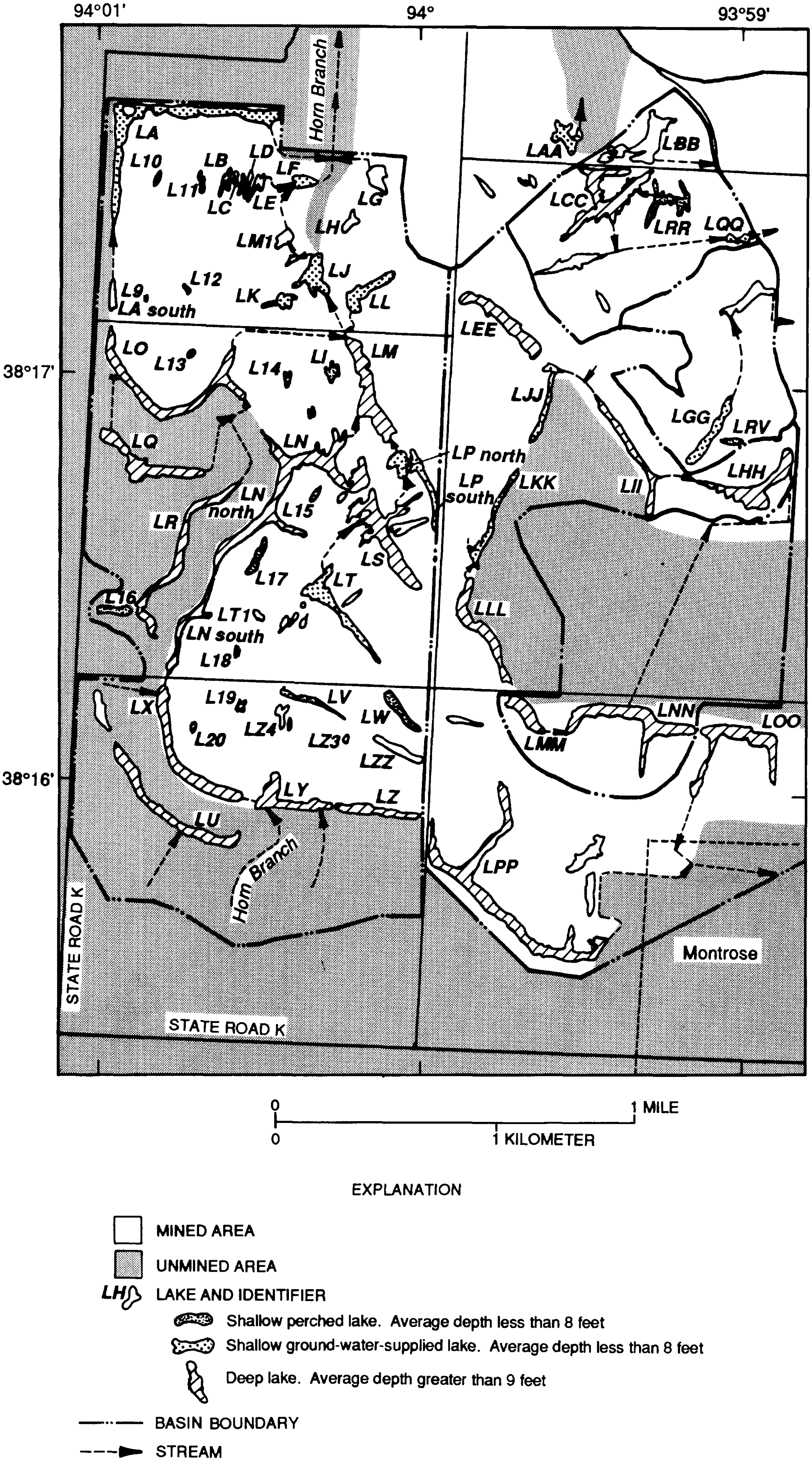


Figure 8.--Lake type.

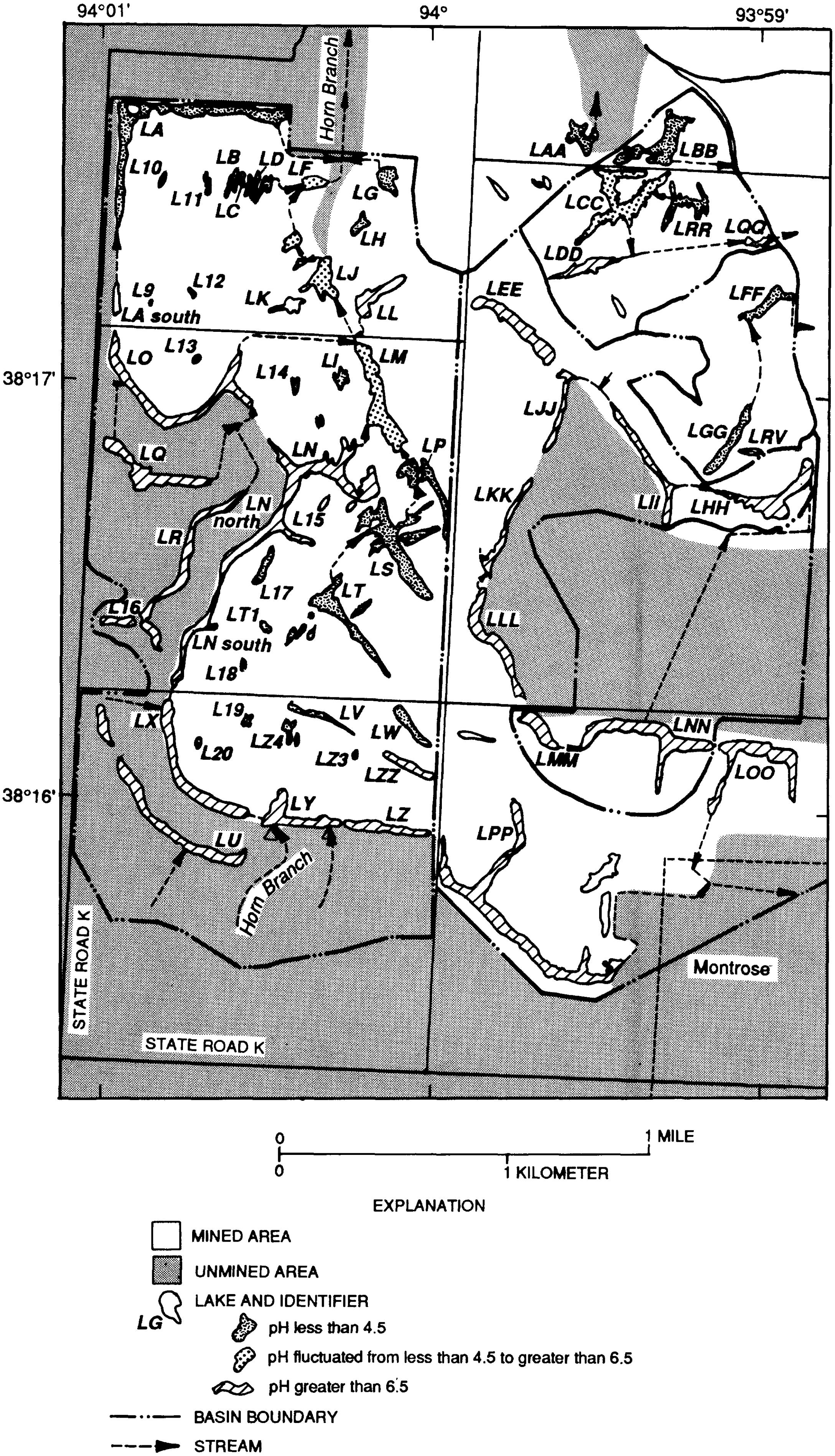


Figure 9.--pH values of lakes during 1986.

Table 6.--*Properties of selected lakes sampled in December 1988 and March 1990*

[Specific conductance, in microsiemens per centimeter at 25 degrees Celsius; temperature, in degrees Celsius; D, indicates no water present in lake; --, no data available]

Lake (fig. 1)	Date	Specific conductance	pH	Water temperature
Shallow perched lakes				
L9	12-16-88	D	D	D
	3-13-90	860	3.7	20.0
L10	12-16-88	D	D	D
	3-12-90	650	3.9	19.0
L11	12-16-88	860	3.3	.5
	3-12-90	600	3.6	17.5
L12	12-16-88	D	D	D
	3-13-90	460	3.9	19.0
L13	12-16-88	1,000	3.9	1.5
	3-12-90	980	4.0	21.5
L14	12-16-88	2,170	2.9	2.5
	3-12-90	2,100	3.0	16.5
L15	12-16-88	D	D	D
	1-27-89	640	4.4	10.5
	3-12-90	780	6.8	22.5
L17	12-16-88	1,390	3.3	1.0
	3-12-90	1,120	3.1	19.0
L19	12-13-88	730	4.1	5.5
	3-12-90	500	4.1	23.0
L20	12-13-88	776	3.6	--
	3-12-90	600	3.5	24.0
LG	12-16-88	1,910	3.5	3.0
	3-12-90	1,800	4.3	14.5
LH	12-16-88	3,020	6.6	2.0
	3-12-90	2,700	7.7	20.0
LT1	12-16-88	1,300	3.3	.5
	3-12-90	1,240	3.6	18.0
LU	12-13-88	490	7.7	3.5
	3-12-90	400	8.1	23.0
LZ3	12-13-88	1,000	3.9	5.0
LZ4	12-13-88	2,160	3.2	2.5
	3-12-90	600	6.1	22.5

Table 6.--*Properties of selected lakes sampled in December 1988 and March 1990*--Continued

Lake (fig. 1)	Date	Specific conductance	pH	Water temperature
Shallow ground-water supplied lakes				
LA	12-16-88	3,270	3.1	2.0
	3-12-90	3,000	3.4	16.5
LA south	12-16-88	4,150	7.7	1.0
	3-13-90	3,900	7.9	19.5
LF	12-16-88	3,190	7.1	3.0
	3-12-90	2,750	7.4	17.5
LI	12-16-88	3,730	3.1	2.5
	3-12-90	3,500	3.3	16.0
LJ	12-16-88	3,090	7.5	3.0
LK	12-16-88	4,420	7.2	3.0
	3-12-90	3,450	7.6	18.5
LL	12-16-88	3,290	8.0	2.0
	3-12-90	3,000	7.8	16.0
LP	12-13-88	3,200	4.4	3.0
	3-12-90	2,950	7.0	16.0
LT	12-13-88	3,140	3.2	3.0
	3-12-90	2,500	3.3	18.0
LV	12-13-88	1,260	3.5	1.5
	3-12-90	1,020	3.8	19.0
Deep lakes				
LM	12-16-88	3,060	7.1	3.5
	3-12-90	2,700	7.3	19.0
LN north	12-16-88	2,600	8.0	2.0
	3-12-90	2,400	8.1	15.5
LN south	12-16-88	2,940	8.1	2.5
LO	12-16-88	2,860	7.1	1.0
	3-12-90	2,120	8.0	16.5
LQ	12-16-88	280	8.0	4.0
	3-13-90	290	8.1	17.0
LR	12-16-88	1,390	7.7	2.0
	3-13-90	890	8.2	17.5
LS	12-13-88	3,290	7.5	--
	3-12-90	2,900	7.8	16.0

Table 6.--*Properties of selected lakes sampled in December 1988 and March 1990*--Continued

Lake (fig. 1)	Date	Specific conductance	pH	Water temperature
		Deep lakes--Continued		
LX	12-13-88	1,530	8.0	4.5
	3-12-90	1,000	8.1	18.0
LY	12-13-88	900	7.6	5.0
	3-13-90	750	7.8	16.5
LZ	12-13-88	740	7.8	4.0
	3-13-90	580	8.0	17.0
LEE	12-16-88	2,540	8.1	3.0
	3-12-90	2,400	8.2	17.0
LZZ	12-13-88	430	7.2	3.5
	3-12-90	440	7.4	18.0
		Lake type not determined		
L16	12-16-88	290	8.1	3.0
	3-13-90	280	9.0	17.0
LB	12-16-88	3,460	3.1	2.0
	3-12-90	3,100	3.2	16.0
LC	12-16-88	3,470	3.1	2.5
	3-12-90	3,200	3.3	17.5
LD	12-16-88	3,360	4.3	2.0
	3-12-90	2,980	4.5	17.0
LE	12-13-88	3,270	7.5	4.0
	3-12-90	3,000	7.7	18.0
LW	12-13-88	832	3.9	2.5
	3-12-90	700	4.6	21.0

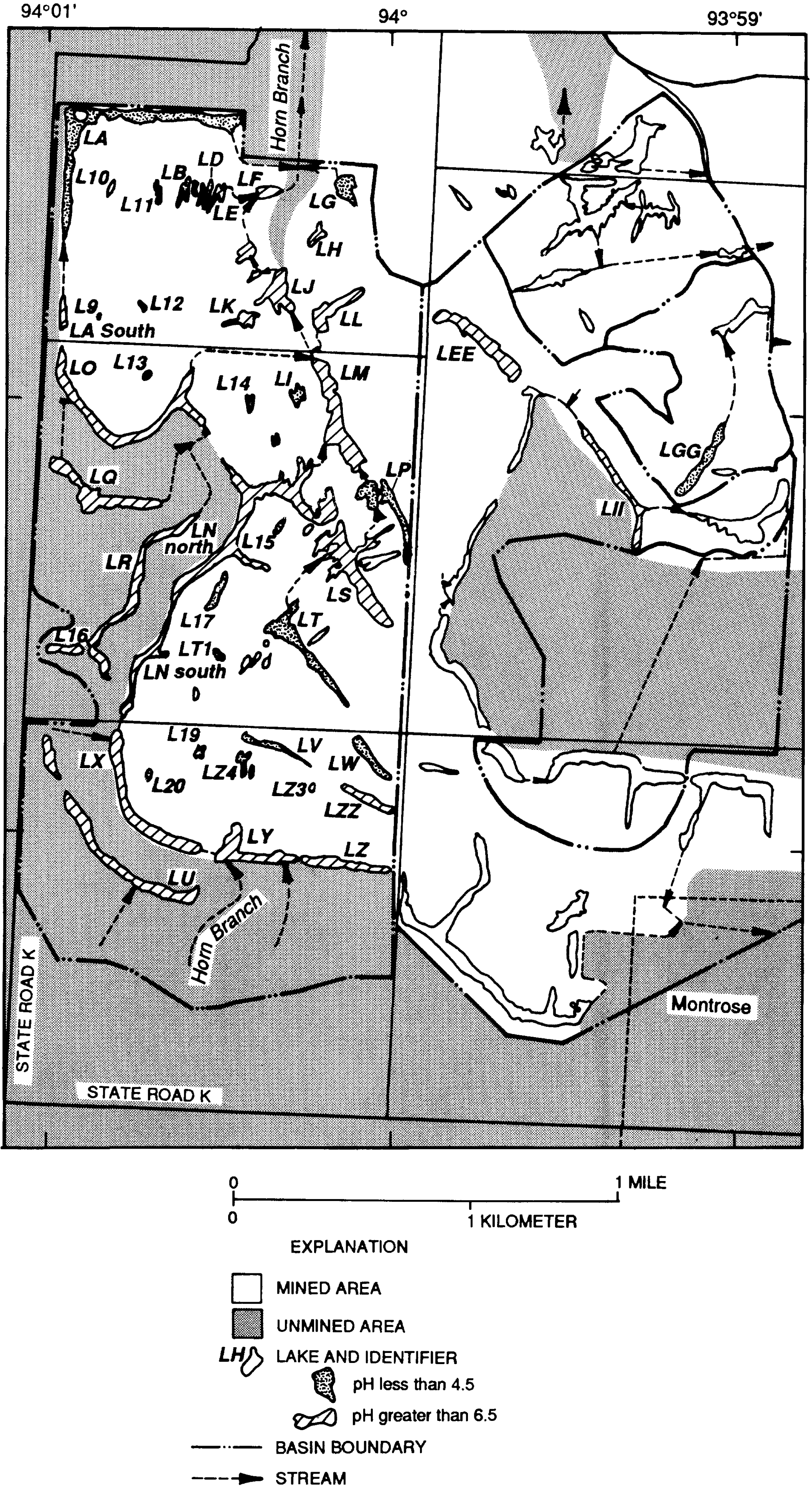


Figure 10.--pH values of lakes, December 1988.

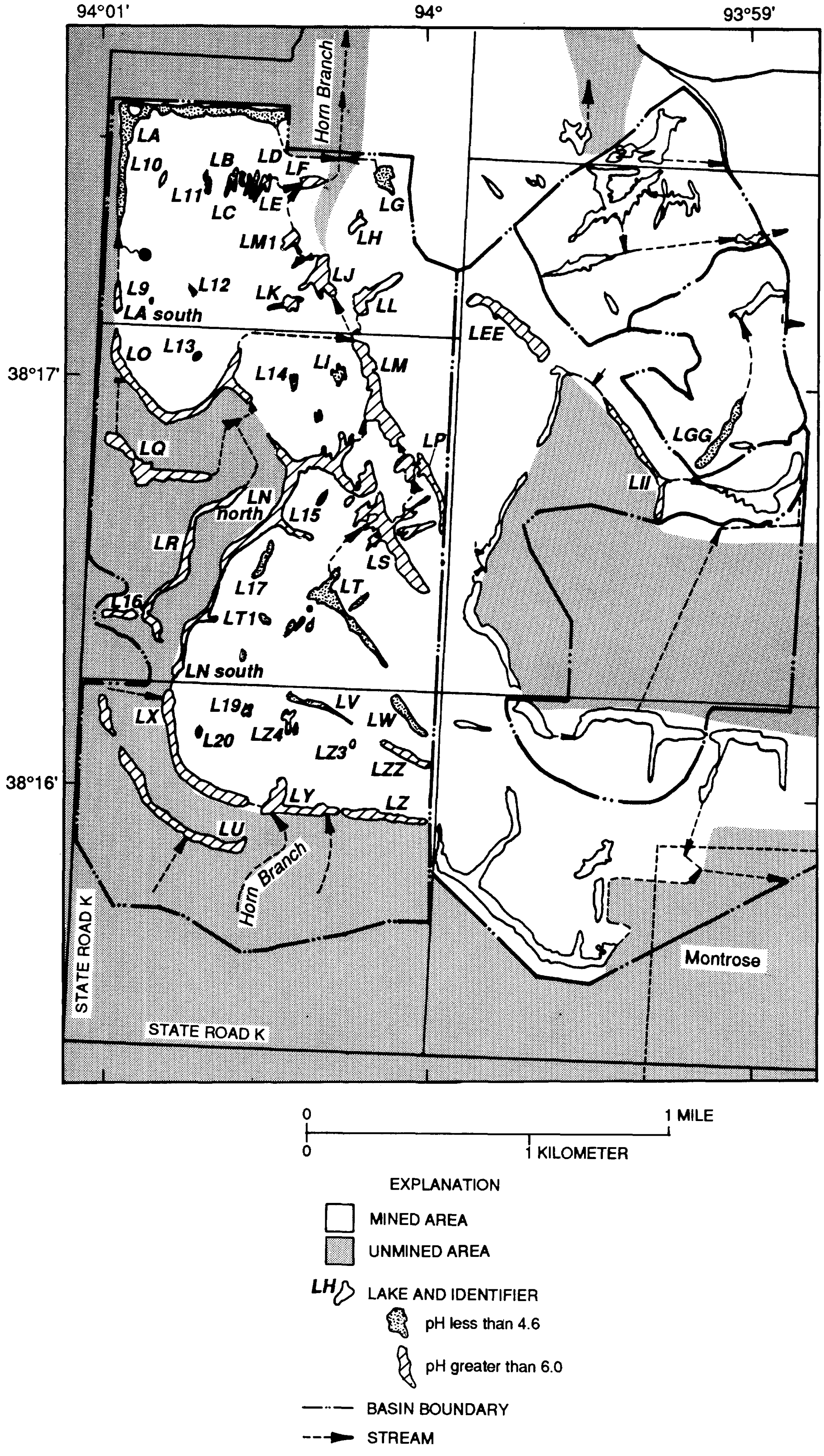


Figure 11.--pH values of lakes, March 1990.

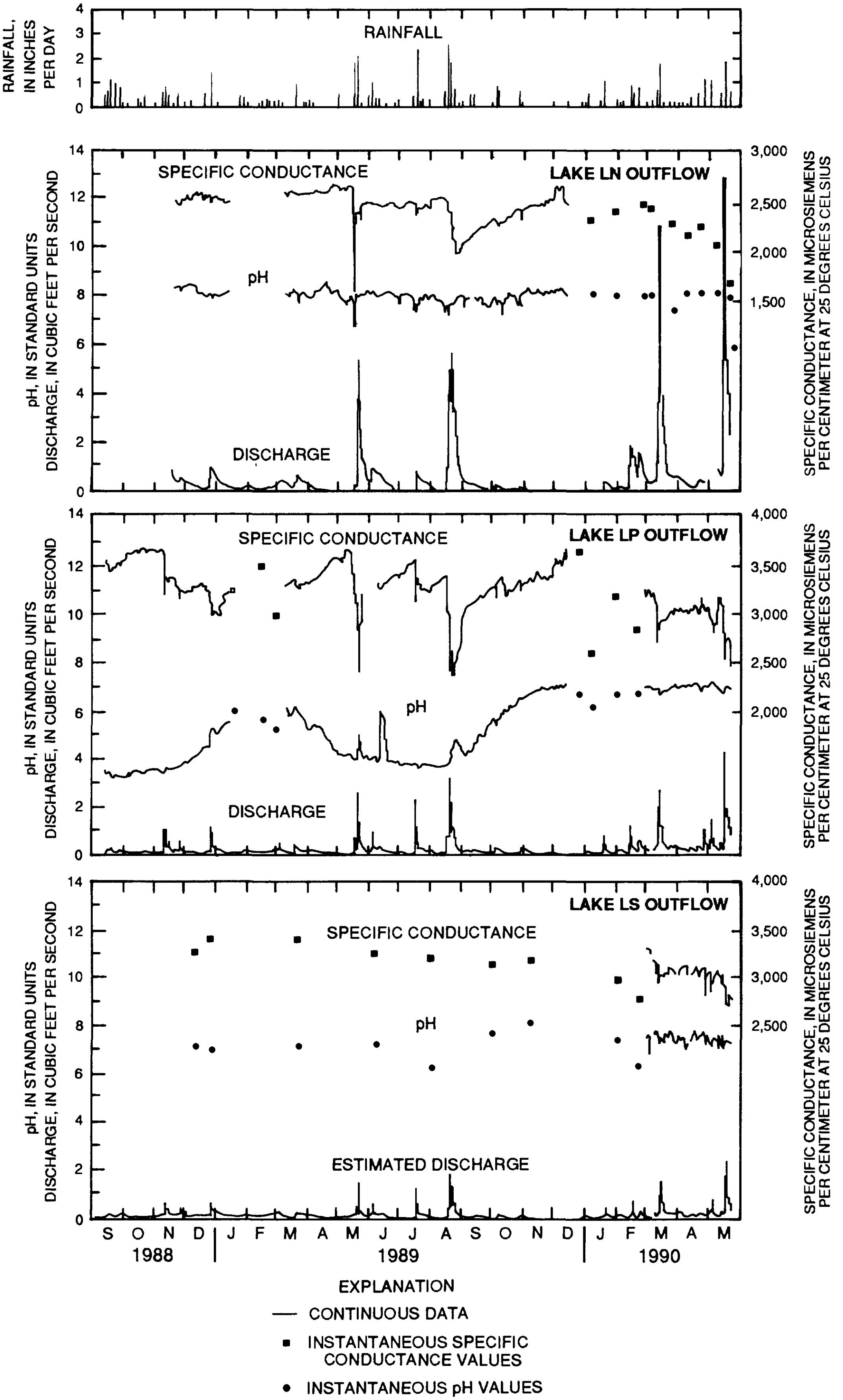


Figure 12.--Daily rainfall at site RG and daily mean discharge, specific conductance, and pH values at outflows of lakes LN, LP, and LS.

lime that was physically transported into lake LS. The most important consequence of the increased pH value of lake LS was the effect that the outflow from lake LS had on water quality in lake LP. Before reclamation, the pH of lake LP was less than 3.5 (Blevins, 1991). During sampling in May 1988, the pH of lake LP was 3.8 (Ziegler, 1989). During monitoring from 1988 through 1990, the pH of outflow from lake LP ranged from a low of 3.2 in September 1988 to a high of 7.2 in April 1990 (fig. 12). Storm runoff generally increased the pH value and decreased the specific conductance of the outflow of lake LP. The pH of lake LP increased from November 1988 through January 1989, and then decreased to less than 4.0 from April 1989 through September 1989. From October 1989 through November 1989, the pH of lake LP again increased from about 5 to about 7, and the pH remained near 7 until the end of monitoring in May 1990. The pH value increased one to two units during short runoff events when the prestorm pH was less than 4.0. Increases in the pH value of lake LP during runoff probably were the result of near-neutral runoff (fig. 4) entering the lake, near-neutral inflow from lake LS, and lime washed from the nearby spoil into lake LP. The primary reason for the sustained pH near 7 in lake LP probably was the large quantity of near-neutral inflow from lake LS. Daily mean discharge from lake LS was estimated from the hydrograph of outflow from lake LP and a linear regression equation developed from 15 synoptic discharge measurements made at the outflows of lakes LP and LS ($r^2 = 0.99$). The estimated mean discharge of lake LS [0.055 ft^3/s (cubic foot per second)] was about 40 percent of the mean discharge of lake LP (0.13 ft^3/s).

During most periods of flow after reclamation, the pH of Horn Branch at the downstream site Q1 was greater than 7.0 (fig. 13). The lowest daily pH at this site was 6.2. The lowest pH and specific conductance values coincided with the largest quantities of runoff, which occurred August 19, 1989, after a total of 2.5 in. of rainfall. These data indicate that after reclamation, runoff remains acidic in the Horn Branch basin but is not sufficiently acidic to decrease the pH at site Q1 to less than 6.2 during most storms. During base-flow conditions, even when there was no flow from lake LN, the pH at site Q1 did not decrease to less than 6.5 because the outflows from lakes LP and LS were neutralized by reclamation.

Mass-balance computations of H^+ indicate a mixture of water from acidic lake LP (before reclamation) and neutral-pH lake LS (after reclamation) in the proportions indicated by the daily mean discharge of the two lake outflows would be expected to result in lake LP having a pH greater than 6. The increased pH value of inflow from lake LS also would have decreased Fe loads (that would have hydrolyzed) into lake LP. The average discharge divided by the volume of lake LP indicates the average residence time of water in lake LP was 120 days. Therefore, several months were required before a sustained increase in pH value was observed in the outflow (fig. 12). During periods of no flow from lake LS, the discharge from lake LP was 0.03 ft^3/s and probably corresponded to the contribution of ground water minus the water lost to evapotranspiration. Two sustained periods of low flow from lake LS occurred in the late spring and summer of 1989, and the late fall and early winter of 1989 and 1990. The pH of lake LP decreased to less than 4.0 following the first dry period (January to May 1989) but decreased to only about 6.0 following the second dry period. The pH values were greater after the second dry period (September to December 1989) probably because lake LP had accumulated more alkalinity just before the second dry period. The alkalinity of lake LP during the first dry period was only 3 mg/L as calcium carbonate at a pH of only 5.3 (table 7). Consequently, acid produced by the oxidation of Fe^{+2} and hydrolysis of Fe^{+3} entering the lake from ground water was sufficient to acidify lake LP for 3 to 4 months before near-neutral inflows from lake LS resumed. The fly-ash area north of lake LP received some of the largest applications of lime in the study area (fig. 3). These data indicate lake LP may reacidify during prolonged periods of no flow from lake LS, especially after lime applications are consumed.

GEOCHEMICAL PROCESSES IN LAKES

Before reclamation, lakes with an average depth of less than 8 ft usually had pH values less than 4.0 (Blevins, 1991). Most shallow lakes were perched and received acidic (pH less than 4.0) runoff, but several shallow lakes such as LA, LT, and LGG received substantial quantities of ground water and

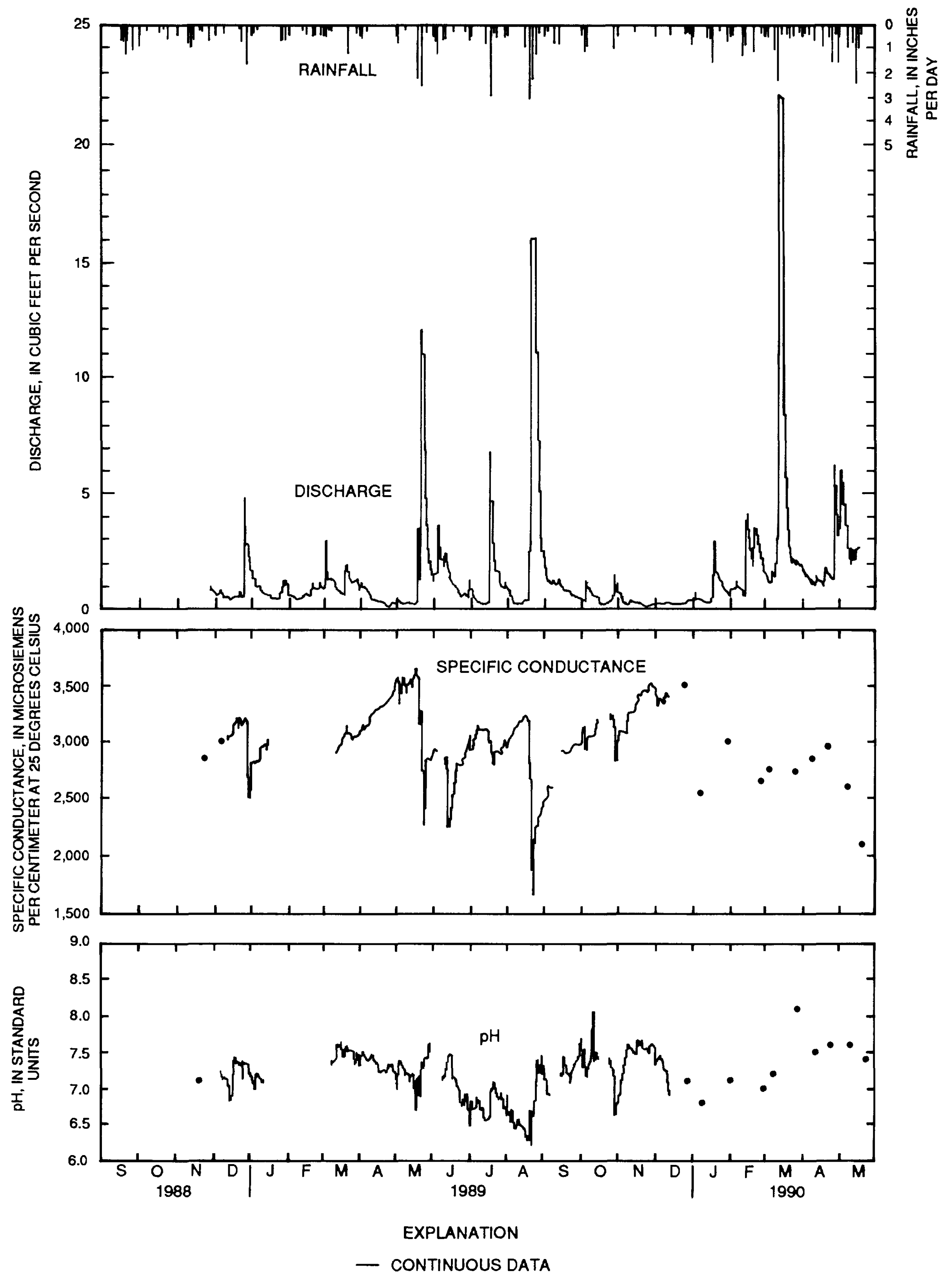


Figure 13.--Daily mean discharge, specific conductance, and pH values at site Q1 and daily rainfall at site RG.

were acidified by the oxidation of Fe^{+2} from ground water. Acidification of ground water to a pH of less than 5.0 upon exposure to the atmosphere (such as in a shallow ground-water-supplied lake) could not occur if the mole ratio of Fe^{+2} to HCO_3 was less than 0.5. This is because two HCO_3 ions are required to neutralize the two H^+ ions produced from the oxidation and hydrolysis of one Fe^{+2} according to:

$$Fe^{+2} + 5/2H_2O + 1/4O_2 + 2HCO_3^- \dashrightarrow Fe(OH)_3 + 2H_2CO_3.$$

At pH less than 5.0, the quantity of HCO_3 in solution is generally insufficient to absorb substantial quantities of the H^+ produced by the oxidation and hydrolysis of Fe^{+2}. Deep lakes (average depth greater than 8 ft) received even larger quantities of Fe-rich ground water because they fully penetrated the spoil aquifer, but did not acidify. Deep lakes did not have pH values less than 6.0 primarily because of lower Fe^{+2} to HCO_3 ratios in deeper ground water. The decrease of this ratio with depth is illustrated in figure 14. Shallow ground-water-supplied lakes intersect only the top few feet of saturated spoil (fig. 15). Shallow ground water in the spoil frequently has Fe^{+2} to HCO_3 ratios greater than 0.5 (table 3). Additionally, the increased pH value of deeper ground water (fig. 7) is a minor neutralizing effect on deep lakes.

Five deep lakes, LN (north and south), LQ, LS, LX, and LEE, were selected to determine the chemical characteristics that maintain the near-neutral pH values (6.2 to 8.5) of the deep lakes. LQ was selected for sampling because mining records indicate that the lake receives only small quantities of ground or surface water from the spoil. Lake LQ is bounded by unmined rocks that are mostly unsaturated and have small permeabilities. Therefore, lake LQ primarily is filled with surface runoff from unmined land and represents a more typical western-Missouri impoundment with the geometry of a deep lake formed by a last-cut excavation. Comparisons of analyses of samples from lake LQ with analyses from deep lakes were used to identify water-quality characteristics caused by mine drainage.

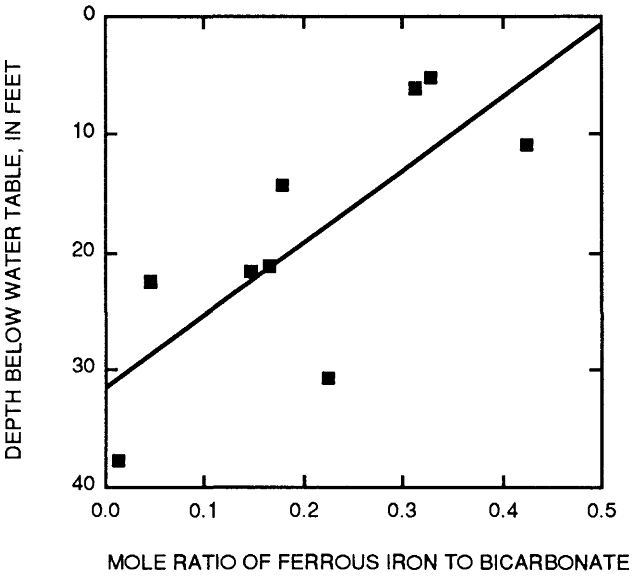
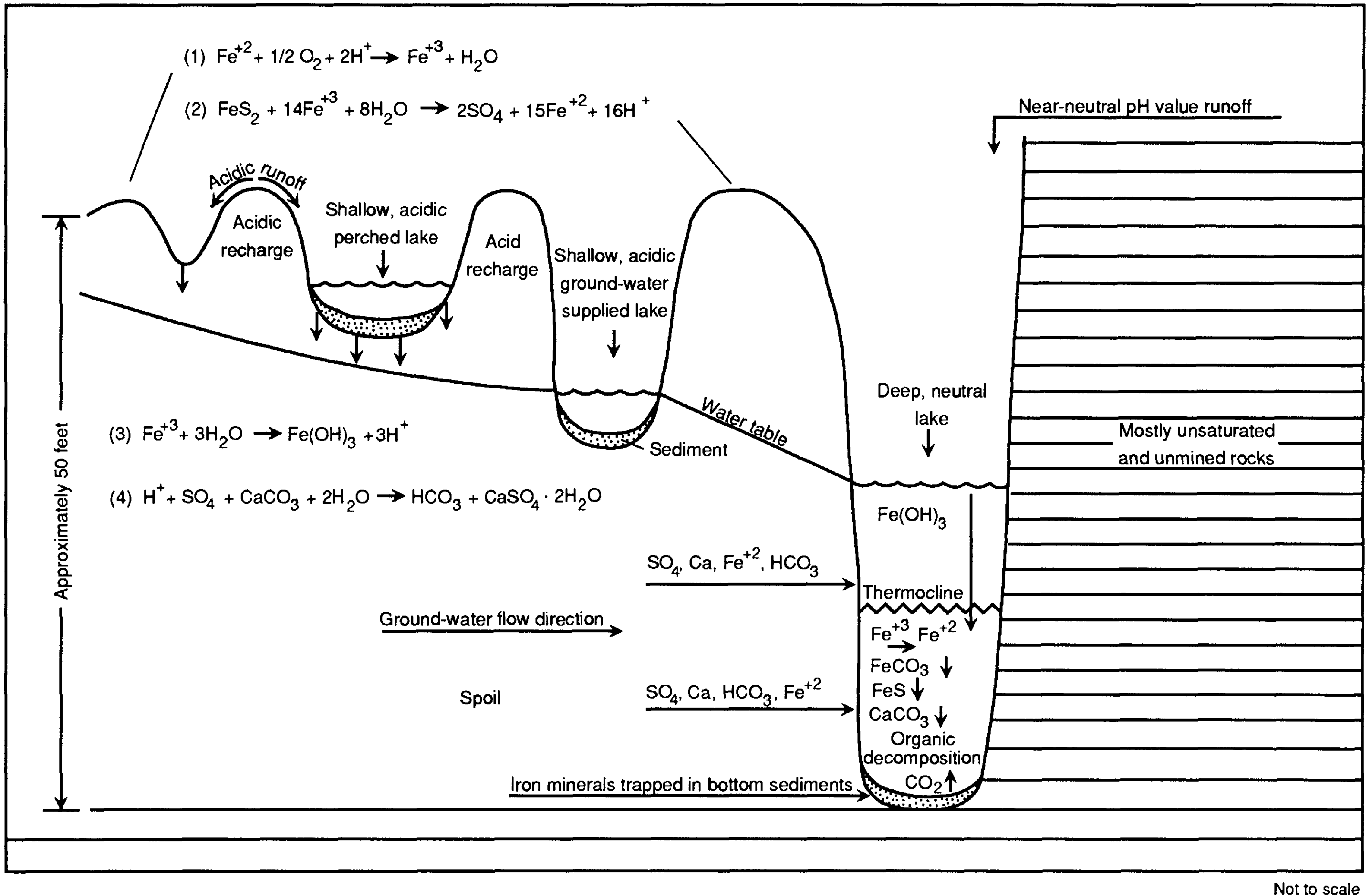


Figure 14.--Changes in the ferrous iron to bicarbonate ratio with depth in deep lakes.



EXPLANATION

HCO_3	BICARBONATE	H^+	HYDRONIUM ION
Ca	CALCIUM	$FeCO_3$	IRON CARBONATE
$CACO_3$	CALCIUM CARBONATE	FeS	IRON SULFIDE
CO_2	CARBON DIOXIDE	O_2	OXYGEN
$Fe(OH)_3$	FERRIHYDRITE	FeS_2	PYRITE
Fe^{+3}	FERRIC IRON	SO_4	SULFATE
Fe^{+2}	FERROUS IRON	H_2O	WATER

Figure 15.--Conceptual geochemical flow path.

Vertical profiles of specific conductance, pH, temperature, and dissolved oxygen of the six deep lakes (figs. 16 and 17) indicate vertical stratification of deeper lakes during the summer and early fall. Seasonal stratification of deep lakes assists in maintaining the near-neutral pH values of deep lakes because Fe^{+2} precipitates from the water as Fe carbonates and sulfides and is buried in lake bottom sediments.

Water samples from the hypolimnions generally were anaerobic, had large concentrations of Fe (as much as 250 mg/L), and had large concentrations of HCO_3 (as much as 1,000 mg/L). Concentrations of most common cations and anions in the hypolimnions were similar to concentrations detected in adjacent ground water (tables 3 and 8, at the back of this report). The metalimnion insulates the hypolimnion from atmospheric oxygen and allows Fe^{+2} to accumulate in the hypolimnion to concentrations large enough to precipitate Fe carbonate and Fe sulfide (table 9). Siderite and Fe sulfide minerals were identified in lake-bottom sediments (table 10) with X-ray diffraction and optical microscopy. Siderite was identified in bottom sediments from all the lakes sampled. Iron disulfide minerals (primarily pyrite) were identified in every sample except the two samples from control lake LQ (minimally affected by mining). The Fe accumulated in the hypolimnions by seepage from Fe-rich ground water and the settling of ferrioxyhydroxides, including ferrihydrite, precipitating in the epilimnion (fig. 15). Large concentrations of CO_2 species in the hypolimnion made conditions favorable for siderite precipitation. Although some Fe minerals may have washed in from the surface, siderite composed as much as 70 percent of the volume of the heavy mineral fraction of some bottom sediments.

Table 9.--*Saturation indices calculated by the computer program WATEQ4F for selected solid phases in water samples from deep lakes, September 11-26, 1989*

Mineral	Chemical formula	Lake (fig. 1) LN north	LN south	LP	LQ	LS	LX	LEE
		Hypolimnion						
Gypsum	$CaSO_4 \cdot 2H_2O$	0.05	0.00	0.03	-2.5	-0.03	-0.20	-0.14
Calcite	$CaCO_3$	.23	.10	.23	-.50	.07	-.31	.25
Rhodochrosite	$MnCO_3$	.50	.08	.29	.76	.35	-.20	.30
Siderite	$FeCO_3$	1.8	1.4	1.7	.11	1.5	.58	1.5
Ferrihydrite	$Fe(OH)_3$	.96	-.30	.64	-.55	.18	-.58	.34
Potassium jarosite	$KFe_3(SO_4)_2(OH)_6$	2.4	.88	2.8	-6.7	2.0	.36	2.4
Greigite	Fe_3S_4	11.8	13.9	12.9	15.9	12.4	10.1	14.5
Mackinawite	$(Fe,Ni)_{1.1}S$	1.7	1.9	1.8	2.7	1.7	.60	2.0
Pyrite	FeS_2	18.4	19.7	18.9	20.5	18.7	18.0	14.5
Sulfur	S	4.4	5.6	4.9	5.5	4.9	5.5	5.9
Amorphous iron sulfide	FeS	.96	1.2	1.1	1.9	.93	-.13	1.3
		Epilimnion						
Gypsum	$CaSO_4 \cdot 2H_2O$	-0.30	-0.23	-0.08	-2.0	-0.10	-0.62	-0.38
Calcite	$CaCO_3$	.24	.37	-1.5	.30	-.45	-.16	-.23
Rhodochrosite	$MnCO_3$	-1.4	.46	-1.5	-1.6	-.74	-1.2	-2.0
Ferrihydrite	$Fe(OH)_3$	.92	2.7	1.6	1.2	.74	1.3	1.1
Potassium jarosite	$KFe_3(SO_4)_2(OH)_6$	1.2	7.0	6.5	-3.0	2.5	3.0	2.2

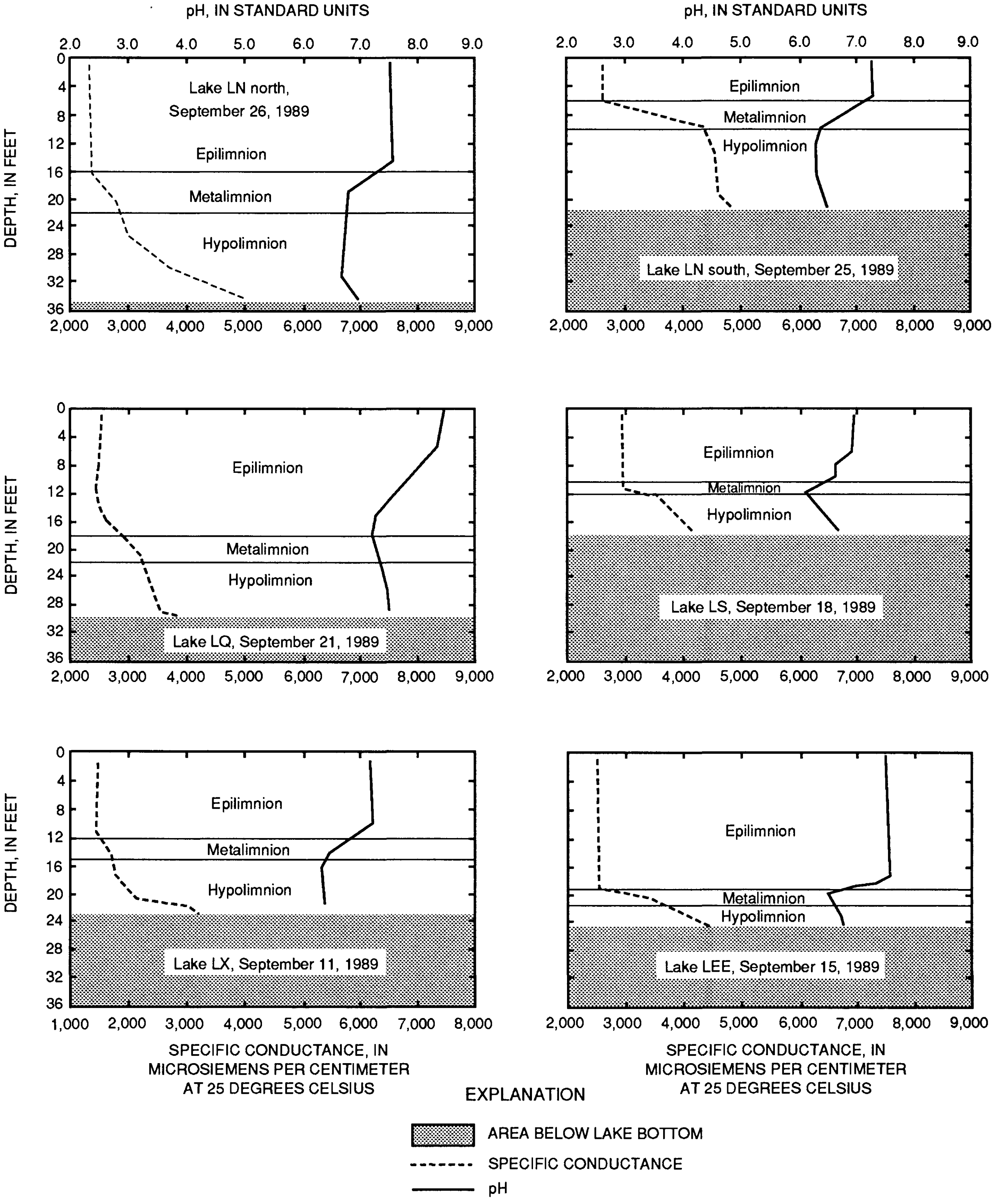


Figure 16.--Vertical profiles of specific conductance and pH values at selected deep lakes.

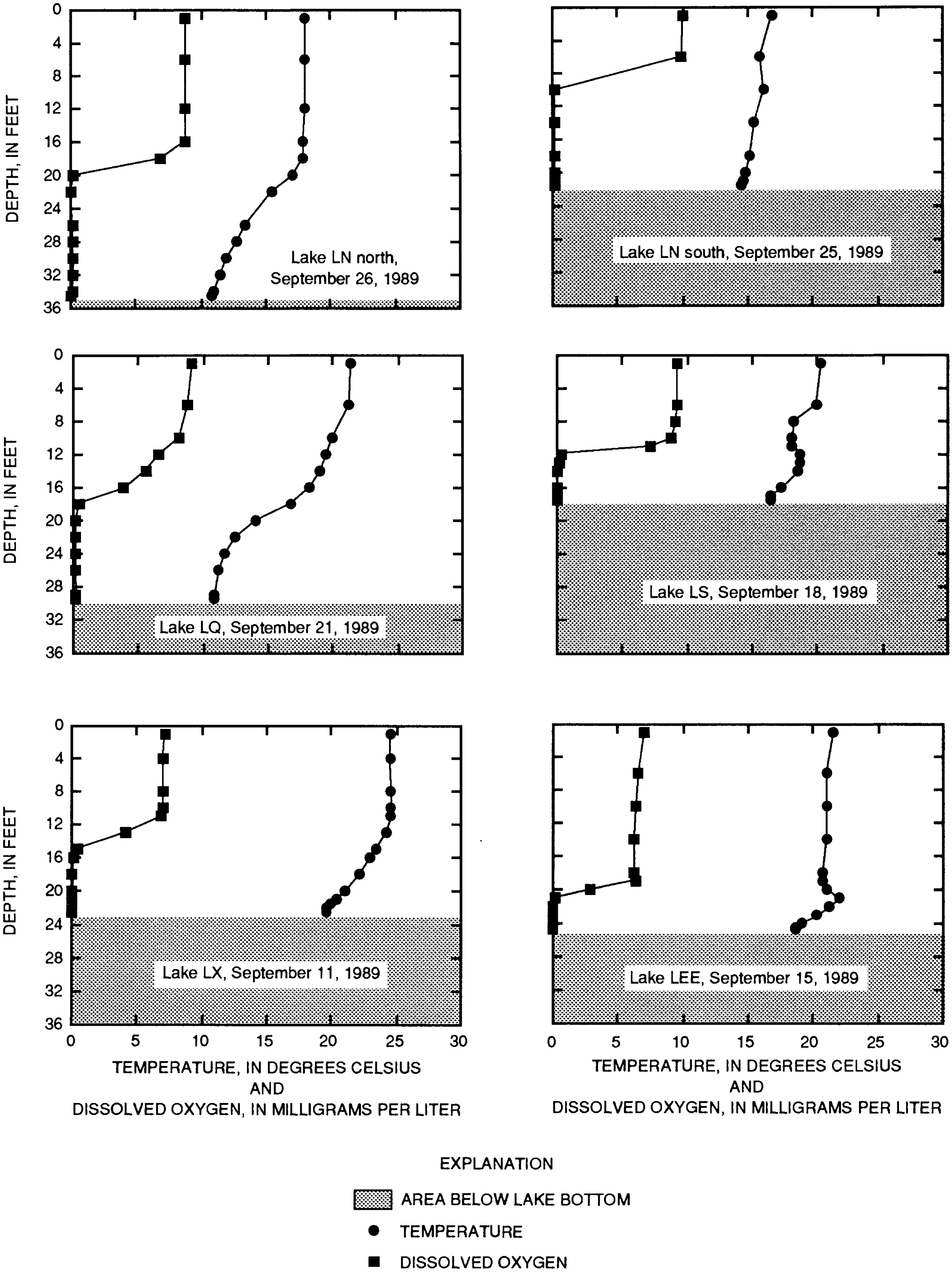


Figure 17.--Vertical profiles of temperature and dissolved oxygen at selected deep lakes.

Table 10.--*Carbon, total iron, and predominant minerals in bulk samples and heavy mineral concentrates from lake-bottom sediments*

[<, less than; --, no data available]

Lake (fig. 1)	Date collected	Lake stratified	Total carbon (percent)	Organic carbon (percent)	Inorganic carbon (percent)	Iron (percent)	Mineralogy of bulk sample (ranked from most to least abundant)					
							Minerals of large abundance			Minerals of small abundance		
							1	2	3	1	2	3
LN north	9-26-89	Yes	1.00	0.70	0.30	5.8	Quartz	Kaolinite	Illite	Feldspars	Gypsum	Calcite
LN south	9-25-89	Yes	1.43	1.02	.41	5.5	Quartz	Kaolinite	Illite	Calcite	Gypsum	Feldspars
LQ	9-27-89	Yes	1.48	1.48	<.01	5.4	Quartz	Kaolinite	Illite	Feldspars	Montmorillonite	--
	1-10-90	No	1.56	1.56	<.01	5.5	Quartz	Kaolinite	Illite	Feldspars	Chlorite	Montmorillonite
LS	9-27-89	Yes	.93	.89	.04	7.6	Quartz	Kaolinite	Illite	Gypsum	Jarosite	Feldspars
	9-27-89	Yes	.83	.80	.03	6.8	Quartz	Kaolinite	Illite	Gypsum	Jarosite	Feldspars
	1-08-90	No	1.04	1.02	.02	6.0	Quartz	Kaolinite	Illite	Gypsum	Jarosite	Feldspars
LEE	9-27-89	Yes	3.85	2.97	.88	6.9	Quartz	Kaolinite	Illite	Calcite	Gypsum	Feldspars
	12-27-89	No	5.60	5.29	.31	5.6	Quartz	Calcite	Kaolinite	Illite	Gypsum	Feldspars

Lake (fig. 1)	Date collected	Percentage by weight of bulk sample	Mineralogy of heavy mineral concentrates (ranked from most to least abundant)						
			Minerals of large abundance				Minerals of small abundance		
			1	2	3	4	1	2	3
LN north	9-26-89	0.65	Goethite	Ankerite	Siderite	--	Calcite	Hematite	Greigite
LN south	9-25-89	.20	Pyrite	Siderite	Goethite	Calcite	Marcasite	Hematite	Pyrrhotite
LQ	9-27-89	<.01	Calcite	Goethite	Siderite	--	Magnetite	--	--
	1-10-90	.01	Goethite	Siderite	--	--	Calcite	Ankerite	Hematite
LS	9-27-89	<.01	Calcite	Siderite	Goethite	--	Pyrite	Hematite	Magnetite
	9-27-89	<.01	Goethite	Siderite	Calcite	--	Hematite	Magnetite	Pyrite
	1-08-90	.05	Goethite	Siderite	--	--	Pyrite	Greigite	Hematite
LEE	9-27-89	.05	Siderite	Goethite	Pyrite	Calcite	Ankerite	Marcasite	Hematite
	12-27-89	1.25	Siderite	Calcite	Pyrite	Goethite	Hematite	Marcasite	--

The large concentrations of HCO_3 in the hypolimnions probably were from ground-water seepage and decomposition of lake-bottom organic matter. For the hypolimnions of the six lake locations listed in table 8, calcite was oversaturated in all except lake LX. Late summer hypolimnions samples had HCO_3 concentrations that were generally about twice as large as HCO_3 concentrations in ground water. Also, in lakes LN and LEE sampled in both the spring and late summer (table 8), HCO_3 concentrations were substantially larger in the late summer than the spring. These data indicate a substantial quantity of HCO_3 in the hypolimnion may be from decomposition of organic matter. However, the undersaturation of calcite in the hypolimnion and the small quantities of inorganic carbon in the bottom sediments of control lake LQ (table 10) indicates the additional CO_3 from ground water is required to precipitate substantial quantities of CO_3 minerals in the deep lakes. Lakes LN and LEE had larger quantities of inorganic carbon in their bottom sediments (table 10). The small quantities of inorganic carbon in bottom sediments from lake LS were probably because lake LS had been acidic until shortly after reclamation. Acidic conditions would not allow CO_3 minerals to precipitate and accumulate in bottom sediments. The large percentage of organic carbon in the bottom-sediment sample from lake LEE (table 10) was expected because of the large masses of aquatic plants growing in the lake during the summer.

The presence of greigite in lake-bottom sediments (table 10) is another indication that Fe-sulfide minerals precipitate in the hypolimnions because greigite is typically detected in recent sediments whose Fe-sulfide minerals are evolving from amorphous Fe sulfide to crystalline pyrite. The Fe^{+3} minerals, such as goethite and jarosite, also were detected in the bottom sediments of deep lakes. These minerals apparently were formed from oxidized precipitates in the epilimnion and from oxidation of bottom sediments during periods of destratification. The removal of Fe through precipitation of large quantities of Fe^{+2} as siderite and Fe sulfides in the hypolimnions prevents the hydrolysis and consequent acidification associated with the precipitation of Fe as a ferric oxyhydroxide. Shallow ground-water-supplied lakes are fully oxygenated all year. Consequently, nearly all Fe is oxidized and precipitated as ferric oxyhydroxide, decreasing the pH to less than 3.5 (Blevins, 1991). In the fall when deep lakes destratify, the large quantities of Fe^{+2} in the hypolimnions oxidize and precipitate as ferric oxyhydroxides, causing deep lakes to turn bright orange for a short time.

The largest components of lake-bottom sediments were quartz, kaolinite, and illite (table 10). These minerals might be expected from the weathered shales that form most of the spoil bordering the lakes. Water samples from the epilimnions in September 1989 were well oxygenated, contained little, if any, dissolved Fe, and had HCO_3 concentrations ranging from 67 to 315 mg/L (tables 7 and 8). Little dissolved Fe was detected leaving lakes LN, LO, LS, and LX in several samples of surface outflows (table 7; Blevins, 1991). Most deep lakes in the study area receive substantial quantities of rainfall and runoff from unmined areas that could affect the pH value. The percentages of surface runoff and ground water in deep lakes can be estimated by dilutions of SO_4, lithium (Li), and strontium (Sr). Lithium is not known to have any weathering products of low solubility and is absorbed less strongly by common ion-exchange minerals in soil than other common elements (Hem, 1985). The SO_4 and Sr may not be as conservative as Li, but they have substantially higher concentrations in ground water than surface runoff and show similar dilutions to Li (table 11). Concentrations of these constituents in surface runoff are small and can be estimated from concentrations detected in control lake LQ, which received little, if any, ground water on September 21, 1989. The larger concentrations of SO_4, Li, and Sr in ground water were estimated by averaging the concentrations of each of these constituents in samples from 11 wells (table 3, wells W18 and W24 were excluded because they were affected by recharge from an acidic perched lake and fly ash). Using this method to estimate runoff dilution, lakes LN north, LN south, LS, and LX contained as much as 68 percent surface runoff (table 11). Lakes LY and LZ, which drain larger unmined areas and have lower specific conductance values than lake LX, probably have even larger percentages of surface runoff.

Table 11.--*Estimated percentage of water from surface runoff in selected deep lakes as calculated by dilution of ground-water concentrations of sulfate, lithium, and strontium*

[-, negative numbers indicate constituent concentrations increased after the lake received storm runoff; average concentrations of sulfate (59 milligrams per liter), lithium (5 micrograms per liter), and strontium (140 micrograms per liter) in surface runoff were estimated from concentrations of these constituents in control lake LQ; average concentrations of sulfate (2,752 milligrams per liter), lithium (201 micrograms per liter), and strontium (5,960 micrograms per liter) in ground water were estimated from the average concentrations of these constituents in samples from 11 wells (wells W18 and W24, table 3, were excluded because of effects from a large recharge lake and fly ash)]

Lake (fig. 1)	Layer	Percentage of surface runoff		
		Sulfate	Lithium	Strontium
LN north[a]	Epilimnion	45	46	48
	Hypolimnion	0	-17	-24
	Weighted mean[b]	32	28	27
LN south[a]	Epilimnion	41	38	39
	Hypolimnion	6	1	-17
	Weighted mean[b]	19	15	4
LS	Epilimnion	20	31	34
	Hypolimnion	2	11	-2
	Weighted mean[b]	14	24	22
LX	Epilimnion	70	78	80
	Hypolimnion	39	46	34
	Weighted mean[b]	60	68	65

[a] Sulfate, lithium, and strontium concentrations are averages of two lake samples collected in April and September.

[b] Weighted by epilimnion and hypolimnion thicknesses.

Rainfall and runoff effects on the specific conductance and pH values at two locations in lake LN are shown in figure 18. The specific conductance and pH values were measured just before and after 4.5 in. of rainfall. In the summer, most dilution from storms occurs in the epilimnion because colder water in the hypolimnion resists mixing with warmer surface runoff. Lake outflows also are from the epilimnion and, therefore, surface water bypasses the hypolimnion and flows across the top of stratified lakes. The pH values in the epilimnion of the deep lakes decreased after rainfall, probably because the pH value of runoff from unmined areas was slightly less, and the pH value of rainfall was substantially less than the prestorm pH value of most deep-lake epilimnions. Therefore, although runoff from unmined areas and rainfall would tend to neutralize the shallow acidic lakes, runoff from unmined areas and rainfall are probably not the major causes of near-neutral pH values in deep lakes. The minimal neutralizing effect of rainfall and runoff from unmined areas also is evidenced by lakes such as LS and LEE that had near-neutral pH values and received small quantities of runoff.

Lake LQ had many physical characteristics in common with deep lakes, such as an oxidizing epilimnion, a reducing hypolimnion, and thermally stratified temperature profiles (fig. 16). Also, pH value and concentrations of chloride, Mn, and total organic carbon were similar to deep lakes. However, lake LQ had much smaller quantities of all other major cations and anions (table 8) because mine drainage has much more opportunity to dissolve minerals, such as calcite and pyrite, than surface runoff from unmined areas. Concentrations of HCO_3, SO_4, and Fe were substantially larger in deep lakes receiving substantial quantities of mine drainage and ground water from the spoil. Concentrations of Fe^{+2} were substantially less in the hypolimnion of lake LQ than in the deep lakes. However, lake LQ was oversaturated with reduced Fe and Mn minerals, such as Fe sulfide, siderite,

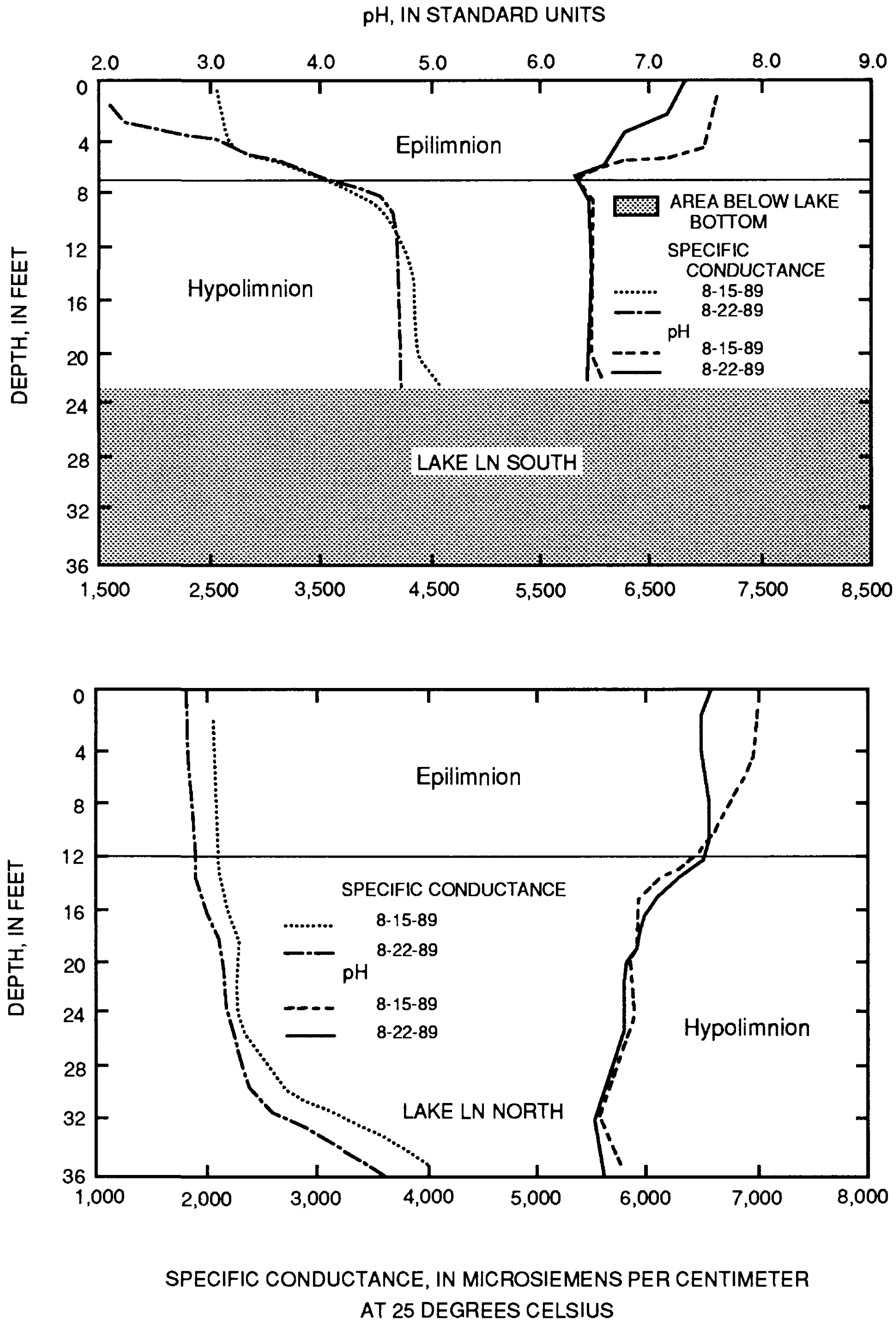


Figure 18.-- Specific conductance and pH values at two locations in lake LN before and after 4.5 inches of rainfall and runoff from mostly unmined areas.

and rhodochrosite, in the hypolimnion (table 9). The lack of Fe sulfide in the bottom sediments of lake LQ (table 9) indicates Fe^{+2} precipitation may occur at a slower rate or all analyzed Fe^{+2} may not be available for reaction.

Calcite was oversaturated in the epilimnion of lake LQ partly because the pH was 8.4. However, unlike the hypolimnions of deep lakes, calcite was undersaturated in the hypolimnion of lake LQ and calcite was not a major constituent of the bottom sediments. Gypsum was near saturation in the hypolimnions of most deep lakes (table 8), but not in control lake LQ. The only bottom-sediment samples that did not have detectable gypsum were from lake LQ.

In summary, the primary reason for near-neutral pH values (6.0 to 8.5) of deep lakes is because deep lakes receive ground water that contains larger concentrations of HCO_3 and smaller concentrations of Fe^{+2} than shallow ground-water-supplied lakes. Also, the removal of Fe^{+2} from the hypolimnions as siderite and iron sulfide contributes to near-neutral pH values.

LABORATORY STUDY OF THE EFFECTS OF MIXING ACIDIC AND NEUTRAL LAKE WATERS

The pH of several shallow lakes with large surface areas, including lakes LA, LI, LT, LV, and LGG, remained less than 4.0 after reclamation. Possible reclamation techniques for water in these lakes include drainage of these shallow acidic lakes into larger neutral lakes or rerouting of deep neutral lake outflows through acidic lakes. Laboratory mixing experiments were performed to determine whether outflow from neutral lake LO could be rerouted through acidic lake LA, acidic lake LI could be drained into neutral lake LM, acidic lake LT could be drained into deep neutral lakes LN or LS, and acidic lake LGG could be drained into neutral lake LII (fig. 11) without the resulting mixtures having pH values less than 6.0. The various mixtures were prepared from grab samples collected in sealed containers from 1 ft below the lake surface near outflow locations on April 20 to 26, 1990, near the typical time of the onset of stratification. Specific conductance and pH values were measured and HCO_3 and Fe concentrations were determined. Mixing experiments were done within 7 hours of sample collection, although some mixtures were held in sealed containers for remeasurement of pH 1 to 4 days later. Between the time of sample collection and the mixing experiments, specific conductance values changed less than 2 percent, pH values of lake samples changed less than 0.1 unit, and temperatures changed from 0.1 to 7.5 °C. Mixtures were prepared by adding aliquots of the samples from the more acidic lake to a constant volume from the near-neutral lake. All mixing experiments were repeated at least once, and two of the experiments were repeated in the reverse, that is aliquots of near-neutral lake water were added to a constant volume of acidic lake water. Specific conductance, pH, and temperature were measured after the addition of each aliquot.

Mixing experiments indicate drainage from shallow ground-water-supplied lakes could be neutralized by mixing with water from deep neutral lakes. Generally, if water from acidic lakes constitutes less than one-third of the volume in a receiving neutral lake, the resulting mixture had a pH greater than 6.0 (fig. 19). Presently (1990), the volume of water and rates of discharge from acidic lakes are substantially less than the volumes and rates of discharge from the neutral receiving lakes. The draining of ground-water-supplied lakes might induce larger discharges because of increased hydraulic head potentials toward the lake bed, but the discharges probably would still be less than one-third of the outflow from the receiving lake.

Lake LS had the lowest alkalinity of the deep lakes tested in the mixing experiments and, therefore, is the most sensitive to acidic drainage (fig. 19). This sensitivity is expected because the pH of lake LS was less than 5.0 before reclamation, partially because lake LS received surface outflows from acidic lake LT. Lake LS is neutral after reclamation, but has a smaller mean alkalinity than most deep lakes in the study area (table 8; fig. 19). However, nearby lake LN has more volume and larger alkalinity than lake LS. Therefore, lake LN is a more likely choice for neutralization of drainage from lake LT.

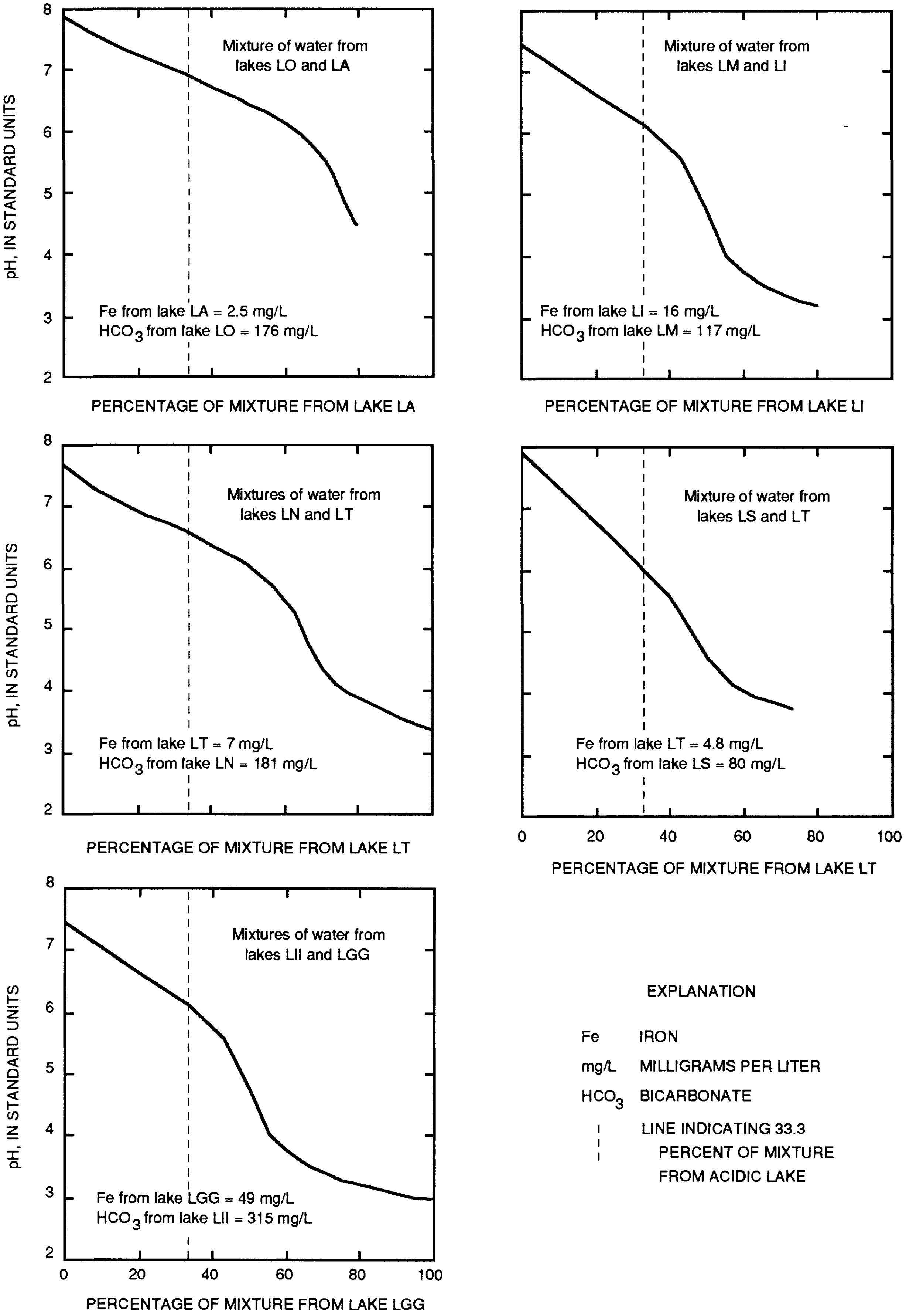


Figure 19.--pH values of laboratory mixtures of acidic- and neutral-lake water.

The pH values of mixtures in the laboratory sometimes changed after setting overnight. If the pH of a mixture was less than 4.3, the pH value decreased only a few hundredths of a pH unit in 24 hours. If the pH was between 4.3 and 6.0, the pH value increased less than 0.2 pH unit. However, if the pH was more than 6.0 immediately after mixing, the pH value increased from 1 to 1.5 pH units 24 hours after mixing. This increase was probably caused by slow outgassing of CO_2 caused by the addition of H^+ and H_2CO_3 from the acidic lake to HCO_3 from the deep lake according to:

$$H^+ + H_2CO_3 + HCO_3^- \longrightarrow 2H_2O + 2CO_2 \uparrow .$$

The pH values of mixtures remained stable for periods longer than 24 hours. The increase of pH values with time causes the pH values of laboratory mixtures to be conservative estimates of final pH values onsite.

SUMMARY

More than 100 lakes and several streams are in 2,400 acres of coal-mine spoil northwest of Montrose, Missouri. During 1986, two-thirds of the spoil was unreclaimed and many of the lakes and streams had pH values less than 4.0. Partial regrading, liming, and revegetation of the spoil was completed on the remaining unreclaimed spoil during 1988. Hydrochemical data were collected to determine the effects of reclamation on water chemistry.

About 20 percent of the mined area had internal drainage before reclamation. This percentage was not substantially changed by reclamation. Consequently, the percentage of rainfall leaving the area by Horn Branch as runoff was only slightly less than before reclamation. The pH of runoff remained less than 4.5 at 8 of 12 sites sampled during at least one storm after reclamation despite the addition of substantial quantities of lime to the spoil surface.

Ground-water levels changed little after reclamation. Ground water generally flowed from shallow perched lakes to deep lakes. Adjacent wells screened near the top and bottom of the spoil had no substantial water-level differences, which indicated little downward gradient or flow. Although ground-water samples from most wells had pH values greater than 6.0 before reclamation, the pH of two previously acidic wells (3.9 to 5.3) increased about one unit after reclamation. Shallow ground water had smaller pH values and HCO_3 concentrations and larger Fe concentrations than ground water near the bottom of the spoil. Precipitation of siderite is a likely control of Fe concentrations at depth.

Only 6 of 25 lakes sampled before and after reclamation had pH values greater than 4.5 after reclamation. The pH of one of these six lakes, lake LS, increased from less than 4.0 to greater than 6.0. The outflow from lake LS no longer caused the pH in Horn Branch to be less than 4.0 for more than 1 mi downstream during summer low flow. Shallow ground-water-supplied lakes generally had pH values less than 4.0 because Fe^{+2} from ground water oxidized and hydrolyzed in the lakes. Deep ground-water-supplied lakes were neutral despite the fact that they received more ground-water inflow than shallow lakes. The deeper lakes were near neutral primarily because they received ground water from the bottom part of the spoil where molar ratios of Fe^{+2} to HCO_3 were substantially less than 0.5. When this ratio is less than 0.5, HCO_3 can absorb all the H^+ produced by the oxidation and hydrolysis of Fe^{+2} without the pH decreasing to less than about 5.0. Conversely, shallow lakes received ground water primarily from the upper part of the spoil where molar ratios of Fe^{+2} to HCO_3 were substantially greater than 0.5. Seasonal stratification of deep lakes also assisted in maintaining the neutral pH value of deep lakes because Fe^{+2} in the anaerobic hypolimnions precipitated as siderite and Fe sulfides and was buried in the lake-bottom sediments. Concentrations of HCO_3, SO_4, and Fe were substantially larger in mine-affected deep lakes than in the deep control lake LQ.

Laboratory mixtures of water from deep neutral lakes and shallow lakes were prepared to determine the effects on pH values of draining the shallow acidic lakes into nearby deep neutral lakes. These experiments indicated the pH values of resulting mixtures would maintain pH values greater than 6.0 if the resulting mixtures contained less than one-third shallow acidic lake water. Discharges from shallow acidic lakes were substantially less than one-third of the discharge from nearby deep neutral lakes and, therefore, the resulting mixtures could be expected to have pH values greater than 6.0.

REFERENCES CITED

Ball, J.W., Nordstrom, D.K., and Zachmann, O.W., 1987, WATEQ4F--A personal computer FORTRAN translation of the geochemical model WATEQ2 with revised data base: U.S. Geological Survey Open-File Report 87-50, 108 p.

Barnes, Ivan, and Clark, F.E., 1964, Geochemistry of ground water in mine drainage problems: U.S. Geological Survey Professional Paper 473-A, 6 p.

Blevins, D.W., 1991, Hydrology and water chemistry of an abandoned surface coal mine, southwestern Henry County, Missouri--1984 to 1986: U.S. Geological Survey Water-Resources Investigations Report 90-4047, 52 p.

Brown, Eugene, Skougstad, M.W., and Fishman, M.J., eds., 1970, Methods for collection and analysis of water samples for dissolved minerals and gases: U.S. Geological Survey Techniques of Water Resources Investigations Report 78-115, 199 p.

Fishman, M.J., and Friedman L.C., 1989, Methods for determination of inorganic substances in water and fluvial sediments: U.S. Geological Survey Techniques of Water Resource Investigations, Chapter A1, Book 5, 626 p.

Hem, J.D., 1985, Study and interpretation of the chemical characteristics of natural water (3d ed.): U.S. Geological Survey Water-Supply Paper 2254, 263 p.

Miller, S.D., 1979, Chemistry of a pyrite strip-mine spoil: New Haven, Conn., Yale University, unpublished Ph.D dissertation, 189 p.

National Oceanic and Atmospheric Administration, 1988-90, Climatological data: Asheville, N.C., National Environmental Data and Information Service, v. 88-90.

Nordstrom, D.K., 1982, Aqueous pyrite oxidation and consequent formation of secondary iron minerals, *in* Kittrick, J.A., Fanning, D.S., and Hossner, L.R., eds., Acid Sulfate Weathering: Madison, Wisc., Soil Society of America, Special Publication 10, Chapter 3, p. 37-56.

Plummer, L.N., Jones, B.F., and Truesdell, A.H., 1976, WATEQF--A Fortran version of WATEQ, a computer program for calculating chemical equilibria of natural waters: U.S. Geological Survey Water-Resources Investigations Report 76-13, 61 p.

Ziegler, A.C., 1989, Experimental leaching of Pennsylvanian sedimentary rocks to determine sources of metals in coal mine waters near Montrose, Missouri: University of Missouri at Kansas City, unpublished M.S. thesis, 102 p.

SUPPLEMENTAL DATA

Table 2.--*Analyses of samples collected from surface runoff on spoil*

[Results are for dissolved constituents; in., inches; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; mg/L, milligrams per liter; NO_2+NO_3, nitrite plus nitrate; µg/L, micrograms per liter; PR, partially reclaimed; <, less than; --, no data available]

Lake location (fig. 4)	Land-surface condition	Total rainfall previous 48 hours (in.)	Date	Time	Specific conductance (µS/cm)	pH (standard units)	Hardness, total as $CaCO_3$ (mg/L)	Hardness, noncarbonate, total as $CaCO_3$ (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)
Near L12	PR	1.83	5-18-89	1835	1,190	3.6	620	620	210	23	1.0
Near LA	PR	1.83	5-18-89	1855	2,350	3.8	1,400	1,400	380	110	81
Near LI	PR	1.83	5-18-89	1840	3,470	3.2	1,700	1,700	420	160	180
Near LM	PR	1.83	5-18-89	1800	1,320	5.9	790	790	270	29	3.4
Near LO	PR	1.83	5-18-89	1830	555	3.8	250	250	79	12	.80
Near LS	PR	1.83	5-18-89	1910	1,230	7.5	740	710	250	29	1.5
Near LT	PR	1.83	5-18-89	1800	1,000	7.6	580	550	190	25	1.1
Near LX	PR	1.83	5-18-89	1815	1,280	3.5	630	630	210	26	1.8
Near LJJ	PR	1.83	5-18-89	1805	1,520	7.4	960	930	320	38	3.4
Near LY	Unmined	1.83	5-19-89	1125	1,100	7.2	--	--	--	--	--
Near L15	PR	.66	8-16-89	0900	1,020	3.4	--	--	--	--	--
Near L17	PR	.66	8-16-89	0855	1,710	4.4	--	--	--	--	--
Near LM	PR	.90	2-22-90	--	1,380	6.8	--	--	--	--	--
Near LS	PR	.90	2-22-90	--	1,020	6.8	--	--	--	--	--
Near LT	PR	.90	2-22-90	--	500	7.0	--	--	--	--	--
Near LEE	PR	.90	2-22-90	--	1,060	6.3	--	--	--	--	--
Near LJJ	PR	.90	2-22-90	--	1,600	3.5	--	--	--	--	--
Near LA	PR	1.89	3-15-90	0905	1,950	5.0	--	--	--	--	--
Near LY	Unmined	1.89	3-15-90	0753	280	7.7	--	--	--	--	--
Near LJJ	PR	1.89	3-15-90	0815	1,500	3.8	--	--	--	--	--

Table 2.--*Analyses of samples collected from surface runoff on spoil*--Continued

Lake location (fig. 4)	Date	Potassium (mg/L)	Bicarbonate, total (mg/L)	Alkalinity, total as $CaCO_3$ (mg/L)	Sulfate (mg/L)	Chloride (mg/L)	Fluoride (mg/L)	Silica (mg/L)	Dissolved solids, residue at 180 degrees Celsius (mg/L)	Iron (mg/L)
Near L12	5-18-89	11	0	0	670	0.60	0.80	8.5	970	0.56
Near LA	5-18-89	10	0	0	1,500	1.5	2.4	10	2,150	.31
Near LI	5-18-89	6.8	0	0	2,400	1.8	1.6	17	1,670	5.3
Near LM	5-18-89	6.3	4	3	770	1.4	.40	4.3	1,130	.010
Near LO	5-18-89	6.9	0	0	250	.60	.40	5.0	373	.13
Near LS	5-18-89	6.1	41	34	680	.90	.60	3.6	1,050	.010
Near LT	5-18-89	6.8	35	29	510	2.0	.40	2.4	804	.008
Near LX	5-18-89	7.5	0	0	730	1.1	.70	12	1,040	1.2
Near LJJ	5-18-89	5.5	31	26	900	1.1	.40	4.6	1,390	.008
Near LY	5-19-89	--	--	--	--	--	--	--	--	--
Near L15	8-16-89	--	--	--	--	--	--	--	--	--
Near L17	8-16-89	--	--	--	--	--	--	--	--	--
Near LM	2-22-90	--	--	--	--	--	--	--	--	--
Near LS	2-22-90	--	--	--	--	--	--	--	--	--
Near LT	2-22-90	--	--	--	--	--	--	--	--	--
Near LEE	2-22-90	--	--	--	--	--	--	--	--	--
Near LJJ	2-22-90	--	--	--	--	--	--	--	--	--
Near LA	3-15-90	--	--	--	--	--	--	--	--	--
Near LY	3-15-90	--	--	--	--	--	--	--	--	--
Near LJJ	3-15-90	--	--	--	--	--	--	--	--	--

Table 2.--*Analyses of samples collected from surface runoff on spoil*--Continued

Lake location (fig. 4)	Date	Manganese (µg/L)	Nitrogen, NO_2+NO_3 (mg/L)	Ortho-phosphate as phosphorous (mg/L)	Aluminum (µg/L)	Barium (µg/L)	Beryllium (µg/L)	Cadmium µg/L)	Chromium (µg/L)	Cobalt (µg/L)
Near L12	5-18-89	2,200	0.66	<0.01	5,900	2	4	2	<5	60
Near LA	5-18-89	5,400	.22	< .01	9,800	<3	7	14	<10	150
Near LI	5-18-89	13,000	.28	< .01	37,000	<3	11	11	20	360
Near LM	5-18-89	1,700	.28	.15	40	<2	< .5	4	<5	30
Near LO	5-18-89	980	.23	< .01	2,100	3	3	1	<5	40
Near LS	5-18-89	230	.32	.02	30	<2	< .5	<1	<5	<3
Near LT	5-18-89	87	.49	.02	20	2	< .5	<1	<5	<3
Near LX	5-18-89	3,000	.67	< .01	14,000	12	6	1	9	130
Near LJJ	5-18-89	250	1.7	< .01	<10	<2	< .5	<1	<5	4
Near LY	5-19-89	--	--	--	--	--	--	--	--	--
Near L15	8-16-89	--	--	--	--	--	--	--	--	--
Near L17	8-16-89	--	--	--	--	--	--	--	--	--
Near LM	2-22-90	--	--	--	--	--	--	--	--	--
Near LS	2-22-90	--	--	--	--	--	--	--	--	--
Near LT	2-22-90	--	--	--	--	--	--	--	--	--
Near LEE	2-22-90	--	--	--	--	--	--	--	--	--
Near LJJ	2-22-90	--	--	--	--	--	--	--	--	--
Near LA	3-15-90	--	--	--	--	--	--	--	--	--
Near LY	3-15-90	--	--	--	--	--	--	--	--	--
Near LJJ	3-15-90	--	--	--	--	--	--	--	--	--

Table 2.--*Analyses of samples collected from surface runoff on spoil*--Continued

Lake location (fig. 4)	Date	Copper (µg/L)	Lead (µg/L)	Lithium (µg/L)	Molybdenum (µg/L)	Nickel (µg/L)	Silver (µg/L)	Strontium (µg/L)	Vanadium (µg/L)	Zinc (µg/L)
Near L12	5-18-89	50	<10	67	<10	230	3.0	270	<6	160
Near LA	5-18-89	70	<30	170	<30	640	<3.0	590	<18	1,000
Near LI	5-18-89	320	<30	300	<30	1,200	4.0	480	<18	1,600
Near LM	5-18-89	<10	<10	28	<10	100	<1.0	90	<6	110
Near LO	5-18-89	50	<10	42	<10	150	5.0	110	<6	130
Near LS	5-18-89	<10	10	22	<10	10	<1.0	150	<6	4
Near LT	5-18-89	<10	<10	15	<10	<10	<1.0	130	<6	5
Near LX	5-18-89	60	<10	95	<10	450	12	210	<6	180
Near LJJ	5-18-89	<10	<10	25	<10	30	<1.0	350	<6	9
Near LY	5-19-89	--	--	--	--	--	--	--	--	--
Near L15	8-16-89	--	--	--	--	--	--	--	--	--
Near L17	8-16-89	--	--	--	--	--	--	--	--	--
Near LM	2-22-90	--	--	--	--	--	--	--	--	--
Near LS	2-22-90	--	--	--	--	--	--	--	--	--
Near LT	2-22-90	--	--	--	--	--	--	--	--	--
Near LEE	2-22-90	--	--	--	--	--	--	--	--	--
Near LJJ	2-22-90	--	--	--	--	--	--	--	--	--
Near LA	3-15-90	--	--	--	--	--	--	--	--	--
Near LY	3-15-90	--	--	--	--	--	--	--	--	--
Near LJJ	3-15-90	--	--	--	--	--	--	--	--	--

Table 3.--*Analyses of samples collected from wells completed in spoil*

[Pre-reclamation samples were collected during 1985-87; post-reclamation samples were collected during 1988-90; wells grouped are in a well nest; results are for dissolved constituents, except as indicated; ft, feet; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mV, millivolts; mg/L, milligrams per liter; $CaCO_3$, calcium carbonate; µg/L, micrograms per liter; NO_2+NO_3, nitrite plus nitrate; <, less than; --, no data available; samples from 1985 and 1986 are from Blevins (1991); samples from 1987 and 1988 are from Ziegler (1989)]

Well number (fig. 6)	Date	Altitude of water surface (ft)	Depth of well (ft)	Height of water column in well (ft)	Specific conductance (µS/cm)	pH (standard units)	Oxidation-reduction potential (mV)	Temperature, water (degrees Celsius)	Oxygen, dissolved (mg/L)	Hydrogen sulfide (mg/L)
W13	9-25-87	804.0	27.6	9.9	4,100	5.9	356	17.5	<0.1	--
	10-11-89	804.9	27.6	10.9	3,500	6.1	188	16.0	< .1	<0.1
W53	10-11-89	804.9	37.6	21.2	3,500	6.3	155	15.5	--	--
W54	10-11-89	804.9	47.2	30.7	3,500	6.3	135	16.0	--	--
W18	9-13-85	--	--	--	3,400	5.8	--	20.0	< .1	--
	4-24-86	818.3	23.4	13.9	3,200	5.3	--	16.0	--	--
	10-24-89	818.2	23.4	13.6	2,550	5.6	226	15.5	< .2	< .1
W24	9-13-85	793.6	36.6	9.9	3,400	5.3	--	16.0	--	--
	4-24-86	793.8	36.6	10.1	3,250	5.2	--	19.0	--	--
	10-20-89	797.0	36.6	13.4	2,520	6.3	188	15.5	< .1	< .1
W30	4-24-86	821.7	18.0	6.1	4,500	5.8	--	15.5	--	--
	9-25-87	822.0	18.0	5.3	4,200	6.0	227	17.5	< .1	--
	5-13-88	823.1	18.0	7.4	3,900	6.0	160	15.5	< .1	--
	10-16-89	821.8	18.0	6.2	4,000	6.3	188	16.0	< .1	< .1
	3-22-90	823.0	18.0	8.2	3,950	6.2	187	14.5	< .1	< .1
W50	10-16-89	821.8	34.4	22.6	3,750	6.6	191	16.0	--	--
W31	4-24-86	825.4	17.5	6.2	5,350	6.1	--	21.0	--	--
	10-24-89	824.0	17.5	6.9	4,800	6.1	187	15.5	< .1	< .1
W37	4-25-86	809.5	26.4	13.5	3,500	6.0	--	17.0	--	--
	5-13-88	810.9	26.4	14.8	3,250	6.6	180	16.5	< .2	--
	10-12-89	810.2	26.4	14.3	3,050	6.1	176	15.5	< .1	< .1
W56	10-12-89	809.3	33.7	21.8	3,300	6.3	134	16.0	--	--
W40	10-10-89	804.4	8.5	5.3	3,500	6.1	126	15.5	< .1	< .1
W41	10-10-89	804.7	46.9	37.8	4,100	6.6	166	16.5	< .1	--
W62	10-19-89	802.6	23.2	7.6	4,500	4.8	362	15.5	< .1	--

Table 3.--*Analyses of samples collected from wells completed in spoil*--Continued

Well number (fig. 6)	Date	Hardness, total as $CaCO_3$ (mg/L)	Acidity as $CaCO_3$ (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Bicarbonate (mg/L)	Alkalinity, total field as $CaCO_3$ (mg/L)	Sulfate (mg/L)
W13	9-25-87	2,200	199	510	230	200	1.1	286	234	2,600
	10-11-89	2,000	--	480	200	160	36	334	274	2,600
W53	10-11-89	--	--	--	--	--	--	525	430	--
W54	10-11-89	2,200	--	530	200	140	28	464	380	2,500
W18	9-13-85	--	640	460	170	8	40	670	550	2,800
	4-24-86	--	600	480	170	10	35	76	62	2,200
	10-24-89	1,500	--	440	88	6.2	27	73	60	1,900
W24	9-13-85	--	700	460	140	43	33	41	34	2,700
	4-24-86	--	420	520	140	43	28	74	61	2,300
	10-20-89	1,500	--	570	29	20	88	21	17	1,800
W30	4-24-86	--	300	490	280	230	30	265	217	3,000
	9-25-87	2,500	169	530	290	230	36	346	284	2,800
	5-13-88	2,300	278	490	270	200	23	370	304	2,700
	10-16-89	2,300	--	500	260	180	31	383	314	2,800
	3-22-90	--	--	--	--	--	--	360	295	--
W50	10-16-89	2,400	--	540	250	160	18	569	466	2,500
W31	4-24-86	--	115	470	380	440	47	460	378	3,600
	10-24-89	2,600	--	460	350	350	43	537	440	3,500
W37	4-25-86	--	60	480	210	170	48	310	254	2,200
	5-13-88	2,000	179	500	190	96	18	310	254	2,200
	10-12-89	1,900	--	470	170	88	42	286	234	2,100
W56	10-12-89	2,200	--	530	220	92	28	456	382	2,400
W40	10-10-89	2,300	--	490	250	120	34	333	273	2,700
W41	10-10-89	2,600	--	500	330	200	43	630	516	2,800
W62	10-19-89	1,900	--	440	200	260	32	41	34	3,600

Table 3.--*Analyses of samples collected from wells completed in spoil*--Continued

Well number (fig. 6)	Date	Chloride (mg/L)	Fluoride (mg/L)	Silica (mg/L)	Dissolved solids, residue at 180 degrees Celsius (mg/L)	Iron (mg/L)	Manganese (µg/L)	Nitrogen, NO_2+NO_3 (mg/L)	Nitrogen, ammonia (mg/L)	Ortho-phosphate as phosphorus (mg/L)
W13	9-25-87	1.7	0.5	9.7	3,910	160	13,000	--	--	--
	10-11-89	1.7	.7	11	3,710	130	10,000	--	2.8	--
W53	10-11-89	--	--	--	--	80	--	--	--	--
W54	10-11-89	1.9	.8	110	3,680	96	8,900	--	2.2	--
W18	9-13-85	2.5	6.6	--	4,330	380	16,000	--	--	--
	4-24-86	1.3	1.7	10	3,890	310	14,000	--	--	--
	10-24-89	2.4	2.1	17	2,760	190	7,100	<0.1	2.1	--
W24	9-13-85	3.2	2.0	17	4,070	300	29,000	--	--	--
	4-24-86	2.6	.4	9.5	3,610	220	25,000	--	--	--
	10-20-89	4.8	.3	6.5	2,630	44	3,900	< .01	1.1	--
W30	4-24-86	3.6	.3	4.4	4,580	190	12,000	--	--	--
	9-25-87	1.6	.5	10	4,210	130	15,000	--	--	--
	5-13-88	10	.5	9.4	4,120	--	13,000	< .10	--	<0.01
	10-16-89	1.7	.4	9.7	3,970	110	12,000	< .01	2.4	--
	3-22-90	--	--	--	--	110	--	--	--	--
W50	10-16-89	1.9	.4	12	3,940	24	12,000	< .01	1.3	--
W31	4-24-86	5.6	.6	4.5	5,540	130	16,000	--	--	--
	10-24-89	2.6	1.2	10	4,980	140	12,000	< .10	3.6	--
W37	4-25-86	1.6	.1	6.9	3,600	48	8,700	--	--	--
	5-13-89	11	.3	15	3,400	52	9,900	< .10	--	.13
	10-12-89	1.8	.2	14	3,130	47	8,700	--	3.0	--
W56	10-12-89	1.6	.7	12	3,550	61	8,200	--	2.1	--
W40	10-10-89	2.3	.9	13	3,840	100	15,000	--	2.5	--
W41	10-10-89	1.2	.2	13	4,370	8.5	12,000	--	3.2	--
W62	10-19-89	1.5	1.8	45	5,010	490	14,000	< .01	3.2	--

Table 3.--*Analyses of samples collected from wells completed in spoil*--Continued

Well number (fig. 6)	Date	Aluminum (µg/L)	Arsenic (µg/L)	Barium (µg/L)	Beryllium (µg/L)	Cadmium (µg/L)	Chromium (µg/L)	Cobalt (µg/L)	Copper (µg/L)	Lead (µg/L)
W13	9-25-87	130	--	37	<5	32	<50	370	<100	<100
	10-11-89	320	--	10	<1	9	<10	280	<20	<20
W53	10-11-89	--	--	--	--	--	--	--	--	--
W54	10-11-89	40	--	13	<1	6	<10	190	<20	<20
W18	9-13-85	3,000	--	--	--	--	--	--	--	--
	4-24-86	1,300	--	--	--	--	--	--	--	--
	10-24-89	1,000	--	7	1	<2	<10	4,300	<20	110
W24	9-13-85	2,700	--	--	--	--	--	--	--	--
	4-24-86	410	--	--	--	--	--	--	--	--
	10-20-89	<10	--	15	<1	<2	<10	60	<20	<20
W30	4-24-86	130	--	--	--	--	--	--	--	--
	9-25-87	310	--	29	<5	23	<50	190	<100	<100
	5-13-88	170	3	38	<2	8	<20	150	<40	<40
	10-16-89	330	--	6	<3	7	<20	230	<50	<50
	3-22-90	--	--	--	--	--	--	--	--	--
W50	10-16-89	20	--	15	<2	<3	<20	10	<30	<30
W31	4-24-86	20	--	--	--	--	--	--	--	--
	10-24-89	240	--	10	1	<1	<5	2,800	<10	40
W37	4-25-86	20	--	--	--	--	--	--	--	--
	5-13-88	40	--	33	<2	4	<20	50	<30	<30
	10-12-89	<10	--	15	<1	4	<10	50	<20	<20
W56	10-12-89	30	--	11	<1	<2	<10	60	<20	<20
W40	10-10-89	120	--	12	<1	7	<10	190	<20	40
W41	10-10-89	<10	--	12	<2	<3	<20	30	<30	<30
W62	10-19-89	21,000	--	10	14	51	<20	<9	<30	120

Table 3.--*Analyses of samples collected from wells completed in spoil*--Continued

Well number (fig. 6)	Date	Lithium (µg/L)	Molybdenum (µg/L)	Nickel (µg/L)	Silver (µg/L)	Strontium (µg/L)	Vanadium (µg/L)	Zinc (µg/L)	Carbon, total organic (mg/L)	Mole ratio of iron to bicarbonate (dimensionless)
W13	9-25-87	290	<100	760	20	6,600	<42	620	--	0.61
	10-11-89	210	<20	540	<2	6,000	<12	470	1.7	.43
W53	10-11-89	--	--	--	--	--	--	--	--	.17
W54	10-11-89	190	<20	380	<2	5,800	<12	200	2.0	.23
W18	9-13-85	--	--	--	--	2,100	--	--	--	.61
	4-24-86	--	--	--	--	2,800	--	--	--	4.5
	10-24-89	120	<20	400	8	1,700	60	140	.9	2.8
W24	9-13-85	--	--	--	--	1,500	--	--	--	8.0
	4-24-86	--	--	--	--	2,200	--	--	--	3.2
	10-20-89	560	400	470	<2	1,700	<12	640	3.6	2.3
W30	4-24-86	--	--	--	--	7,100	--	--	--	.78
	9-25-87	280	<100	430	24	7,100	<1	160	--	.41
	5-13-88	200	<40	310	<4	6,600	<24	230	--	.32
	10-16-89	200	<50	310	<5	6,500	<30	210	3.3	.31
	3-22-90	--	--	--	--	--	--	--	--	.33
W50	10-16-89	120	<30	70	<3	4,600	<18	60	.9	.05
W31	4-24-86	--	--	--	--	8,000	--	--	--	.31
	10-24-89	210	<10	410	<1	5,900	35	170	2.0	.28
W37	4-25-86	--	--	--	--	10,000	--	--	--	.17
	5-13-88	210	<30	160	4	8,900	<18	120	--	.18
	10-12-89	180	<20	140	3	8,200	<12	52	3.0	.18
W56	10-12-89	150	20	160	<2	5,400	<12	120	25	.15
W40	10-10-89	210	<20	460	2	5,400	<12	410	.8	.33
W41	10-10-89	260	<30	110	<3	9,300	<18	110	19	.02
W62	10-19-89	380	<30	740	<3	1,000	<18	1,300	1.2	13

Table 7.--*Analyses of samples collected from lake and stream sites during low-flow conditions*

[Results are for dissolved constituents, except as indicated; ft, feet; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mV, millivolts; mg/L, milligrams per liter; $CaCO_3$, calcium carbonate; µg/L, micrograms per liter; NO_2+NO_3, nitrite plus nitrate; R, lake is a net recharger to the ground-water system; D, lake is a net discharger from the ground-water system; <, less than; --, missing data; samples from 1987 and 1988 are from Ziegler (1989)]

Lake or stream site (fig. 8)	Relation to ground water	Average depth of lake (ft)	Date	Discharge, instantaneous (cubic feet per second)	Specific conductance (µS/cm)	pH (standard units)	Oxidation reduction potential (mV)	Temperature, water (degrees Celsius)	Oxygen, dissolved (mg/L)	Hardness, total as $CaCO_3$ (mg/L)
					Shallow perched lake					
L15	R	<8	10-25-89	0.000	1,620	3.1	713	17.0	10.5	900
					Shallow ground-water-supplied lakes					
LA outflow	D	8	5-12-88	0.000	2,810	3.2	680	24.5	8.8	1,600
		8	4-18-89	.02	3,190	3.2	709	14.5	10.1	1,900
		8	10-25-89	< .01	3,300	3.2	716	15.0	9.9	1,700
LE outflow	--	--	4-18-89	.02	3,390	7.3	380	14.5	9.4	2,100
LF outflow	D	4	9-25-87	.27	3,400	5.8	425	19.5	10.6	1,800
		4	5-12-88	.65	3,110	7.3	400	27.0	11.1	1,700
		4	4-18-89	.59	3,300	7.4	412	16.5	9.4	1,800
LI[a]	R	<8	10-25-89	.000	4,000	3.0	733	17.0	10.1	1,800
LJ outflow	--	--	4-18-89	.42	2,880	7.6	395	16.5	9.3	1,700
LK outflow	D	--	4-17-89	.06	4,600	7.5	388	17.5	9.9	2,300
LP outflow	D	7	9-24-87	.070	3,500	3.4	705	22.5	6.8	2,100
		7	5-12-88	.090	3,120	3.8	600	20.5	6.3	2,000
		7	4-17-89	.087	3,650	5.3	386	15.5	9.2	2,000
LT	D	4	4-17-89	.000	3,200	3.2	717	17.0	9.5	1,500
		4	10-25-89	.000	3,000	3.1	714	15.5	10.3	1,600
Seep near lake LT	--	--	4-17-89	.002	3,980	2.9	707	17.0	.5	2,200
LV[a]	R	<8	10-24-89	.000	1,180	3.4	632	18.0	9.8	520
LGG outflow	D	<5	4-18-89	< .001	4,070	2.9	696	15.5	10.7	2,300
					Deep lakes					
LM outflow	D	11	4-17-89	0.39	3,110	7.2	210	20.0	10.0	1,800
LN outflow	D	16	9-24-87	.080	2,110	8.2	517	24.0	9.8	1,200
		16	5-12-88	.17	2,240	7.9	350	24.0	10.1	1,100
		16	4-17-89	.094	2,730	8.2	385	17.0	10.9	1,400
LO outflow	D	17	4-17-89	.059	2,620	7.2	380	16.0	9.4	--
LS outflow	D	11	4-17-89	.020	3,550	7.1	342	17.5	8.7	2,200

Table 7.--*Analyses of samples collected from lake and stream sites during low-flow conditions*--Continued

Lake or stream site (fig. 8)	Date	Acidity as $CaCO_3$ (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Bicarbonate (mg/L)	Alkalinity, total as $CaCO_3$ (mg/L)	Sulfate (mg/L)	Chloride (mg/L)
				Shallow perched lake						
L15	10-25-89	273	310	31	5.2	5.7	--	--	960	0.9
				Shallow ground-water-supplied lakes						
LA outflow	5-12-88	114	360	160	120	15	0	0	2,000	9.3
	4-18-89	--	440	190	130	23	0	0	2,200	2.6
	10-25-89	119	410	170	130	29	0	0	2,200	2.6
LE outflow	4-18-89	--	520	200	120	11	53	44	2,300	.8
LF outflow	9-25-87	9.9	410	190	200	10	6	5	2,200	3.3
	5-12-88	25	370	180	180	17	73	60	2,000	11
	4-18-89	--	410	190	190	22	98	80	2,100	2.3
LI[a]	10-25-89	184	430	170	220	14	--	--	2,500	1.8
LJ outflow	4-18-89	--	380	180	180	23	100	82	2,000	2.7
LK outflow	4-17-89	--	490	250	410	29	315	258	2,800	1.3
LP outflow	9-24-87	104	450	230	120	11	0	0	2,300	3.5
	5-12-88	35	420	220	120	22	0	0	2,300	11
	4-17-89	--	420	230	120	26	4	3	2,300	2.2
LT	4-17-89	--	350	150	79	27	0	0	2,000	2.3
	10-25-89	149	390	150	73	37	0	0	1,900	2.0
Seep near lake LT	4-17-89	--	500	220	110	18	0	0	2,600	2.2
LV[a]	10-24-89	109	160	28	2.6	10	--	--	640	1.8
LGG outflow	4-18-89	--	380	320	270	15	0	0	3,100	.9
				Deep lakes						
LM outflow	4-17-89	--	390	190	160	24	78	64	2,000	2.5
LN outflow	9-24-87	< 5.0	270	120	130	2.3	116	95	1,300	3.6
	5-12-88	5.0	240	110	120	17	132	108	1,200	9.7
	4-17-89	--	310	150	160	20	190	156	1,500	3.0
LO outflow	4-17-89	--	--	--	--	--	--	--	--	--
LS outflow	4-17-89	--	450	250	120	32	36	30	2,300	1.9

Table 7.--*Analyses of samples collected from lake and stream sites during low-flow conditions*--Continued

Lake or stream site (fig. 8)	Date	Fluoride (mg/L)	Silica (mg/L)	Dissolved solids, residue at 180 degrees Celsius (mg/L)	Iron (mg/L)	Iron, ferrous (mg/L)	Manganese (µg/L)	Nitrogen, NO_2+NO_3 (mg/L)	Nitrogen, ammonia (mg/L)	Ortho-phosphate as phosphorus (mg/L)
				Shallow perched lake						
L15	10-25-89	1.0	12	1,330	3.8	0.72	5,600	--	--	--
				Shallow ground-water-supplied lakes						
LA outflow	5-12-88	1.1	9.9	2,730	4.3	0.60	11,000	<0.1	--	0.18
	4-18-89	1.2	15	3,240	13	.47	15,000	--	--	--
	10-25-89	1.2	15	2,960	5.4	.48	12,000	< .01	0.11	--
LE outflow	4-18-89	.9	1.7	3,450	.30	.28	1,300	--	--	--
LF outflow	9-25-87	.8	4.8	3,300	.090	< .01	3,100	--	--	--
	5-12-88	.8	1.6	2,920	< .009	< .01	2,400	< .1	--	.16
	4-18-89	.7	1.0	3,190	.013	< .02	2,500	--	--	--
LI[a]	10-25-89	1.2	16	3,510	14	.65	12,000	--	--	--
LJ outflow	4-18-89	.6	.70	3,080	< .006	< .01	2,700	--	--	--
LK outflow	4-17-89	.6	5.1	4,480	< .012	< .02	11,000	--	--	--
LP outflow	9-24-87	.8	9.4	3,500	2.3	.55	11,000	--	--	--
	5-12-88	.6	3.7	3,270	.59	.50	8,100	< .1	--	.17
	4-17-89	.6	6.8	3,490	1.3	.35	7,200	--	--	--
LT	4-17-89	.6	11	2,820	6.6	.50	8,600	--	--	--
	10-25-89	.6	13	2,680	7.8	.88	8,800	< .01	.08	--
Seep near lake LT	4-17-89	.7	21	3,740	33	3.4	19,000	--	--	--
LV[a]	10-24-89	1.0	4.8	872	.94	--	2,800	.075	.24	--
LGG outflow	4-18-89	1.0	22	4,460	67	8.6	15,000	--	--	--
				Deep lakes						
LM outflow	4-17-89	0.5	1.2	2,970	0.72	0.66	4,100	--	--	--
LN outflow	9-24-87	.5	1.1	2,020	.026	< .01	36	--	--	--
	5-12-88	.5	.35	1,820	.024	< .01	91	<0 .10	--	0.16
	4-17-89	.5	.16	2,320	< .006	< .01	130	--	--	--
LO outflow	4-17-89	--	--	--	--	--	--	--	--	--
LS outflow	4-17-89	.6	1.7	3,400	.035	< .02	240	--	--	--

Table 7.--*Analyses of samples collected from lake and stream sites during low-flow conditions--Continued*

Lake or stream site (fig. 8)	Date	Aluminum (µg/L)	Arsenic (µg/L)	Barium (µg/L)	Beryllium (µg/L)	Cadmium (µg/L)	Chromium (µg/L)	Cobalt (µg/L)	Copper (µg/L)	Lead (µg/L)
					Shallow perched lake					
L15	10-25-89	37,000	--	<2	10	<1	20	250	180	<10
					Shallow ground-water-supplied lakes					
LA outflow	5-12-88	5,500	<1	43	<2	<3	<20	130	<30	<30
	4-18-89	6,800	--	4	<1	<2	<10	150	20	<20
	10-25-89	6,500	--	19	3	<2	<10	250	<20	<20
LE outflow	4-18-89	60	--	4	<1	<2	<10	<6	<20	<20
LF outflow	9-25-87	110	--	28	<2	<3	<20	20	<30	<30
	5-12-88	<10	<1	81	<2	<3	<20	10	<30	<30
	4-18-89	<10	--	6	<1	<2	<10	20	<20	<20
LI[a]	10-25-89	8,300	--	5	3	3	<10	480	30	20
LJ outflow	4-18-89	20	--	7	<1	<2	<10	30	<20	<20
LK outflow	4-17-89	<10	--	12	<2	<4	<20	70	<40	<40
LP outflow	9-24-87	6,300	--	56	2	6	<10	120	<30	<30
	5-12-88	1,400	<1	53	<2	<3	<20	70	<30	<30
	4-17-89	310	--	7	<1	<2	<10	70	<20	<20
LT	4-17-89	8,600	--	65	<1	<3	<10	90	50	<20
	10-25-89	9,500	--	5	3	3	<10	100	20	<20
Seep near lake LT	4-17-89	3,500	--	42	<2	<3	<20	180	<30	<30
LV[a]	10-24-89	13,000	--	<2	6	2	6	130	70	<10
LGG outflow	4-18-89	18,000	--	<4	3	<4	<20	310	50	<40
					Deep lakes					
LM outflow	4-17-89	10	--	8	<1	<2	<10	30	<20	50
LN outflow	9-24-87	30	--	69	<2	<3	<20	<9	<30	<30
	5-12-88	<10	--	24	<1	<2	<10	<6	<20	<20
	4-17-89	10	--	13	<1	<2	<10	<6	<20	<20
LO outflow	4-17-89	--	--	--	--	--	--	--	--	--
LS outflow	4-17-89	10	--	7	<1	<2	<10	<6	<20	<20

Table 7.--*Analyses of samples collected from lake and stream sites during low-flow conditions*--Continued

Lake or stream site (fig. 8)	Date	Lithium (µg/L)	Molybdenum (µg/L)	Nickel (µg/L)	Selenium (µg/L)	Silver (µg/L)	Strontium (µg/L)	Vanadium (µg/L)	Zinc (µg/L)	Carbon, total organic (mg/L)
					Shallow perched lake					
L15	10-25-89	120	<10	780	--	<1	230	<6	400	--
					Shallow ground-water-supplied lakes					
LA outflow	5-12-88	140	<30	470	3	<3	1,800	<18	540	--
	4-18-89	150	<20	530	--	<2	2,100	<12	520	--
	10-25-89	130	<20	430	--	4	2,000	<12	410	1.0
LE outflow	4-18-89	110	<20	50	--	<2	2,400	<12	19	--
LF outflow	9-25-87	120	<30	170	<1	11	3,400	<1	100	--
	5-12-88	140	<30	60	--	<3	3,300	<18	54	--
	4-18-89	130	<20	110	--	2	3,500	<12	18	--
LI[a]	10-25-89	180	<20	620	--	8	2,600	<12	450	--
LJ outflow	4-18-89	130	<20	100	--	<2	3,400	<12	19	--
LK outflow	4-17-89	180	<40	230	--	<4	5,500	<24	<12	--
LP outflow	9-24-87	170	<30	430	<1	11	3,800	<5	430	--
	5-12-88	170	<30	250	1	4	3,700	<18	440	--
	4-17-89	150	<20	220	--	<2	3,700	<12	170	--
LT	4-17-89	130	<20	270	--	3	2,700	<12	270	--
	10-25-89	140	<20	280	--	<2	2,800	<12	250	.2
Seep near lake LT	4-17-89	170	<30	430	--	7	2,500	<18	310	--
LV[a]	10-24-89	89	<10	390	--	3	120	<6	260	.1
LGG outflow	4-18-89	220	<40	920	--	<4	2,400	<24	1,200	--
					Deep lakes					
LM outflow	4-17-89	140	<20	120	--	8	3,500	<12	27	--
LN outflow	9-24-87	91	<30	<30	<1	8	2,600	<1	10	--
	5-12-88	89	<20	<20	--	<2	2,400	<12	10	--
	4-17-89	110	<20	20	--	<2	3,500	<12	<6	--
LO outflow	4-17-89	--	--	--	--	--	--	--	--	--
LS outflow	4-17-89	170	<20	40	--	<2	4,500	<12	7	--

[a] Lake intersects water table but has no surface outflow.

Table 8.--*Analyses of samples collected from six deep lake locations and shallow lake LP*

[Results are for dissolved constituents, except as indicated; ft, feet; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mV, millivolts; mg/L, milligrams per liter; $CaCO_3$, calcium carbonate; µg/L, micrograms per liter; NO_2+NO_3, nitrite plus nitrate; <, less than; >, greater than; --, no data]

Lake (fig. 8)	Sample depth (ft)	Date	Time	Specific conductance (µS/cm)	pH (standard units)	Oxidation reduction potential (mV)	Temperature, water (degrees Celsius)	Oxygen, dissolved (mg/L)
LN north	0.5	4-24-89	1345	2,600	8.3	349	20.0	10.1
	24.0	4-24-89	1515	2,590	7.6	358	10.0	10.4
	34.0	4-24-89	1650	4,800	6.9	91	8.0	< .1
	12.0	9-26-89	1130	2,370	7.5	376	18.0	8.8
	22.0	9-26-89	1230	2,800	6.7	255	15.5	.10
	34.0	9-26-89	1400	4,700	6.8	67	11.0	.02
LN south	.5	4-21-89	1300	2,800	7.9	365	16.5	10.7
	15.0	4-21-89	1400	4,320	6.5	172	10.5	< .1
	21.0	4-21-89	1520	4,620	6.8	146	10.0	< .1
	4.0	9-25-89	1230	2,740	7.4	379	16.5	9.9
	21.0	9-25-89	1330	4,550	6.5	86	14.5	.01
LQ	4.0	9-21-89	1200	265	8.4	330	21.5	9.0
	29.0	9-21-89	1300	365	7.2	27	11.0	.01
	15.0	1-10-90	1130	290	7.9	270	4.5	12.2
LS	4.0	9-18-89	1200	3,020	7.1	360	20.0	9.2
	12.0	9-18-89	1300	3,400	6.2	368	18.5	.4
	17.0	9-18-89	1400	4,000	6.7	84	16.0	.02
	10.0	1-08-90	1315	3,200	7.4	326	3.5	14.4
LX	6.0	9-11-89	1400	1,510	7.3	350	24.5	7.1
	21.6	9-11-89	1500	3,100	6.4	108	21.0	< .01
	12.0	12-20-89	1130	1,650	8.0	371	3.0	13.8
LEE	5.0	5-18-89	1530	2,610	8.5	363	20.5	10.6
	23.0	5-18-89	1400	3,410	6.6	309	13.0	>20.0
	8.0	9-15-89	1215	2,460	7.5	364	21.5	6.5
	24.0	9-15-89	1400	4,200	6.7	93	19.0	< .02
	11.0	12-27-89	1130	2,600	7.9	391	2.5	13.4
LP north	5.0	5-16-89	0900	3,810	4.2	572	21.0	8.7
	27.0	5-15-89	1630	3,800	6.3	150	8.0	< .1
	2.0	9-14-89	1400	3,150	4.5	444	18.5	7.8
	26.5	9-14-89	1445	4,100	6.8	77	14.0	.03
LP south	1.0	5-16-89	1030	3,950	7.0	90	18.5	>20.0
	1.0	9-14-89	1030	3,100	6.5	317	14.0	8.5

Table 8.--*Analyses of samples collected from six deep lake locations and shallow lake LP*--Continued

Lake (fig. 8)	Date	Oxygen, dissolved (percent saturation)	Hydrogen sulfide, total (mg/L)	Hardness, total as $CaCO_3$ (mg/L)	Hardness, noncarbonate as $CaCO_3$ (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)
LN north	4-24-89	113	--	1,400	1,300	320	150	160
	4-24-89	94	--	1,400	1,200	310	150	160
	4-24-89	--	--	2,100	1,400	440	240	330
	9-26-89	93	--	1,200	1,100	280	120	130
	9-26-89	--	<0.1	1,300	1,200	320	130	150
	9-26-89	0	trace	2,100	1,400	430	250	340
LN south	4-21-89	111	--	1,500	1,300	340	160	170
	4-21-89	--	--	2,300	1,700	510	250	320
	4-21-89	--	--	2,300	1,600	540	240	310
	9-25-89	102	--	1,400	1,200	320	150	170
	9-25-89	0	.2	2,300	1,500	520	250	310
LQ	9-21-89	102	--	120	54	31	9.9	5.6
	9-21-89	--	2.0	140	0	39	11	6.2
	1-10-90	95	--	130	57	33	11	5.7
LS	9-18-89	102	--	1,800	1,800	400	200	100
	9-18-89	4	--	2,300	2,100	470	260	130
	9-18-89	0	.1	2,400	1,900	480	280	150
	1-08-90	111	--	2,300	2,200	490	260	130
LX	9-11-89	85	--	670	590	180	53	66
	9-11-89	--	trace	1,500	1,200	370	140	210
	12-20-89	102	--	790	690	210	64	88
LEE	5-18-89	119	--	1,200	1,200	260	140	230
	5-18-89	--	--	1,700	1,400	360	200	350
	9-15-89	74	--	1,100	1,000	230	120	200
	9-15-89	--	.2	1,900	1,200	390	220	400
	12-27-89	99	--	1,200	1,100	260	140	220
LP north	5-16-89	99	--	2,400	2,500	500	290	150
	5-15-89	--	--	2,300	2,200	460	270	150
	9-14-89	84	--	1,800	1,800	400	200	110
	9-14-89	0	.1	2,200	1,600	470	260	190
LP south	5-16-89	--	--	2,600	2,300	550	290	150
	9-14-89	83	--	1,800	1,800	400	200	110

Table 8.--*Analyses of samples collected from six deep lake locations and shallow lake LP*--Continued

Lake (fig. 8)	Date	Sodium adsorption ratio	Potassium (mg/L)	Bicarbonate, total (mg/L)	Carbonate, total as CO_3 (mg/L)	Alkalinity as $CaCO_3$ (mg/L)	Carbon dioxide, dissolved (mg/L)	Sulfate (mg/L)
LN north	4-24-89	2	12	196	0	161	1.7	1,600
	4-24-89	2	19	208	0	171	8.4	1,600
	4-24-89	3	45	805	0	660	162	2,600
	9-26-89	2	22	153	0	126	7.1	1,500
	9-26-89	2	21	231	0	189	68.8	1,500
	9-26-89	3	100	925	0	758	229	2,900
LN south	4-21-89	2	21	315	0	258	6.3	1,600
	4-21-89	3	26	783	0	642	405	2,400
	4-21-89	3	31	908	0	744	236	2,500
	9-25-89	2	27	303	0	248	20.7	1,700
	9-25-89	3	41	1,000	0	820	506	2,700
LQ	9-21-89	.2	5.1	80	1	66	.5	59
	9-21-89	.2	6.2	209	0	172	19.7	18
	1-10-90	.2	5.3	83	0	68	16.7	63
LS	9-18-89	1	34	67	0	55	8.5	2,200
	9-18-89	1	39	242	0	198	244	2,400
	9-18-89	1	48	615	0	505	206	2,700
	1-08-90	1	46	102	0	84	5.9	2,500
LX	9-11-89	1	13	102	0	84	8.4	730
	9-11-89	2	25	422	0	346	257	1,700
	12-20-89	1	15	127	--	104	1.9	920
LEE	5-18-89	3	23	77	5	71	.4	1,600
	5-18-89	4	30	421	0	345	181	2,200
	9-15-89	3	26	64	0	52	3.3	1,500
	9-15-89	4	38	898	0	736	261	2,400
	12-27-89	3	26	98		80	1.9	1,700
LP north	5-16-89	1	23	0	0	0	.0	2,800
	5-15-89	1	33	98	0	80	73.3	2,700
	9-14-89	1	33	0	0	0	.0	2,200
	9-14-89	2	42	752	0	616	191	2,700
LP south	5-16-89	1	28	280	0	230	44.8	2,700
	9-14-89	1	32	31	0	25	16.8	2,200

Table 8.--*Analyses of samples collected from six deep lake locations and shallow lake LP*--Continued

Lake (fig. 8)	Date	Chloride (mg/L)	Fluoride (mg/L)	Silica (mg/L)	Dissolved solids, residue at 180 degrees Celsius (mg/L)	Iron, total recoverable (mg/L)	Iron (mg/L)	Iron, ferrous (mg/L)
LN north	4-24-89	2.8	0.5	0.20	2,420	0.11	0.034	<0.01
	4-24-89	2.7	.5	.39	2,420	.08	.014	< .01
	4-24-89	3.1	.8	12	4,200	230	250	190
	9-26-89	2.2	.5	1.9	2,090	--	.004	--
	9-26-89	2.3	.5	5.6	2,300	--	.012	--
	9-26-89	1.8	.8	12	4,130	--	250	--
LN south	4-21-89	3.1	.6	.80	2,520	.29	< .009	< .01
	4-21-89	3.0	.5	13	4,230	50	53	31
	4-21-89	2.5	.5	15	4,360	94	100	71
	9-25-89	2.2	.5	1.9	2,540	--	.29	--
	9-25-89	2.0	.5	16	4,210	--	130	--
LQ	9-21-89	4.7	.4	1.7	172	--	.007	--
	9-21-89	5.6	.5	5.3	207	--	3.1	--
	1-10-90	4.9	.4	.23	161	--	.007	--
LS	9-18-89	2.1	.7	4.2	3,110	--	< .006	--
	9-18-89	2.0	.8	7.7	3,700	--	.056	--
	9-18-89	2.0	.0	13	4,000	--	160	--
	1-08-90	2.4	.8	2.7	3,660	--	< .009	--
LX	9-11-89	3.5	.4	2.2	1,120	--	.015	--
	9-11-89	3.2	.4	8.8	2,730	--	35	--
	12-20-89	4.0	.4	1.9	1,430	--	< .003	--
LEE	5-18-89	1.2	.5	.54	2,340	.060	.013	.02
	5-18-89	1.3	.5	4.7	3,480	.87	.090	.007
	9-15-89	1.2	.5	.91	2,220	--	< .006	--
	9-15-89	1.6	.7	20	3,870	--	87	--
	12-27-89	1.6	.6	.55	2,570	--	< .009	--
LP north	5-16-89	2.2	.6	7.1	3,860	1.9	1.3	.96
	5-15-89	2.6	.5	8.7	3,710	36	43	33
	9-14-89	2.2	.6	5.7	3,130	--	.52	--
	9-14-89	2.7	.0	12	3,880	--	220	--
LP south	5-16-89	1.4	.8	8.6	2,000	5.2	.56	.55
	9-14-89	2.2	.7	5.8	3,110	--	1.3	--

Table 8.--*Analyses of samples collected from six deep lake locations and shallow lake LP*--Continued

Lake (fig. 8)	Date	Manganese, total recoverable (µg/L)	Manganese (µg/L)	Nitrogen, NO_2+NO_3 (mg/L)	Nitrogen, ammonia (mg/L)	Orthophosphate as phosphorus (mg/L)	Aluminum, total recoverable (µg/L)	Aluminum (µg/L)
LN north	4-24-89	180	170	<0.10	--	<0.01	50	<10
	4-24-89	300	320	< .10	--	< .01	50	<10
	4-24-89	12,000	11,000	< .10	--	.02	130	<10
	9-26-89	--	100	--	--	--	--	40
	9-26-89	--	1,600	--	.41	--	--	30
	9-26-89	--	13,000	--	14	--	--	120
LN south	4-21-89	1,600	1,300	.11	--	< .01	70	60
	4-21-89	4,300	4,600	< .10	--	.03	60	<10
	4-21-89	5,000	5,000	< .10	--	.02	40	10
	9-25-89	--	6,300	--	--	--	--	20
	9-25-89	--	5,700	--	5.5	--	--	30
LQ	9-21-89	--	6	--	--	--	--	10
	9-21-89	--	12,000	--	3.4	--	--	20
	1-10-90	--	89	--	--	--	--	<10
LS	9-18-89	--	3,200	--	--	--	--	20
	9-18-89	--	16,000	--	--	--	--	20
	9-18-89	--	15,000	--	5.7	--	--	30
	1-08-90	--	810	.03	.22	--	--	<10
LX	9-11-89	--	270	--	--	--	--	10
	9-11-89	--	7,600	--	2.4	--	--	10
	12-20-89	--	64	.01	--	< .01	--	<10
LEE	5-18-89	10	7	< .10	--	< .01	20	<10
	5-18-89	2,500	2,800	< .10	--	< .01	<10	<10
	9-15-89	--	66	--	--	--	--	20
	9-15-89	--	7,100	--	6.2	--	--	20
	12-27-89	--	3	< .01	--	< .01	--	<10
LP north	5-16-89	4,800	9,100	< .10	--	< .01	850	800
	5-15-89	9,500	9,000	< .10	--	< .01	220	150
	9-14-89	--	5,000	--	--	--	--	50
	9-14-89	--	8,700	--	11	--	--	20
LP south	5-16-89	8,000	8,500	< .10	--	< .01	850	10
	9-14-89	--	5,600	--	--	--	--	60

Table 8.--*Analyses of samples collected from six deep lake locations and shallow lake LP*--Continued

Lake (fig. 8)	Date	Barium (µg/L)	Beryllium (µg/L)	Cadmium, total recoverable (µg/L)	Cadmium (µg/L)	Chromium (µg/L)	Cobalt, total recoverable (µg/L)	Cobalt (µg/L)
LN north	4-24-89	14	<2	<1	<3	<20	4	<3
	4-24-89	14	<2	<1	<1	<20	4	<3
	4-24-89	46	<2	<1	12	<20	80	70
	9-26-89	20	< .5	--	<1	<5	--	<3
	9-26-89	18	<1	--	<2	<10	--	10
	9-26-89	430	< .5	--	<21	<7	--	<390
LN south	4-21-89	16	<2	1	<3	<20	10	<9
	4-21-89	20	<2	<1	<3	<20	40	20
	4-21-89	24	<5	<1	4	<50	40	<30
	9-25-89	24	<1	--	<2	<10	--	20
	9-25-89	22	<2	--	<3	<20	--	40
LQ	9-21-89	34	< .5	--	<1	<5	--	<3
	9-21-89	67	< .5	--	<1	<5	--	<3
	1-10-90	33	< .5	--	<1	<5	--	<3
LS	9-18-89	10	<1	--	<2	<10	--	<6
	9-18-89	20	<1	--	<2	<10	--	40
	9-18-89	23	< .5	--	12	<10	--	190
	1-08-90	8	<2	--	5	<20	--	<9
LX	9-11-89	28	< .5	--	<1	<5	--	<3
	9-11-89	120	<1	--	<2	<10	--	80
	12-20-89	23	< .5	--	<1	<5	--	<3
LEE	5-18-89	17	<2	<1	<1	<20	<1	<9
	5-18-89	24	<2	<1	9	<20	10	10
	9-15-89	17	<1	--	<2	<10	--	<6
	9-15-89	47	<2	--	8	<20	--	50
	12-27-89	18	<2	--	<3	<20	--	<9
LP north	5-16-89	13	<2	1	<3	<20	80	80
	5-15-89	9	<2	<1	7	<20	70	50
	9-14-89	12	1	--	<2	<10	--	40
	9-14-89	39	1	--	19	<10	--	190
LP south	5-16-89	12	<2	<1	<3	<20	50	50
	9-14-89	77	1	--	<2	<10	--	40

Table 8.--*Analyses of samples collected from six deep lake locations and shallow lake LP*--Continued

Lake (fig. 8)	Date	Copper (µg/L)	Lead (µg/L)	Lithium (µg/L)	Molybdenum (µg/L)	Nickel, total recoverable (µg/L)	Nickel (µg/L)
LN north	4-24-89	<30	<30	120	<30	21	<30
	4-24-89	<10	<30	120	<30	23	<30
	4-24-89	<10	<10	240	<10	88	80
	9-26-89	<10	<10	99	<10	--	20
	9-26-89	<20	<20	110	<20	--	<20
	9-26-89	<10	<60	230	<10	--	<60
LN south	4-21-89	<30	<30	130	<30	37	<30
	4-21-89	<30	<30	200	<30	86	60
	4-21-89	<30	<30	210	<30	86	70
	9-25-89	<20	<20	120	<20	--	30
	9-25-89	<30	<30	190	<30	--	30
LQ	9-21-89	<10	<10	5	<10	--	<10
	9-21-89	<10	<10	6	<10	--	<10
	1-10-90	<10	<10	5	<10	--	10
LS	9-18-89	<20	<20	140	<20	--	40
	9-18-89	<20	<20	160	<20	--	50
	9-18-89	<10	30	180	<10	--	30
	1-08-90	<30	<30	170	<30	--	<30
LX	9-11-89	<10	<10	48	<10	--	10
	9-11-89	<20	<20	110	<20	--	30
	12-20-89	<10	10	56	<10	--	<10
LEE	5-18-89	<30	<30	99	<30	2	<30
	5-18-89	<30	40	160	<30	40	60
	9-15-89	<10	<20	89	<20	--	<20
	9-15-89	<30	50	190	<30	--	<30
	12-27-89	<30	<30	98	<30	--	<30
LP north	5-16-89	<30	30	200	<30	300	250
	5-15-89	<30	60	170	>30	200	180
	9-14-89	<20	<20	140	<20	--	120
	9-14-89	<20	70	170	<10	--	<20
LP south	5-16-89	<30	<30	210	<30	200	150
	9-14-89	<20	<20	140	<20	--	140

Table 8.--*Analyses of samples collected from six deep lake locations and shallow lake LP*--Continued

Lake (fig. 8)	Date	Silver (µg/L)	Strontium (µg/L)	Vanadium (µg/L)	Zinc, total recoverable (µg/L)	Zinc (µg/L)	Carbon, total organic (mg/L)
LN north	4-24-89	<3	3,500	<18	<10	10	2.4
	4-24-89	4	3,400	<18	<10	<9	2.2
	4-24-89	<20	7,400	<18	40	<60	8.0
	9-26-89	<1	2,800	<6	--	6	2.4
	9-26-89	<2	3,300	<12	--	13	1.9
	9-26-89	<4	7,300	<27	--	<3	6.7
LN south	4-21-89	<3	3,900	<18	20	13	3.5
	4-21-89	4	6,900	<18	20	21	2.1
	4-21-89	<10	7,100	<18	30	10	2.8
	9-25-89	<2	3,500	<12	--	16	2.7
	9-25-89	<3	6,800	19	--	44	5.2
LQ	9-21-89	<1	140	<6	--	5	3.8
	9-21-89	1	190	<6	--	<3	8.9
	1-10-90	<1	150	<6	--	<3	4.0
LS	9-18-89	3	4,000	<12	--	15	2.6
	9-18-89	<2	5,400	<12	--	16	4.5
	9-18-89	8	6,100	<6	--	34	4.6
	1-08-90	<3	5,000	<18	--	19	1.9
LX	9-11-89	<1	1,300	<6	--	9	3.0
	9-11-89	<2	4,000	<12	--	37	4.4
	12-20-89	<1	1,700	<6	--	<3	--
LEE	5-18-89	<3	2,200	<18	20	18	2.1
	5-18-89	<3	4,300	<18	<10	33	5.1
	9-15-89	<2	2,100	<12	--	18	2.9
	9-15-89	3	5,400	<18	--	<9	7.2
	12-27-89	<3	2,300	<18	--	<9	2.6
LP north	5-16-89	4	4,500	<18	190	190	1.5
	5-15-89	<3	4,100	<18	130	110	3.1
	9-14-89	<2	3,700	<12	--	110	1.2
	9-14-89	3	4,300	<6	--	23	6.5
LP south	5-16-89	10	6,300	<18	30	28	1.4
	9-14-89	<2	3,800	<12	--	140	1.6

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