Effects of Highway Deicing Chemicals on Shallow Unconsolidated Aquifers in Ohio—Final Report

By Allison E. Kunze and Bernard N. Sroka

Prepared in cooperation with the
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16. Abstract

As a result of concerns about salt intrusion into drinking-water aquifers, the effects of highway deicing chemicals on shallow aquifers were studied at eight locations in Ohio from 1988 through 2003. Sites were selected along major undivided highways where drainage is by open ditches and ground-water flow is approximately perpendicular to the highway. Records of deicer application were kept, and apparent movement of deicing chemicals through shallow, unconsolidated aquifers was monitored by means of periodic measurements of specific conductance and concentrations of dissolved sodium, calcium, and chloride. The counties and corresponding sections of State routes monitored were the following: State Route (SR) 3 in Ashland County, SR 84 in Ashtabula County, SR 29 in Champaign County, SR 4 in Clark County, SR 2 in Lucas County, SR 104 in Pickaway County, SR 14 in Portage County, and SR 97 in Richland County. Routine ground-water sampling began in January 1991 and continued through September 1999. A multilevel, passive flow ground-water sampling device was constructed and used. Other conditions monitored on a regular basis included ground-water level (monitored continuously), specific conductance, air and soil temperature, precipitation, chloride concentration in soil samples, and deicing chemical application times and rates. Evidence from water analysis, specific-conductance measurements, and surface-geophysical measurements indicates that three of the eight sites (Ashtabula County, Lucas County, and Portage County sites) were affected by direct application of deicing chemicals. Climatic data collected during the study indicate that cold weather, and therefore deicing chemical application rate, varied widely across the State. As a consequence, only minor traces of dissolved chloride (mean 24-43 mg/L) above background concentrations (mean 13-23 mg/L) were determined in ground-water samples from the Pickaway County, Clark County, and Champaign County sites. At the Ashland and Richland County sites, dissolved chloride concentrations increased above background concentrations only intermittently (mean background concentrations 4-41 mg/L, rising to a mean of 40-56 mg/L in downgradient wells). At the Lucas County, Portage County, and Ashtabula County sites, deicing-chemical application was consistent throughout the winter, and downgradient dissolved chloride concentrations (mean 124-345 mg/L) rarely returned to background concentrations (mean 7-37 mg/L) throughout the study period. Other factors that may affect the movement of deicing chemicals through an aquifer were precipitation amounts, the types of subsurface materials, ground-water velocity and gradient, hydraulic conductivity, soil type, land use, and Ohio Department of Transportation deicing priority.

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Conversion Factors, Datum, and Abbreviations

Multiply	By	To obtain
inch (in)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
micrometer (µm)	0.00003937	inch
millimeter (mm)	0.03937	inch
meter (m)	3.281	foot
inch per year (in/yr)	25.4	millimeter per year
foot per day (ft/d)	0.3048	meter per day
gallon (gal)	3.785	liter
ton	0.9072	megagram
pound per two-lane mile (lb/2-ln mi)	0.2819	kilogram per two-lane kilometer
ton per two-lane mile (ton/2-ln mi)	0.5638	megagram per two-lane kilometer

Temperature is given in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by use of the following equation:

$$°F = 1.8\,(°C) + 32$$

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD of 1929).

Other abbreviated units used in this report: Chemical concentrations are given in milligrams per liter (mg/L), a unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water. Specific conductance of water is expressed in microsiemens per centimeter at 25 degrees Celsius (µS/cm). Electrical conductivity of subsurface materials is given in millisiemens per meter (mS/m). Small volumes of water are expressed in milliliters (mL). Periods of record are sometimes given in reference to water year (WY), the 12-month period October 1 through September 30, designated by the calendar year in which it ends.

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By Allison E. Kunze and Bernard N. Sroka

Abstract

As a result of concerns about salt intrusion into drinking water aquifers, the effects of highway deicing chemicals on shallow aquifers were studied at eight locations in Ohio from 1988 through 2002. The study was done by the U.S. Geological Survey, in cooperation with the Ohio Department of Transportation and the Federal Highway Administration. Sites were selected along major undivided highways where drainage is by open ditches and ground-water flow is approximately perpendicular to the highway. Records of deicer application rates were kept, and apparent movement of deicing chemicals through shallow, unconsolidated aquifers was monitored by means of periodic measurements of specific conductance and concentrations of dissolved sodium, calcium, and chloride. The State routes monitored were the following: State Route (SR) 3 in Ashland County, SR 84 in Ashtabula County, SR 29 in Champaign County, SR 4 in Clark County, SR 2 in Lucas County, SR 104 in Pickaway County, SR 14 in Portage County, and SR 97 in Richland County.

The study began in 1988 with background data collection, extensive literature review, and site selection. This process, including drilling of wells at numerous test sites and the eight selected sites, lasted 3 years. Routine ground-water sampling at 4- to 6-week intervals began in January 1991 and continued through September 1999. A multilevel, passive flow ground-water sampling device was constructed and used. Other conditions monitored on a regular basis included ground-water level (monitored continuously), specific conductance, air and soil temperature, precipitation, chloride concentration in soil samples, and deicing-chemical application times and rates.

Evidence from water analysis, specific-conductance measurements, and surface-geophysical measurements indicates that three of the eight sites (Ashtabula County, Lucas County, and Portage County sites) were affected by direct application of deicing chemicals. Climatic data collected during the study show that cold weather, and therefore deicing-chemical application rates, varied from south to north across the State. As a consequence, only minor traces of dissolved chloride (mean, 24–43 mg/L (milligrams per liter)) above background concentrations (mean, 13–23 mg/L) were determined in ground-water samples from the southernmost sites (approximately 39°30' to 40° N latitude—Champaign County, Clark County, and Pickaway County). At the Ashland and Richland County sites (approximately 40°30' N latitude), dissolved-chloride concentrations increased above background concentrations only intermittently (mean background concentrations 4–41 mg/L, rising to a mean of 40–56 mg/L in downgradient wells). At the northernmost sites (41° 30' to 42° N latitude—Lucas County, Portage County, and Ashtabula County), deicing-chemical application was consistent throughout the winter, and downgradient dissolved-chloride concentrations (mean, 124–345 mg/L) rarely returned to background concentrations (mean, 7–37 mg/L) throughout the study period.

Other factors than application rate that may affect the movement of deicing chemicals through an aquifer were precipitation amounts, the types of subsurface materials, ground-water velocity and gradient, hydraulic conductivity, soil type, land use, and Ohio Department of Transportation deicing priority.

Introduction

Sodium chloride (road salt) is still the most widely used highway deicing material in the United States. Road salt applied to highways during winter months is a primary source of solutes to ground water in Ohio. Although alternatives have been developed, most of them are still too expensive for general use. In 1980, the State of Ohio abandoned its "bare pavement" policy for a new directive that is more selective about salt application; however, the State still attempts to clear highways "as soon as possible" after cessation of a storm, in order of priority. Adding road salt to snow and ice lowers the freezing point of water and creates a brine that may run off the highway surface, therefore clearing it. This brine may travel a variety of pathways after application. Melted saltwater may run off into nearby streams or into ditches, where it infiltrates into the ground. Plowed snow from the highway, splash caused by vehicles, and wind may also transport salt considerable distances. Many researchers have studied various aspect of salt's effects on soils, plants, surface water, and ground water. Past evidence shows that many factors affect whether salt will prove to be damaging to the environment in a specific situation. In general, there has been a lack of detailed knowledge about the fate and transport of deicing chemicals after application to the highway. According to the National Research Council, road-salt use in the United States ranges from 8 million to 12 million tons of sodium chloride per year. States such as Massachusetts, New Hampshire, and New York report even higher annual loadings (National Research Council, 1991). Historically, regulators in the management of nonpoint-source pollution have been concerned with nutrients, hydrocarbons, pathogens, heavy metals, and sediment from stormwater runoff from road surfaces entering nearby surface- and ground-water supplies. However, growing concern over roadside-habitat degradation and water-quality issues have prompted regulators and researchers to examine deicing chemicals and their effect more closely.

In Ohio, the Ohio Department of Transportation (ODOT) is attempting to gather background data on the environmental implications of the use of highway deicing chemicals. As part of this data-collection effort, the U.S. Geological Survey (USGS), in cooperation with ODOT and the Federal Highway Administration (FHWA), began a study in 1988 to monitor the use and fate of highway deicing chemicals in shallow (less than 50 ft deep), unconsolidated aquifers. ODOT will use these long-term data to help determine how deicing practices affect ground-water quality and to develop a baseline data base from which to monitor changes over time to better serve citizens who would like not only safe roadways but also high-quality water resources.

Purpose and Scope

The purpose of this report is to describe the data collected at eight sites in Ohio designed to monitor the effects of application of highway-deicing chemicals on shallow, unconsolidated aquifers. Data include information on ground-water quality, environmental setting, and hydrology of each site.

This report is the followup to the interim report (Jones and Sroka, 1997), which included data collected through 1993. This report includes information about all data collected through 1999. Water samples were collected from January 1991 through September 1999. The section "Methods of Investigation," provides technical information about data collection and analysis. The eight modules under "Effects of Highway Deicing Chemicals, by Site" present descriptive data in narrative, tabular, and graphical form; these modules are designed to be useful to readers who may be interested in only one or a few specific sites in a particular part of Ohio. Several sections or parts of sections in this report are repeated from the interim report to make this report understandable on its own. However, to obtain all of the information from this project, readers should also refer to the interim report (Jones and Sroka, 1997). Because of the large volume, raw data are not presented in either report; they can be retrieved from the USGS NWISWeb page at http://waterdata.usgs.gov/oh/nwis/. A list of well numbers and names at each site is provided in the appendix (table A-1 in the appendix) to assist in retrieving data.

Previous Investigations

For many years, scientists have assumed that most of the deicing chemicals applied to highways are flushed away each season by overland flow and that subsurface effects are minimal. However, researchers are finding evidence of elevated chloride levels in ground water, suggesting that some of the salt may be retained in the local ground-water basin and may affect the environment. Howard and Haynes (1997) found that only 45 percent of the salt applied to an urban watershed in the Toronto, Ont., area was being removed annually and that the remainder was entering temporary storage in shallow ground water. They predicted that if present rates of deicing were maintained, average chloride concentrations in ground water discharging as springs would reach 426 mg/L, possibly within a 20-year period. In southern Massachusetts, Granato and others (1995) found that concentrations of major and trace chemical constituents of highway runoff in ground water were substantially higher downgradient than upgradient from the highway. This mobilization is potentially caused by deicing-chemical migration (Granato and others, 1995), and deicing chemicals themselves may account for a substantial source of annual chemical loads to ground water (Granato, 1995). Rosenberry and others (1999) found that ground water in a shallow aquifer in New Hampshire was contaminated with deicing chemicals; the contamination was not due to direct runoff, but to a contaminated stream through a reversal of gradient (from a gaining stream to a losing stream), likely during periods of transpiration by trees.

Pilon and Howard (1987) reported chloride concentrations as high as 13,000 mg/L in shallow ground water along an urban Toronto highway. In Burlington, Mass., Toler and Pollock (1974) found that chloride concentrations in local ground water exceeded 250 mg/L as the result of the application of deicing chemicals. Huling and Hollocher (1972) also found a significant increase in the steady-state chloride concentration in ground water from the east-central part of Massachusetts. Similar problems were reported in Illinois (Wulkowicz and Saleem, 1974) and Wisconsin (Eisen and Anderson, 1980).

There is increasing evidence that some of the salt applied to highways may be retained in the drainage basin and may gradually migrate to the water table through the soils and unsaturated zone (Diment and others, 1973; Eisen and Anderson, 1980; Pilon and Howard, 1987). Toler and Pollock (1974) found that 15 to 55 percent of chloride from deicing chemicals that enter the ground is retained in the soil and unsaturated zone. Physical properties of each site control the actual amount retained. Hawkins (1976) noted that salts may accumulate in a local ground-water basin and may not necessarily be flushed out each spring. Howard and others (1993) found from their model simulations that concentrations of sodium and chloride in ground water within a few hundred meters of highways may be 3 to 4 times the baseline concentrations. Church and Friesz (1993) reported that 20 to 50 percent of the chloride load in highway runoff was found in the ground water in areas where closed drainage and snow berms had been installed during initial highway construction. Heisig (2000) found a positive linear relation for chloride concentration in base flow of an urban New York watershed and the annual rate of road-salt application to the watershed. He found that ground waters that sustain base flows are a consistent source of chloride, unlike stormflows, which typically have the highest chloride concentrations in the spring.

Mason and others (1999) found that road salt significantly increased the concentrations of calcium, potassium, and magnesium in a stream in Maine through cation exchange in the soil downgradient from a heavily salted State highway. In a study of road salt in the vadose zone in Saskatchewan, Canada, Gutiw and Jin (1998) found that sodium and chloride ion retention characteristics within the sites were affected greatly by the local soil composition. In sand and gravel deposits, little retention was observed. At sites with soil composed of a greater proportion of silt and clay, however, the deposits were more effective in retaining the deicer. Although the ion profiles were specific to the time of sampling, the classification of roadside environments based on deicer retention characteristics of the soil can serve as a potentially useful measure.

Springs from shallow ground water in the Toronto lakefront area contained an average chloride concentration of 400 mg/L (Eyles and Howard, 1988). Even in areas where shallow ground water is not used for public or private supply, groundwater discharge can be a major component of stream water, which, in turn, may discharge to and eventually affect the quality of receiving waters, such as the Great Lakes (International Joint Commission, 1988; Duda, 1989; Hodge, 1989).

In some studies, borehole and surface geophysics were used to investigate ground-water quality affected by deicing chemicals. Risch and Robinson (2001) found that electromagnetic-conductivity data indicated the presence of a saltwater plume near the bottom of thick sand and gravel aquifer in Indiana. Five years of monitoring these wells indicated that the plume had moved about 60–100 ft/yr. Surface geophysics in areas without monitoring wells and a conceptual model helped to understand the effects of a salt-storage facility on groundwater quality.

Deicing Chemicals

Evidence indicates that elevated sodium concentrations (above background concentrations) may have serious health implications. Sodium has been linked with the development of hypertension, a condition affecting perhaps 20 percent of the U.S. population (Moses, 1980; Craun, 1984; Tuthill and Calabrese, 1979). Elevated sodium concentrations have also been associated indirectly with hypernatremia, a kidney ailment (World Health Organization, 1984). A general recommendation is that sodium concentrations in drinking water should not exceed 20 mg/L for those with hypertension or congestive heart failure; for those in good health, an esthetic guideline of 200 mg/L has been issued by many agencies (Ontario Ministry of the Environment, 1991). The U.S. Environmental Protection Agency (2002) states that although high levels of salt intake may be associated with hypertension in some individuals, sodium levels in drinking water are usually low and unlikely to be a significant contribution to adverse health effects. However, sodium remains on the USEPA drinking-water contaminant candidate list (CCL). A future reassessment of the sodium guidance may establish a new level at which sodium occurrence would not meet the criteria for inclusion on the CCL as a drinking-water contaminant of concern.

Water containing elevated chloride concentrations poses the greatest human health hazard to those with heart or kidney diseases. The problem is generally more esthetic than health related because salty water is generally not palatable (Hutchinson, 1970). Most agencies maintain a chloride concentration guideline of 250 mg/L as a taste threshold (Ontario Ministry of the Environment, 1991). USEPA maintains a secondary standard for chloride of 250 mg/L (U.S. Environmental Protection Agency, 1992).

Highway deicing chemicals differ from many other ground-water contaminants in that the source mass, chemistry, release characteristics, and transport behavior are relatively well known when compared to other contaminants. Chloride is the best indicator of road-salt application because it is a primary component of all highway-deicing chemicals, and it is chemically unreactive in most environments. California and Nevada restrict road-salt use in some areas to reduce chloride injury to roadside trees. Massachusetts uses alternative deicers to prevent sodium contamination of residential drinking water. New York State proposed a pilot study in New York City to look at deicing-chemical alternatives that might help protect drinking water (Wenger and Yaggi, 2001).

Highway deicing chemicals are released to the soil during snowmelt at various times throughout each winter. High levels of salt in soils may limit the availability of soil water to plants, whereas excessive exchangeable sodium causes breakdown of soil aggregates, decreased pore size and reduced permeability of the soil to air and water (Jones and others, 1992). High concentrations of sodium may be decreased by exchange for calcium and magnesium at exchange sites on sediments in the unsaturated zone and the shallow ground-water flow system. Secondary sources of sodium may be domestic-wastewater and water-softening-system discharges (Heisig, 2000). Sodium may also be adsorbed on exchange sites within the soil (Villamil and Kent, 1980), although several winters of deicing-material application can exhaust the adsorptive capacity of the soil (Howard and Beck, 1993). Therefore, sodium can enter the underlying aquifer, where it may reach levels that pose a threat to human health (Vitaliano, 1992).

Methods of Investigation

Site Selection

A detailed site-selection process was used to find eight sites in Ohio that fit the study criteria. The eight study sites are shown in figure 1. During the first 2 years of the study (1988–90), a large group of candidate sites were identified on the basis of information gathered from a literature search, well logs, geologic maps, and geophysical data. The following criteria had to be met for a site to be suitable for further investigation: undivided State highway with open drainage, preferably with first or second priority for deicing by ODOT; unconfined and unconsolidated aquifer materials beneath and adjacent to the highway; ground-water flow generally perpendicular to the alignment of the highway; shallow water table (less than 25 ft below land surface); area of potential snowfall each winter (varying amounts among sites was preferable); suitable for access by drilling rigs; and landowners on both sides of the highway willing to participate in the study for at least 10 years. At all sites, highway deicing was ongoing for an unknown number of years before the study began. More than 50 potential sites were investigated to select the final group of sites. Once a site was determined to be a potential study site "on paper," project personnel visited the site and met with landowners. If all affected landowners were willing to participate in the study, the selection process proceeded with geophysical testing and test drilling.

Geophysical Tests

Electromagnetic (EM) ground-conductivity surveys were used to characterize the general hydrogeology of potential study sites. The electromagnetic conductivity of earth materials can be measured by use of the electromagnetic induction technique, whereby an EM field is imparted to the land surface and the electrical response is measured. A Geonics EM-34-3 ground conductivity meter was used to obtain this information. The EM-34-3 can be used at three fixed spacings of 10, 20, or 40 m and in the vertical or horizontal mode. Depending on the subsurface materials being investigated, materials up to a maximum of 60 m deep can be characterized. For the regular periodic surveys, only the 10-m spacing was needed to reach the depths of interest in each aquifer.

When the meter is operating, the transmitter coil is

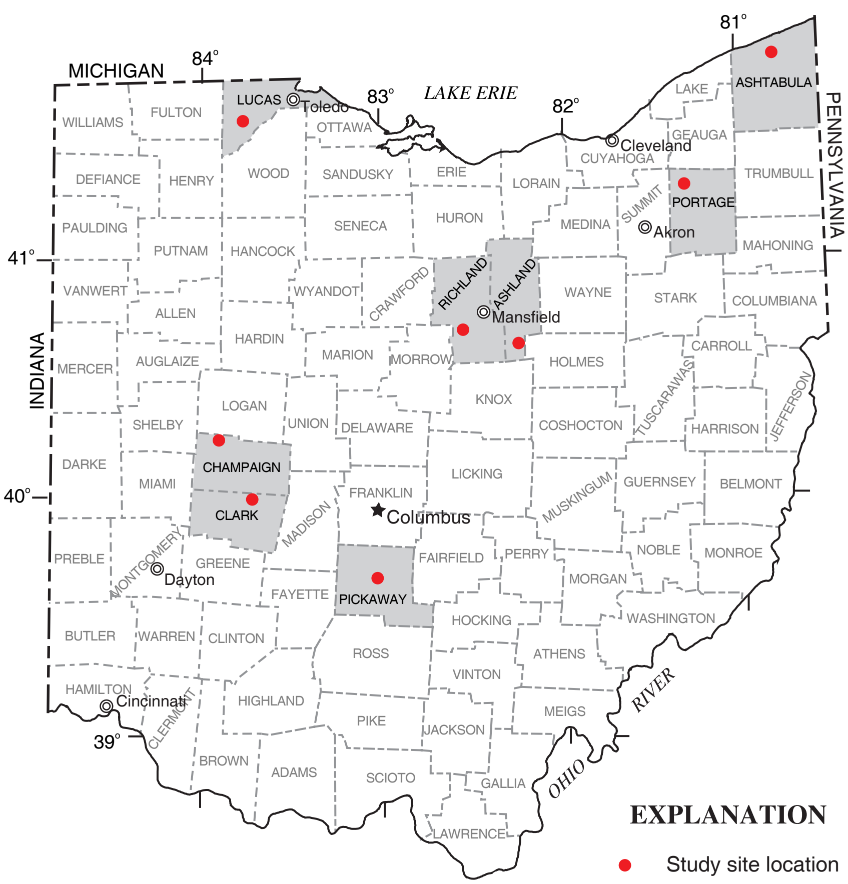


Figure 1. Location of sites monitored for effects of highway deicing chemicals on shallow ground water in Ohio.

energized with an alternating current that induces electrical current in subsurface conductors. Electrical currents in the earth materials produce a secondary magnetic field, which is proportional to the electrical conductivity of the subsurface material and fluid and can be measured at the surface with the receiver coil. The voltage generated in the receiver can then be related directly to the apparent conductivity of these subsurface materials and fluid.

The electrical conductivity of earth materials measured by surface EM, in conjunction with drillers' logs, can be used to help define the general lithologic characteristics of a site. In general, fine-grained materials, specifically clays and silts, typically have low hydraulic conductivities and high surface EM responses (generally in the 10–20+ mS/m range). Conversely, coarser materials, such as sands and gravels, typically have higher hydraulic conductivities and lower surface EM responses (generally in the 1–10 mS/m range). If a potential site was in an area where interference with the EM instrument would cause readings to be inaccurate, this test was bypassed. However, in many cases, measuring the EM response was useful for determining the need for drilling test wells at potential sites.

Test Drilling and Well Installation

If geophysical tests indicated the presence of unconsolidated sand and gravel, or if electromagnetic measurements were not possible, test wells were drilled by use of a hollow-stem auger. Lithologic logs from test wells were used to define the extent of the subsurface materials. Observation wells were constructed in each borehole, and the wells were developed. Measurement of water-level elevations in several wells allowed the direction of the ground-water flow to be determined. Ground-water samples were collected, and the specific conductance of the water also was measured. All test and observation wells were installed by the ODOT Foundation Exploration drilling crew or one of various private drilling firms.

Hollow-stem augers were used to install the wells, and split-spoon samples were collected to log the formations. Wells were augered to a depth where a major change in formation was reached; that is, where bedrock or a clay confining layer was encountered or to the limit of the hollow-stem auger, about 50 to 60 ft maximum. Wells were screened throughout the saturated thickness of the aquifer. The method of completion depended on the characteristics of the formation materials. If the materials were loose, they were allowed to collapse around the casing as the augers were removed. If they did not collapse, or collapsed only partially, the borehole was filled with washed sand or gravel as the augers were removed to about 2 ft above the top of the screen. Several feet of bentonite fill was placed above the sand to prevent downward infiltration of land-surface runoff. Finally, a concrete seal was placed at the surface around the polyvinyl chloride (PVC) casing and the protective steel casing.

At each site, one sampling well was placed upgradient from the highway at a sufficient distance to prevent splash and runoff from reaching it, generally about 50 ft. Four other sampling wells at each site were placed downgradient from the highway, generally in line with the ground-water flowpath (determined by water-level gradient), each increasingly distant from the highway. The interval between wells ranged from 40 ft at some sites to about 55 ft at others, depending on the ground-water velocity estimated from aquifer-test results and hydraulic gradient. (See "Data Collection" section.)

Data Collection

Data for each site were collected from eight main sources:

- Deicing chemicals—amount and type—applied to the highway were recorded by ODOT maintenance personnel each time a site was deiced. The information was sent monthly to USGS and ODOT management personnel.
- Water-quality data were collected on a regular basis by use of three types of ground-water sampling devices.
- Physical data—Geophysical data and elevation data were collected: geophysical data to periodically monitor ground-conductivity changes attributable to changes in water quality, and elevation data to determine the topographic layout of each site.
- Aquifer materials were collected during the well-installation phase and analyzed for grain size. Geology and soil type of each site were determined from test drilling and areal geophysical surveys, as well as local well logs and county soil surveys.
- Aquifer properties—Ground-water flow directions were determined by measurement of water levels in a series of test wells. Several single-well aquifer tests (slug tests) were done at one test well at each site to determine an average hydraulic conductivity for each site.
- Soils data were collected to determine the amount of dissolved chloride in soil-water extract, near the highway and beyond the splash distance.
- Temporal data—that is, ground-water temperature, air temperature, soil temperature, ground-water level, specific conductance, and precipitation—were measured and recorded hourly.
- Climatic data were obtained from the nearest Midwestern Regional Climate Center (MRCC) or National Oceanic and Atmospheric Administration (NOAA) weather station to supplement precipitation and air temperature data collected at each site.

The following sections detail the eight main types of data.

Deicing Material Application Data

Deicing chemicals used during the winters 1990–91 through 1998–99 by each county outpost that contained a study site are listed in table 1 (Ohio Department of Transportation, written commun., 1999). These data provide a general idea of the magnitude of use of deicing chemicals in each study-site county, but they do not indicate the exact amounts or percentages of chemicals (sodium chloride or calcium chloride) applied at each site.

Deicing-material application amounts and rates were recorded by ODOT personnel working at the outpost closest to each of the study sites. A form was completed each time a driver passed the site on his or her route. The forms were then collected monthly by a district supervisor and sent to the ODOT headquarters, where they were recorded and sent to the USGS office. Items recorded on the form included date and time, weather conditions, rate at which deicing material was applied from the truck, amount of sodium chloride, calcium chloride, and abrasives being applied, whether or not plowing was done simultaneously, and date of last spreader calibration. This careful recording of material application amounts enabled the investigators to compare continuously recorded specific-conductance values and chloride concentrations from water samples to deicing-chemical application times and amounts and precipitation events. Therefore, data collected separately by maintenance truck drivers for each of the study sites were useful.

Water-Quality Data

Ground-water samples were collected to monitor deicing-chemical-related constituent concentrations by use of multilevel sampling wells on the upgradient and downgradient sides of the highway along the path of ground-water flow. Two sampling routines were followed, and three types of samplers were used. All samples were analyzed by standard

Table 1. Countywide sodium chloride and calcium chloride amounts applied by Ohio Department of Transportation (ODOT), by year.

[e, estimates by ODOT]

	County								Season total	Season average	State wide total (tons)	Tons per lane-mile, average
	Ashtabula	Portage	Ashland	Richland	Lucas	Clark	Champaign	Pickaway				
	Sodium chloride (tons)											
1990-91	e15,000	e7,000	5,754	5,220	4,892	4,087	2,858	998	45,809	5,726	322,698	7.54
1991-92	e17,000	e7,000	6,510	4,712	4,310	2,672	1,723	782	44,709	5,589	338,268	7.90
1992-93	e21,000	e6,000	6,974	4,660	4,503	3,470	1,976	1,071	49,654	6,207	375,264	8.72
1993-94	26,079	6,706	8,065	5,842	5,332	1,733	1,518	2,145	57,420	7,178	514,323	11.97
1994-95	17,494	8,356	4,588	4,252	3,680	2,709	1,289	1,643	44,011	5,501	338,735	7.88
1995-96	43,769	13,514	10,766	8,844	4,592	4,721	2,936	2,540	91,682	11,460	628,616	14.69
1996-97	32,620	9,441	6,605	5,246	3,915	2,902	2,327	698	63,754	7,969	339,834	7.94
1997-98	25,658	9,148	5,278	4,829	2,029	2,082	1,554	924	51,502	6,438	280,820	6.56
1998-99	35,492	16,096	10,259	8,852	5,146	4,971	3,882	2,758	87,456	10,932	599,371	14
Total	234,112	83,261	64,799	52,457	38,399	29,347	20,063	13,559	535,997	67,000		
Average	26,012	9,251	7,200	5,829	4,267	3,261	2,229	1,507	59,555	7,444		9.69
	Calcium chloride (gallons)											
1990-91	Data not available										2,854.1	
1991-92											3,101.0	
1992-93											4,023.5	
1993-94	135,844	28,496	10,566	26,022	4,092	0	0	0	205,020	0	4,773.0	
1994-95	44,995	11,680	4,425	1,710	1,780	0	0	0	64,590	316,168	59.5	
1995-96	96,313	24,373	14,549	22,665	4,768	0	0	0	162,668	735,937	71.1	
1996-97	61,481	5,019	7,550	4,863	4,581	0	0	0	83,494	337,502	13.1	
1997-98	61,081	2,881	6,900	0	1,587	0	0	0	72,449	206,160	1.2	
1998-99	81,075	10,198	23,319	6,150	11,695	330	0	0	132,767	681,410	29.4	
Total	480,789	82,647	67,309	61,410	28,503	330	0	0	720,988	2,277,177	4,947.3	
Average	80,132	13,775	11,218	10,235	4,750	55	0	0	120,165	379,530	824.6	

methods at the USGS National Water Quality Laboratory (NWQL) in Denver, Colo.

The three types of ground-water samplers used were (1) a conventional submersible pump, (2) a multilevel dialysis sampler, and (3) a multilevel tube sampler. The multilevel sampler designs are described below. Each type of sampler was used for a specific purpose as described below.

Multilevel Dialysis Sampler

To collect an undisturbed, vertically specific ground-water sample, a multilevel dialysis sampler design was adapted from one first described by Ronen and others (1987). The adaptation is shown in figure 2. Six passive-flow sampling sections were installed inside each 3-in.-diameter, fully screened well. The sampling device itself consists of a series of six 10-in.-long sampling sections of 2-in.-diameter PVC well screen (0.020-in. slot size or larger), each one connected by varying lengths of 1-in.-diameter PVC pipe. The PVC sampling device, pipe, and fittings were glued or screwed together. To help prevent vertical mixing or movement of water entering the well, synthetic rubber rings ("baffles" in fig. 2) were installed between each level of the sampler and the inside diameter of the 3-in. well, and plastic disks were placed above and below the screened sections of the sampler.

The string of sampling sections was lowered into the screened section of each well. Each sampling section contained two or three lengths of dialysis tubing filled with deionized water that had been prepared in the laboratory and carried to the field sites in containers of deionized water to prevent drying. Each tubing section was cut to a length of approximately 8 to 12 in. from rolls of medical-grade cellulose ester dialysis membrane. The product used in this study has a molecular-weight cutoff of 10,000 daltons and a flat width of 31 mm. The properties of the dialysis tubing itself do not interfere with the diffusion of ground water (molecular weight cutoff or charge, for example). Tubing sections were then filled with deionized water and were clipped at both ends.

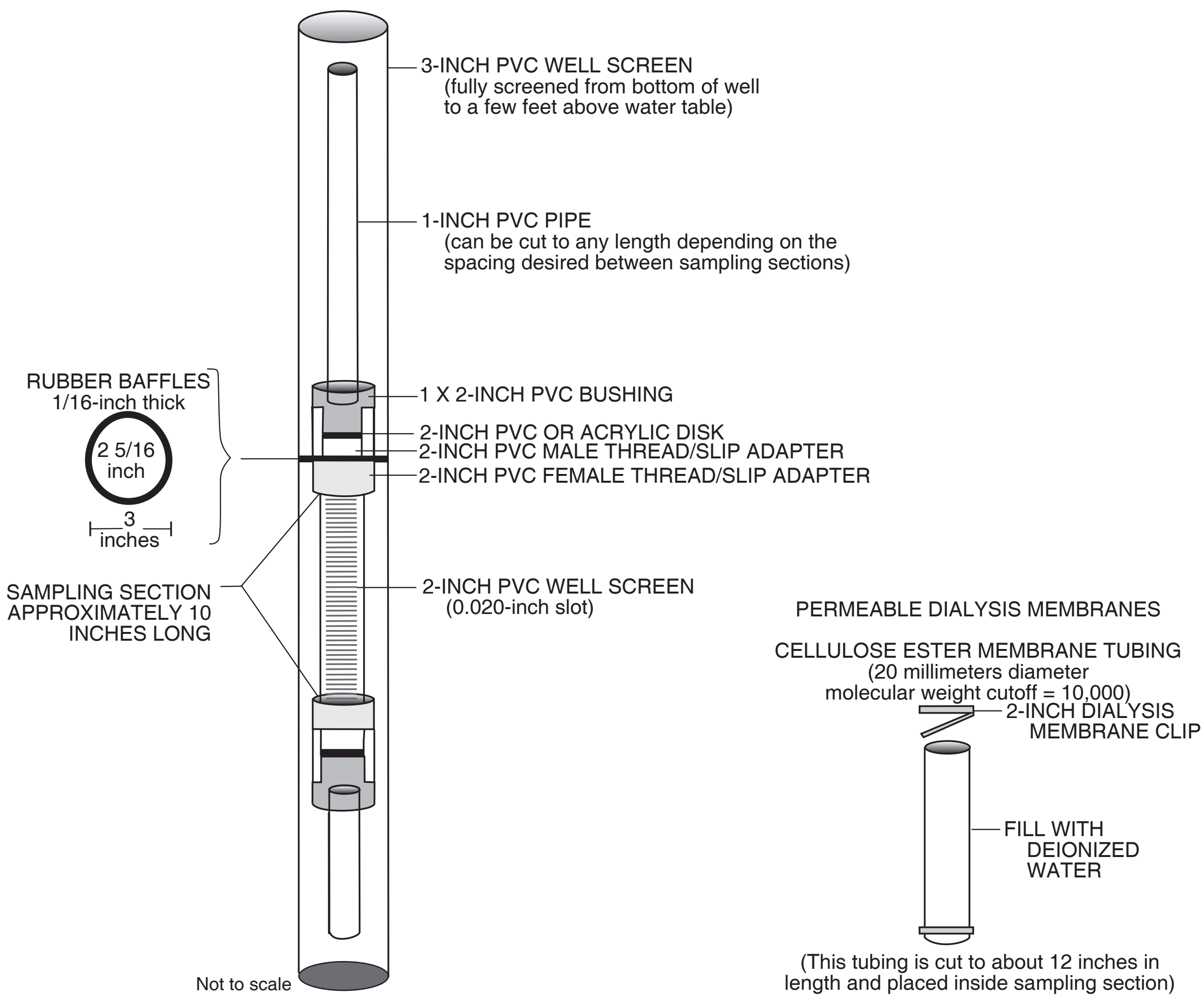


Figure 2. Screened interval and multilevel dialysis sampler.

Once these tubes were lowered into each of the sampling sections, diffusion of the ground water displaces the deionized water in the dialysis cells, allowing them to come to equilibrium with the surrounding ground water. This multilevel sampling system allows for passive sampling, but this sampling device has the limitation that only a finite amount of water is available for analysis. For example, a maximum of approximately 150 mL of sample water can be obtained from each level at any one time using the sampler described above.

Multilevel Tube Sampler

A conventional multilevel tube sampler was installed adjacent to one of the downgradient multilevel dialysis samplers at each site. This sampler consisted of a 2-in.-diameter PVC casing with the bottom at the same depth as the well next to it. Before installation, six lengths of 1/8-in.-diameter polyethylene tubing were lowered inside the casing and inserted into 100-mesh stainless steel screened ports placed in the sides of the casing at levels approximately corresponding to the levels of the sampling sections of the multilevel dialysis sampler adjacent to it. A peristaltic pump was used to draw water from each of the tubes. Each level was pumped for a short time until the tubing was flushed and the water was clear; a sample was then collected. With this sampling device, only water in the immediate vicinity of the port is available for sampling. The device also clogs easily if the formation consists of a large amount of very fine sand or silt.

Sampling Frequency and Procedures

Both multilevel samplers were visited periodically according to two routines. In routine 1, ground-water samples were collected at each site from each of the six levels of all multilevel dialysis samplers and one multilevel tube sampler monthly the first year and every 6 weeks thereafter. Depending on the fluctuation of the water levels in the aquifer, some of the upper levels were dry during some sample-collection periods. Sampling at the Champaign, Clark, and Pickaway County sites was temporarily suspended at times during mild winters. Samples from the multilevel dialysis sampler were collected by removing the string of sampling sections from the 3-in. outer well and unscrewing each section to retrieve the dialysis cells. A clip was removed from the end of each cell, and the sample was poured into a prepared sample bottle. No filtering was required because the dialysis membrane acts as an ionic filter. A sample was also collected from each of the six levels in the one multilevel tube sampler. A 0.45-µm-pore-size filter was connected to the tubing for filtered samples. Samples collected by use of both of these sampling techniques were preserved as required by the NWQL. Samples were analyzed for concentrations of dissolved calcium, sodium, chloride, and bromide. Specific conductance also was measured.

In routine 2, samples were collected once or twice per year at each site by use of a conventional submersible pump placed in the first downgradient well after removing the multilevel sampler. A sample was collected after pH, specific conductance, and water temperature stabilized during the well-purging process. These data were used as background information about the general characteristics of the ground water at each site. These samples were analyzed for concentrations of dissolved organic carbon, cyanide, total dissolved solids, nutrients, major ions, and trace elements. Onsite field measurements of specific conductance, pH, water temperature, and alkalinity also were made by use of the methods discussed in Fishman and Friedman (1989); alkalinity was determined by use of the incremental titration method.

More than 13,100 ground-water samples were collected from the eight sites from January 1991 through September 1999; because of the large amount of samples, the individual sample data are not presented in this report. They are available-from the USGS NWISWeb page at http://waterdata.usgs.gov/oh/nwis/. A list of well numbers and names at each site, is provided in the appendix (table A-1) to assist those interested in retrieving the sample data.

Physical Data

Geophysical data were collected at potential sites as a screening tool to characterize subsurface materials and at final sites to periodically monitor ground-conductivity changes attributable only to changes in water quality. Elevation data were collected to determine the topographic layout of each site as well as exact locations of each test well and water-quality sampling well.

Aquifer Materials

Test wells were constructed as conventional wells by use of 2-in.-diameter casing and 5-ft-long slotted screen. At each site, aquifer materials were collected during the well-installation phase and analyzed for grain size. The geology and soil type of each site were determined from test drilling and surface-geophysical surveys, as well as local well logs and county soil surveys.

Aquifer Properties

Ground-water flow directions were determined by measurement of water levels in a series of test wells. Several single-well aquifer tests (slug tests) were done at one of the test wells at each site to determine a bulk hydraulic conductivity for the site. The method described by Bouwer and Rice (1976) was used to analyze these data.

After water-quality data had been collected in the multilevel wells for 9 years, peaks of chloride concentrations were used in an alternative method to calculate ground-water velocity and hydraulic conductivity. Dissolved-chloride concentrations were plotted against time for all downgradient wells, at each level. Each time a noticeable peak was recognized in a well, the next downgradient well was examined to determine the date, time, and location of the corresponding peak. Each succeeding downgradient well was used in a calculation where a corresponding peak was recognized. The date of each peak was recorded and was incorporated into the following equations:

$$\bar{v} = \frac{d}{t},$$

where

$\bar{v}$ is average ground-water flow velocity,

d is distance travelled, in feet, between the two wells with corresponding chloride peaks,

and

t is time, in days, between a chloride peak in one well and a corresponding peak in the next well.

Average velocity determined by this calculation was then incorporated into the following equation to determine bulk hydraulic conductivity between the wells:

$$K = \frac{\bar{v} n_e}{dh/dl},$$

where

K is average bulk hydraulic conductivity between the wells,

n_e is the estimated porosity of aquifer materials based on grain-size analysis done after test-well drilling,

and

dh/dl is the average hydraulic gradient of the water table determined from water-level measurements from test wells.

An example of a plot used in this method is shown in figure 3. The numbered circles around the points refer to a specific peak of dissolved chloride moving from one well to the next. This method was used only at sites where chloride peaks were easily selected (Ashland, Ashtabula, Lucas, and Richland Counties).

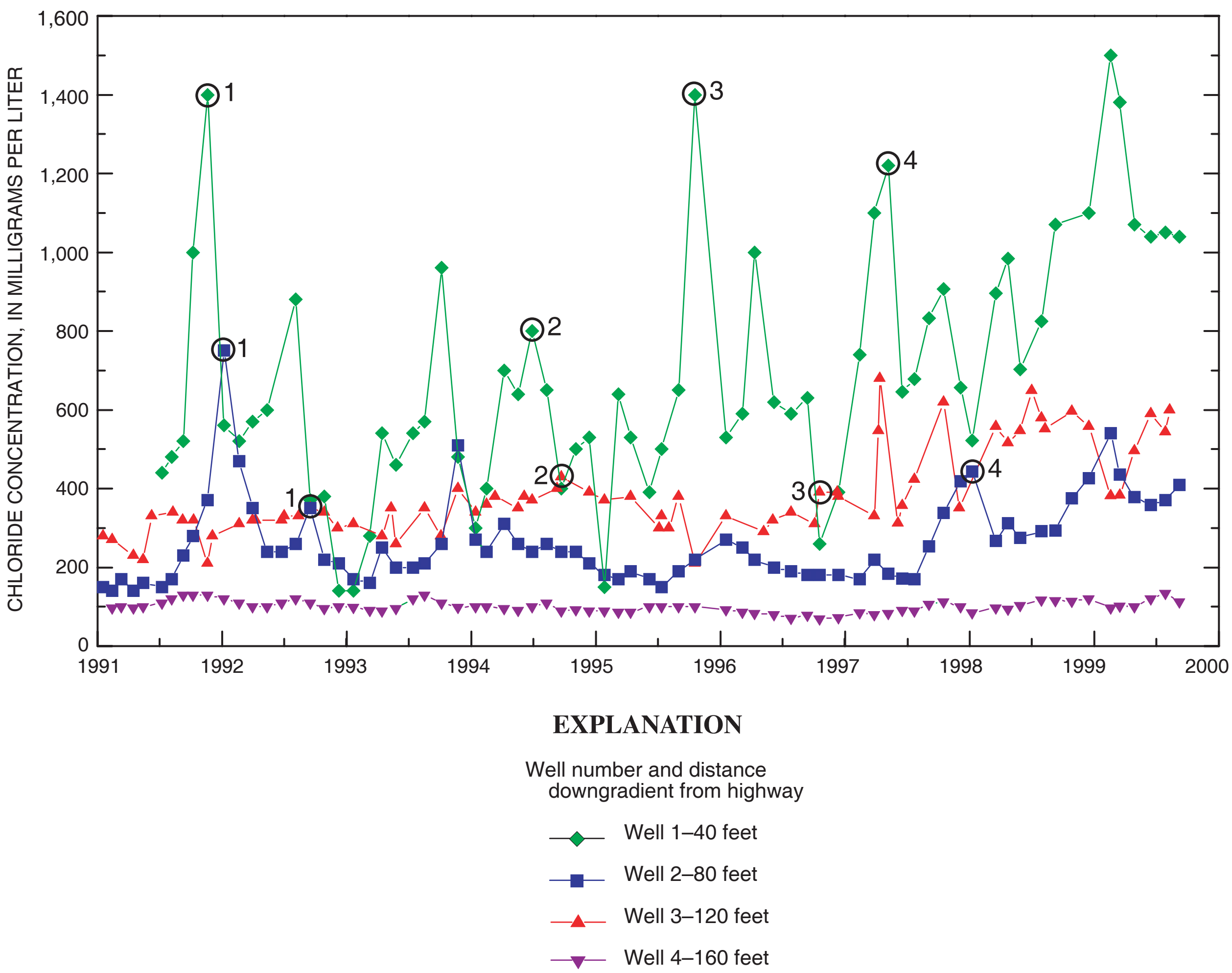


Figure 3. Example plot of chloride concentration showing peaks as they move downgradient from one well to the next—this distance was used to determine average ground-water velocity and bulk hydraulic conductivity.

Soils Data

Soil samples were collected periodically at each site to monitor the chloride concentration in water extracted from a paste of soil and water by use of the saturation extract procedure (Page and others, 1982). Samples were collected at each site nine times (four from Ashland County site) during the study period by use of a hand-driven percussion split-spoon sampler. On each occasion, samples were collected from one or more depths (as much as 2 ft) in the bottom of the ditch along the downgradient side of the road and at a distance of approximately 40–80 ft from the highway, away from any road splash or overland runoff. In the interval of 0–1 ft, the near-surface soil was assumed to have the greatest potential to retain salts because it generally has greater organic material content, finer textures, and (most likely) larger cation and anion exchange capacities than the underlying sand and gravel. Sample extracts were prepared and sent to the NWQL for determination of dissolved-chloride concentration. Data are listed in the appendix in table A-2.

Temporal Data

An electronic data logger was installed at each site to collect hourly data for the following characteristics: precipitation, air temperature, soil temperature, ground-water level at first downgradient well, ground-water temperature (at one to four depths below land surface), and specific conductance (at one to four depths below land surface). All continuously measured characteristics were recorded from February 1991 through September 1999.

Each site was instrumented with a propane-heated precipitation gage; precipitation data were compared to corresponding water-level changes in the monitoring wells. These data sets helped in the determination of some recharge characteristics. Air temperature was measured from a probe housed within a standard air-temperature probe shield 3 ft above the ground surface. Soil temperature was measured with a standard soil probe buried 6 in. below ground, as recommended by the manufacturer. Water level was measured by use of a standard 2-in. diameter float and wire. Ground-water temperature and specific conductance were measured by use of one to four downhole specific-conductance/water-temperature probes. Calibration was checked quarterly or more often as needed. Data were downloaded during each sampling trip from the data logger to a personal field computer, then later downloaded and processed in the USGS National Water Information System.

Climatic Data

Average annual temperature, average annual precipitation, and average annual snowfall data for 1961–90 were obtained from the MRCC climatographic summary for Ohio. MRCC and NOAA data from the weather sites nearest to each of the eight study sites were used (table 2).

In the discussion of the effects of highway deicing chemicals by site, average annual climatological data referenced are from MRCC and NOAA. Data referring to the site itself during the study period are from the onsite instrumentation.

Quality Assurance

A quality-assurance plan was formulated to monitor (1) the accuracy of the multilevel dialysis sampler in collecting representative water-quality samples and (2) the precision and accuracy of laboratory and field techniques. The use of the passive-flow multilevel dialysis sampler is relatively new compared to other sampling techniques; therefore, as mentioned previously, studies were completed in the laboratory to determine the ability of the dialysis membranes to collect a representative ground-water sample (details in the “Well

Table 2. Temperature, precipitation, and snowfall sites from the Midwestern Regional Climate Center and National Oceanic and Atmospheric Administration. Secondary sites were used when the primary site’s data were incomplete.

[AP, airport; WW or WWTP, wastewater-treatment plant; WSO, National Weather Service Office]

Study site	Temperature site	Precipitation site	Snowfall site
Ashland County	Ashland 2 SW	Greer; Ashland 2 SW	Greer; Ashland 2 SW
Ashtabula County	Ashtabula; Dorset	Ashtabula; Dorset	Ashtabula; Dorset
Champaign County	Urbana WWTP	Urbana WWTP	Urbana WWTP; Piqua
Clark County	Urbana WWTP; Springfield New WW	Urbana WWTP; Springfield New WW	Urbana WWTP; Springfield New WW; New Carlisle
Lucas County	Toledo Express WSO AP	Toledo Express WSO AP	Toledo Express WSO AP
Pickaway County	Circleville	Circleville	Circleville
Portage County	Hiram	Hiram; Ravenna 2 S	Hiram; Ravenna 2 S
Richland County	Mansfield WSO AP; Mansfield 5 W	Mansfield WSO AP; Mansfield 5	Mansfield 5 W; Mansfield WSO AP

Installation" section of the report). Also as mentioned previously, one additional multilevel well at each site was constructed as a multilevel tube sampler (conventional multilevel ground-water sampler) and used to compare performance with that of the adjacent multilevel dialysis sampler. To determine the precision of sample-collection techniques, one sequential replicate sample was collected from one multilevel tube well during each site visit. Equipment blanks—inorganic- or organic-free water passed through the sampling equipment to detect contamination in sample collection, handling, and (or) shipping—were collected on a regular basis. Once per field trip, a trip blank containing deionized water was carried in the field vehicle along with regular samples and was analyzed for the same constituents as the samples to check for possible contamination from the vehicle environment.

Project personnel participate annually in the National Field Quality Assurance (NFQA) program, whereby employee skill and field-instrument accuracy are monitored. The NWQL routinely analyzes laboratory quality-control samples to verify the quality of analytical procedures and to determine internal corrective action (if needed). The NWQL participates in outside programs such as the USEPA round-robin rotation and the Standard Reference Water Sample (SRWS) program (Pirkey and Glodt, 1998).

Effects of Highway Deicing Chemicals on Shallow Unconsolidated Aquifers, by Site

Effects of highway deicing chemicals were evident during the study at the three northernmost sites (Ashtabula, Portage, and Lucas County sites, approximately 41°30' to 42° N latitude) but less evident at the other five sites (approximately 39°30' to 41° N latitude), where lesser amounts of deicing chemicals were detected during some periods. Site information indicates that the highest average annual salt use was in Ashtabula County and the lowest in Pickaway County. All eight sites are along State highways with first or second priority for deicing.

Climatic data for the period January 1991 through September 1999 indicate that cold weather and resultant deicing-chemical application rates varied widely across the State. Only traces of dissolved chloride above background concentrations (mean, 13–43 mg/L) were present in ground-water samples from the Champaign, Clark, or Pickaway County sites. At the Ashland and Richland County sites, dissolved-chloride concentrations increased above background levels only intermittently because of infrequent application of deicing chemicals and the resulting lack of consistent input to the aquifer (mean background concentrations of 4–41 mg/L, rising to a mean of 40–56 mg/L). At the Ashtabula, Lucas, and Portage County sites, deicing chemicals were applied frequently throughout the winters, and downgradient dissolved-chloride concentrations (mean, 124-345 mg/L) rarely returned to background concentrations (mean, 7–37 mg/L) throughout the period.

The results from each site are described separately in this report. Four aspects of each site are described: site characteristics, climate, hydrogeology, and effects of highway deicing chemicals on shallow, unconsolidated aquifers. Site characteristics include location, topography, land use, highway characteristics, geology, soil type, and deicing practices. Climatic information includes regional and site-specific data, including snowfall. Hydrogeologic information includes aquifer properties, ground-water levels, and flow direction. Effects of highway deicing chemicals on water quality are described in terms of (1) descriptions of field-monitored characteristics such as continuous ground-water levels; precipitation; air, ground-water and soil temperatures; deicing-chemical application amounts and the general flux in specific conductance; and (2) descriptions of laboratory-determined characteristics such as concentrations of sodium, calcium, bromide and chloride, and specific conductance. Summary facts that supplement the individual descriptions of each site are listed in table 3. Annual values referred to in the individual site descriptions are based on a water year that begins on October 1 and ends the following September 30.

Ashland County Site

Site Characteristics

The Ashland County site (fig. 4) is on State Route (SR) 3, 1/4 mi northeast of the SR 97 junction in Hanover Township and about 3 mi southwest of Loudonville at the entrance to the Mohican State Park campground. SR 3 has a second-priority designation for ODOT deicing. Although the site itself is nearly flat, it is surrounded by fairly high relief and is on the southern boundary of Ohio's glaciated area and near a glacial outwash stream (White, 1977). The site slope is approximately 2.5 ft over 340 ft, or 0.007, toward the Black Fork of the Mohican River. Until 1995, the downgradient side of the highway was an unused, unmowed field covered mostly with weeds and brush; however, in 1995 this site was discontinued because the downgradient side was used to relocate a nearby bridge. The upgradient side is a mowed lawn in front of a paved parking area (not deiced) at the entrance to the Mohican State Park.

SR 3 is a two-lane, undivided highway that runs southwest to northeast. Drainage is by shallow, grassy, open ditches. Total pavement width, including the shoulders, is 23 ft, and the gravel berm is 3–4 ft wide. The highway is fairly straight and flat at this site but begins to bend to the north and rise up a slight grade about 1,000 ft from the site.

The soils are of the Shoals-Lobdell association; the moderately well-drained Lobdell silt loam is distributed throughout the site (U.S. Department of Agriculture, 1980a). Beneath the soils layer, the surficial material at the site ranges from a clayey, fine sandy soil to a very coarse sand and gravel. Bedrock beneath the site is the Cuyahoga Shale of Mississippian age (Swinford, 1995; Kriz, 1995). Driller's logs obtained from

Table 3. Site information and hydrologic features of each highway study site.

[ODOT, Ohio Department of Transportation; NOAA, National Oceanic and Atompspheric Admistration]

Study sites	ODOT de-icing priority	Average annual salt use per county, (in tons)[1]	Average annual snowfall values for nearest NOAA site (in inches)	Average annual precipitation values for nearest NOAA site (in inches)	Depth range of water table at recording well (in feet, below land surface)	Average water-table gradient at site (feet per foot)	Average ground-water velocity at site (feet per foot)[2]
Ashland	2nd	7,200	38.4	38.41	0.55-7.18	0.010	0.10
Ashtabula	2nd	26,012	51.0	38.67	2.11-10.66	.036	.20
Champaign	2nd	2,229	13.4	38.39	4.64-10.62	.002	.27
Clark	1st	3,261	13.4	38.39	17.00-22.61	.003	.31
Lucas	1st	4,267	38.8	32.97	3.21-8.10	.003	.04
Pickaway	2nd	1,507	16.4	38.61	6.50-13.11	.003	.14
Portage	1st	9,251	62.9	41.47	4.35-9.47	.006	.32
Richland	2nd	5,829	42.6	39.66	10.56-18.31	.052	.65

[1] Nine-year average during study (1990–99).

[2] As a factor of the water-table gradient and the hydrologic conductivity.

Ohio Department of Natural Resources (ODNR), Division of Water, indicate the depth to this formation varies from 17 to 43 ft within a half-mile area. An individual well log was constructed for each of the wells and a geologic section of the site was constructed on the basis of these logs (fig. 5).

The nine-winter (1990–99) average annual use of sodium chloride in Ashland County, as a whole, was 7,200 tons (table 1). The maximum for this nine-winter-season period was 10,766 tons in 1995–96, and the minimum for this period was 4,588 tons in 1994–95. The five-winter (1990–95) average annual use of sodium chloride during the study for this county as a whole was 6,378 tons. The maximum for this five-winter period was 8,065 tons in 1993–94, and the minimum for this period was 4,588 tons in 1994–95. Data collected at this site (table 4) indicate the five-winter average annual use of sodium chloride was 5.69 ton/2-ln mi (11,382 lb/2-ln mi), which is 35 percent less than the State average of 8.8 ton/2-ln mi (17,604 lb/2-ln mi) (Ohio Department of Transportation, written commun., 1999). During this study, no calcium chloride ($CaCl_2$) was applied to the highway at this site, although calcium chloride was applied in other areas of the county.

Climate

Average annual precipitation for the area is 38.4 in. (table 3). Average annual temperature for the area is 8.8° C (47.9° F), with the monthly normal high of 28.0° C (82.4° F) in July and the monthly normal low of -10.0° C (14.0° F) in January (Midwestern Regional Climate Center, 2000). Annual precipitation based on data collected at the site, as well as precipitation at the nearest NOAA site, is listed by year in the table below. Average annual snowfall is 38.4 in. for nearby reporting areas. The annual snowfall for the nine-winter study period averaged 31.5 in (Midwestern Regional Climate Center, 2000.)

Ashland County site		
Water year	Onsite precipitation (inches)	Nearest NOAA site[1] precipitation (inches)
1991	[2]3.45	[3]21.64
1992	20.88	36.66
1993	37.84	[3]34.13
1994	[3]45.00	[3]39.74
1995	[3]37.06	[3]34.22

[1] Refer to table 2 for site name.

[2] No measurements made until May 1991.

[3] Incomplete data.

Hydrogeology

The ground-water level ranged from 0.5 to 7.2 ft below land surface during the study period at this site (table 3). During the study, the direction of flow varied from about 66° to 104° to the alignment of the highway, as determined by the triangulation method using available wells; average water-table gradient is about 0.010. At this site, the ground-water levels respond to precipitation within 1 day, owing to the porous aquifer materials at the surface and the shallow water table. Additional data regarding water-table gradient and flow direction can be found in the appendix in table A-3.

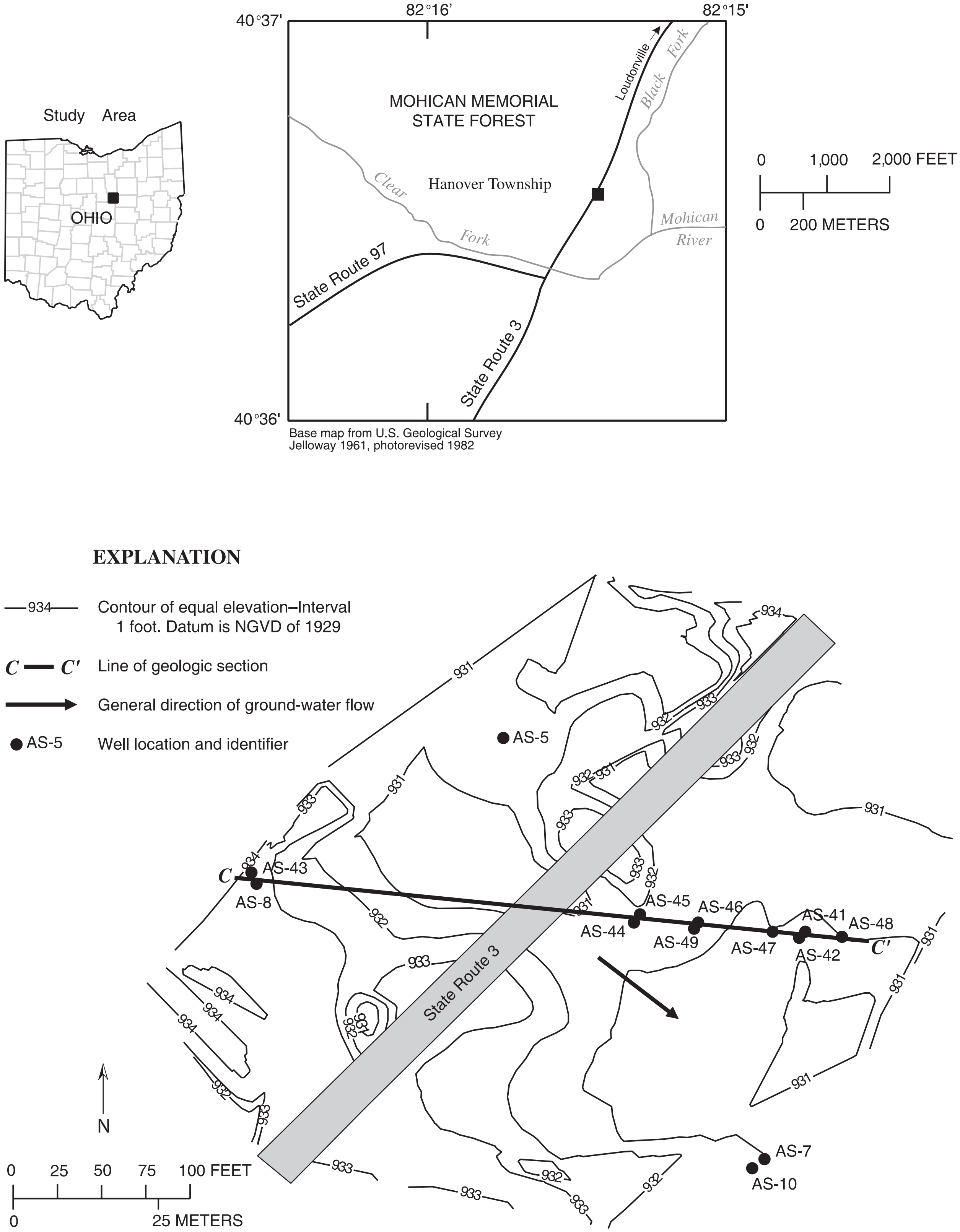
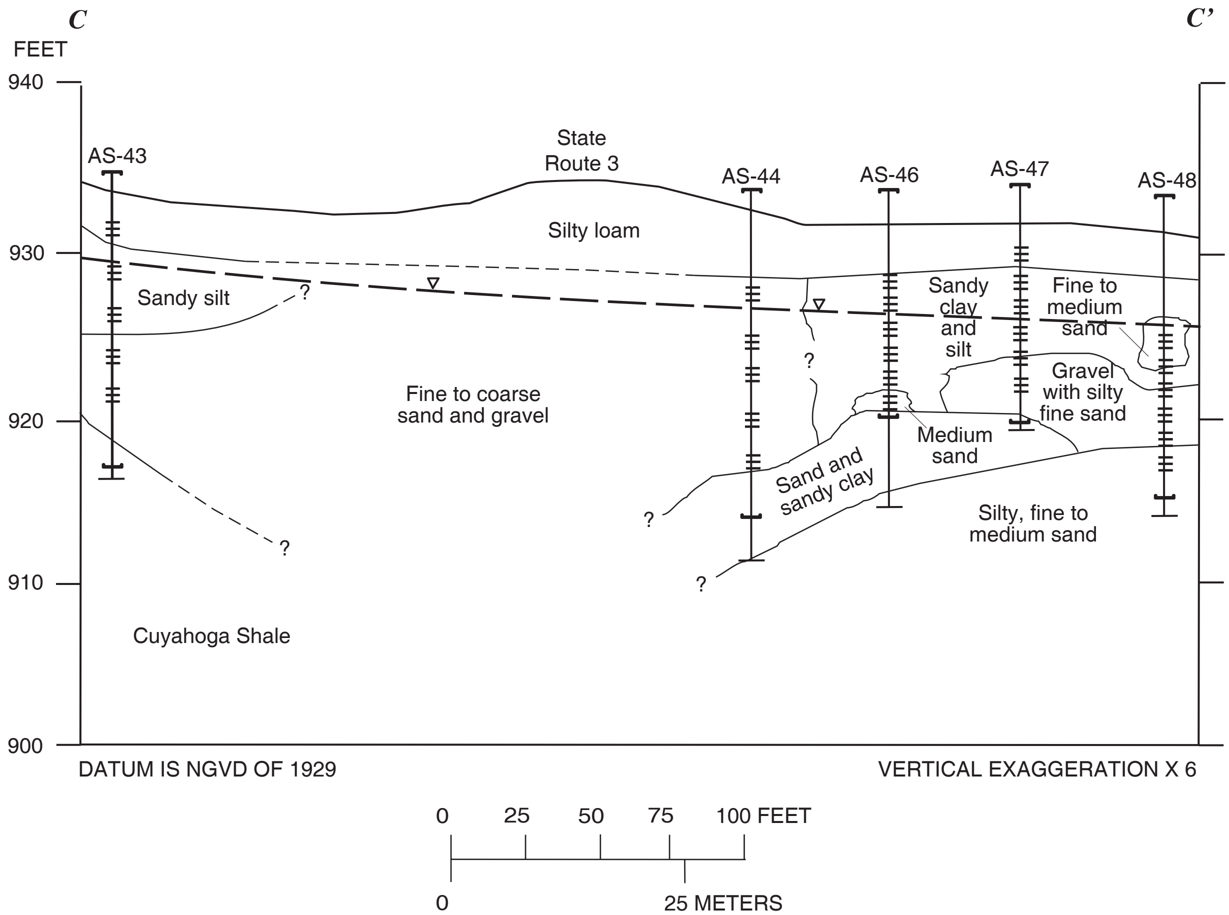


Figure 4. Topography, well locations, and ground-water flow direction at Ashland County, Ohio, study area.



EXPLANATION

AS-44 Well location and identifier–Well logs on file with the U.S. Geological Survey, Columbus, Ohio, office

Top of casing

Sampling interval–Wells with multiple sampling intervals are screened the full length of casing

Bottom of well

Bottom of boring–Wells in which the bottom of the boring extends below the bottom of the well were backfilled to the depth shown as the bottom of the well

Mean water level

Geologic contact–Dashed where approximately located

Figure 5. Geologic section *C-C'*, Ashland County, Ohio, study site. (Section trace shown in fig. 4.)

Table 4. Sodium chloride application amounts by month and year, Ashland County, Ohio, study site.

[Amounts measured by pounds per 2-lane mile]

	October	November	December	January	February	March	April	Yearly total
1990-91	0	0	1,600	4,200	2,300	1,100	0	9,200
1991-92	0	800	400	6,400	1,200	1,600	0	10,400
1992-93	0	400	1,600	3,100	4,500	2,900	0	12,500
1993-94	0	0	3,200	6,600	4,400	2,000	200	16,400
1994-95	0	0	200	5,350	1,860	1,000	0	8,410
1995-96	Site discontinued October 1995							
1996-97								
1997-98								
1998-99								
Total	0	1,200	7,000	25,650	14,260	8,600	200	56,910
Average	0	240	1,400	5,130	2,852	1,720	40	11,382

Results of single-well aquifer tests (slug tests) indicate that hydraulic conductivity is 4 ft/d. Assuming an average gradient of 0.010 and an effective porosity of 40 percent, the ground-water velocity was computed to be approximately 0.10 ft/d.

The ground-water velocity and bulk hydraulic conductivity also were computed by use of water-quality data. Peaks of dissolved-chloride concentration were noted at sites where enough road salt was applied to result in obvious peaks over at least a 4-year period. Using the procedure described in the "Methods" section of this report, the median of the computed average ground-water velocities and the median bulk hydraulic conductivity were computed. At the Ashland County site, the computation was done four times, resulting in a median of the average ground-water velocities of 0.14 ft/d (*s* (standard deviation) = 0.089) and a median bulk hydraulic conductivity of 5.14 ft/d (*s*= 3.29).

Effects of Highway Deicing Chemicals on Water Quality

Field-monitored characteristics (rainfall, specific conductance, and ground-water levels recorded from dedicated instrumentation at a well near the first downgradient sampling well) and the amount of sodium chloride applied to the highway are shown in figure 6. The amounts of sodium chloride applied to the highway adjacent to the site, as recorded by each ODOT outpost driver, are listed in table 4. Plots of these characteristics can be used to help compare the events that resulted in increased specific conductance with ambient site conditions and deicer applications. Movement of chloride and other deicing-related constituents from the highway, with time, is indicated by boxplots of laboratory-determined data in wells in downgradient order (figs. 7 and 8).

Field-Monitored Characteristics

Specific Conductance

Specific conductance of ground water varied somewhat during the study period (fig. 6). As is evident from the table below, specific conductance recorded continuously in well AS-45 near the first downgradient water-quality sampling well at this site ranged from a maximum of 907 µS/cm in 1993 to a minimum of 688 µS/cm in 1995. For comparison, the mean specific conductance of the samples from the upgradient well (AS-43) for the study period was 632 µS/cm (table 5). Deicing chemicals were applied in relatively small quantities; however, gradual rises of specific conductance can be seen in the spring months, especially after the winters of 1992–93 and 1993–94. The shallow water table contributes to the gradual changes in specific conductance.

Ashland County site, well AS-45		
Water year	Specific conductance, maximum (µS/cm)[1]	Specific conductance, minimum (µS/cm)
1991	[2]843	[2]811
1992	847	722
1993	907	798
1994	829	727
1995	791	688

[1] µS/cm, microsiemens per centimeter.

[2] No measurements made until May 1991.

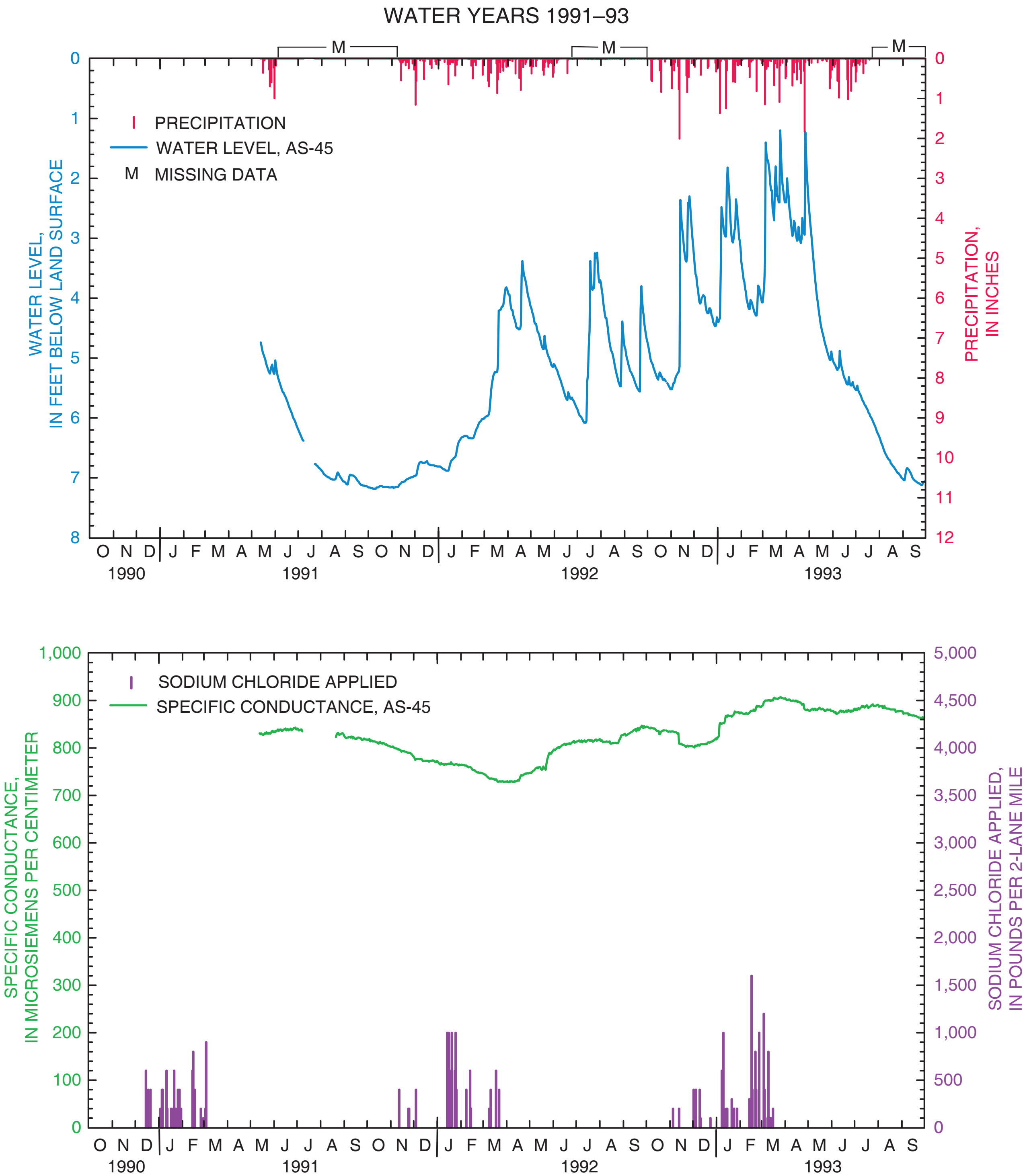
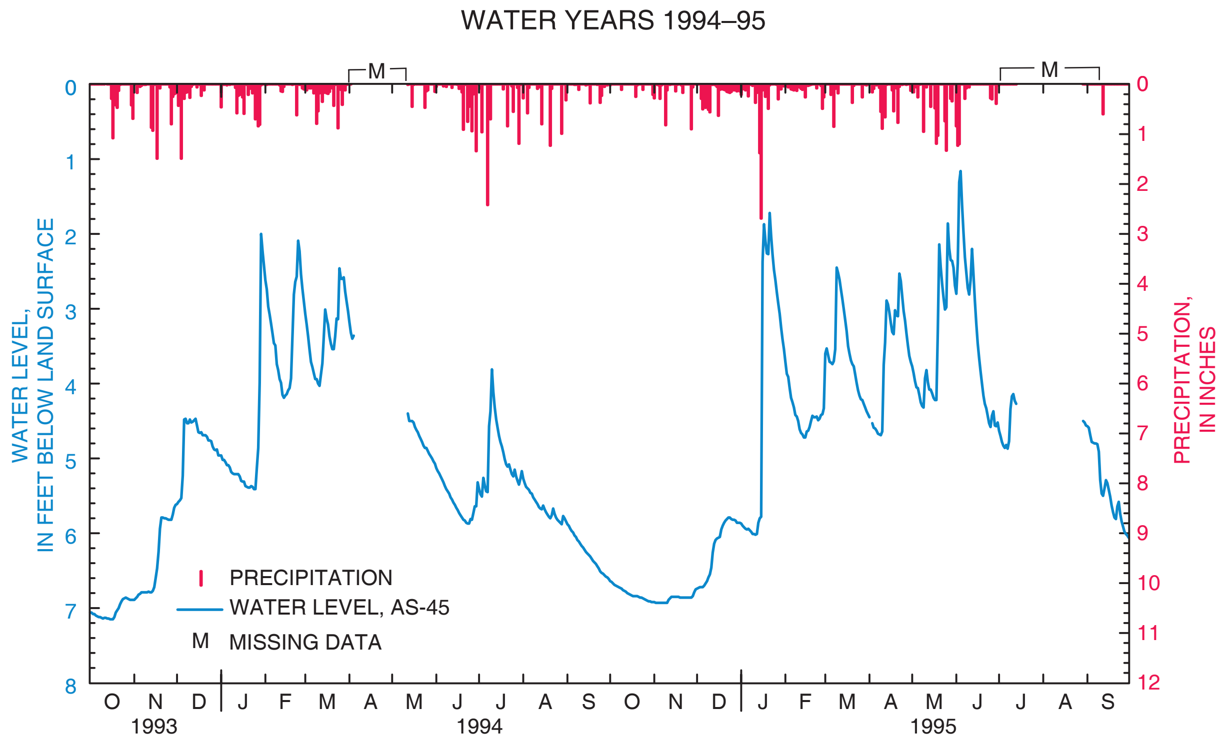


Figure 6. Ground-water levels, precipitation, specific conductance, and sodium chloride application, Ashland County, Ohio, study site, water years 1991-95.



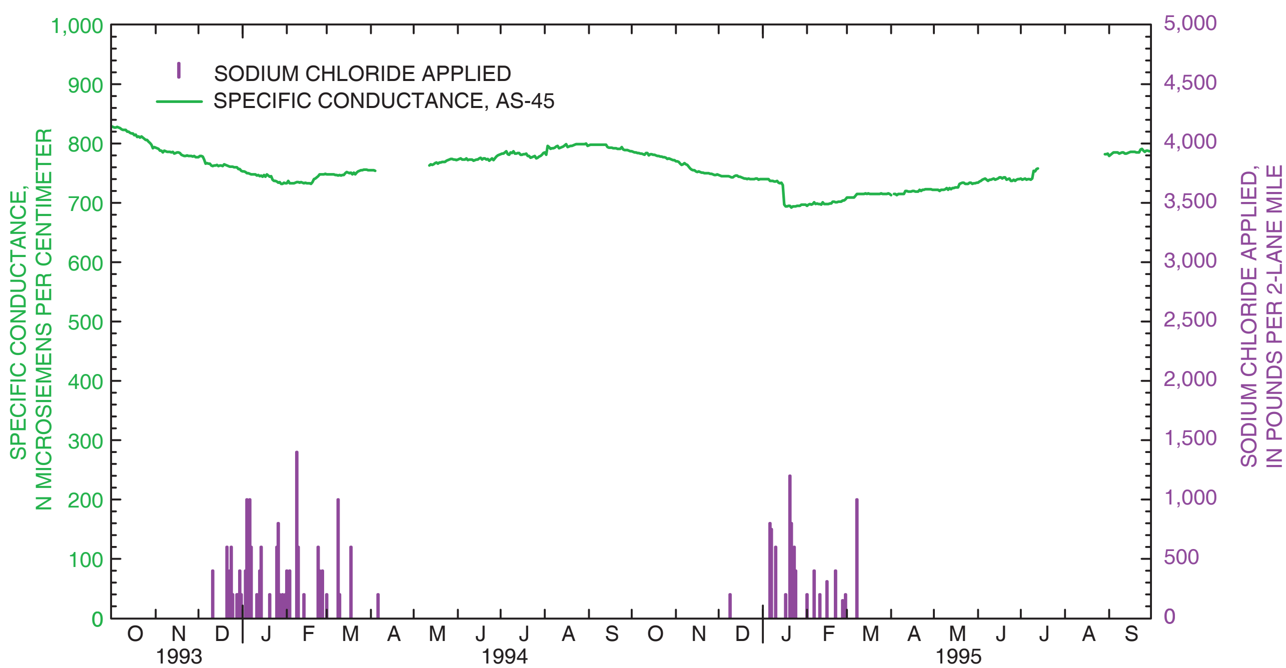


Figure 6. Ground-water levels, precipitation, specific conductance, and sodium chloride application, Ashland County, Ohio, study site, water years 1991-95.—Continued

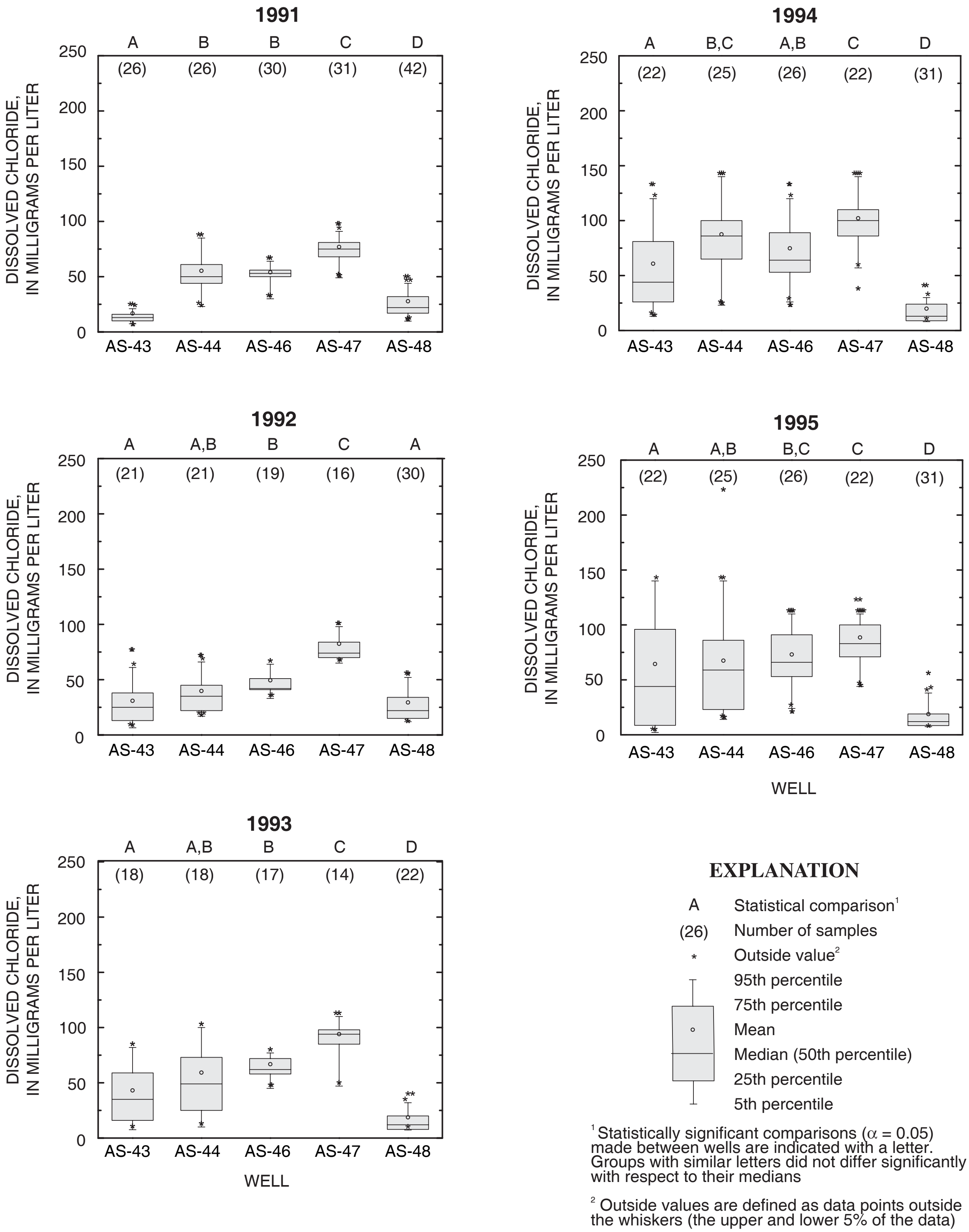


Figure 7. Distribution of concentrations of dissolved chloride in ground-water samples, Ashland County, Ohio, study site, January 1991-September 1995. (Plots are shown in downgradient order from left to right. Far left plot is upgradient from highway; others are downgradient.)

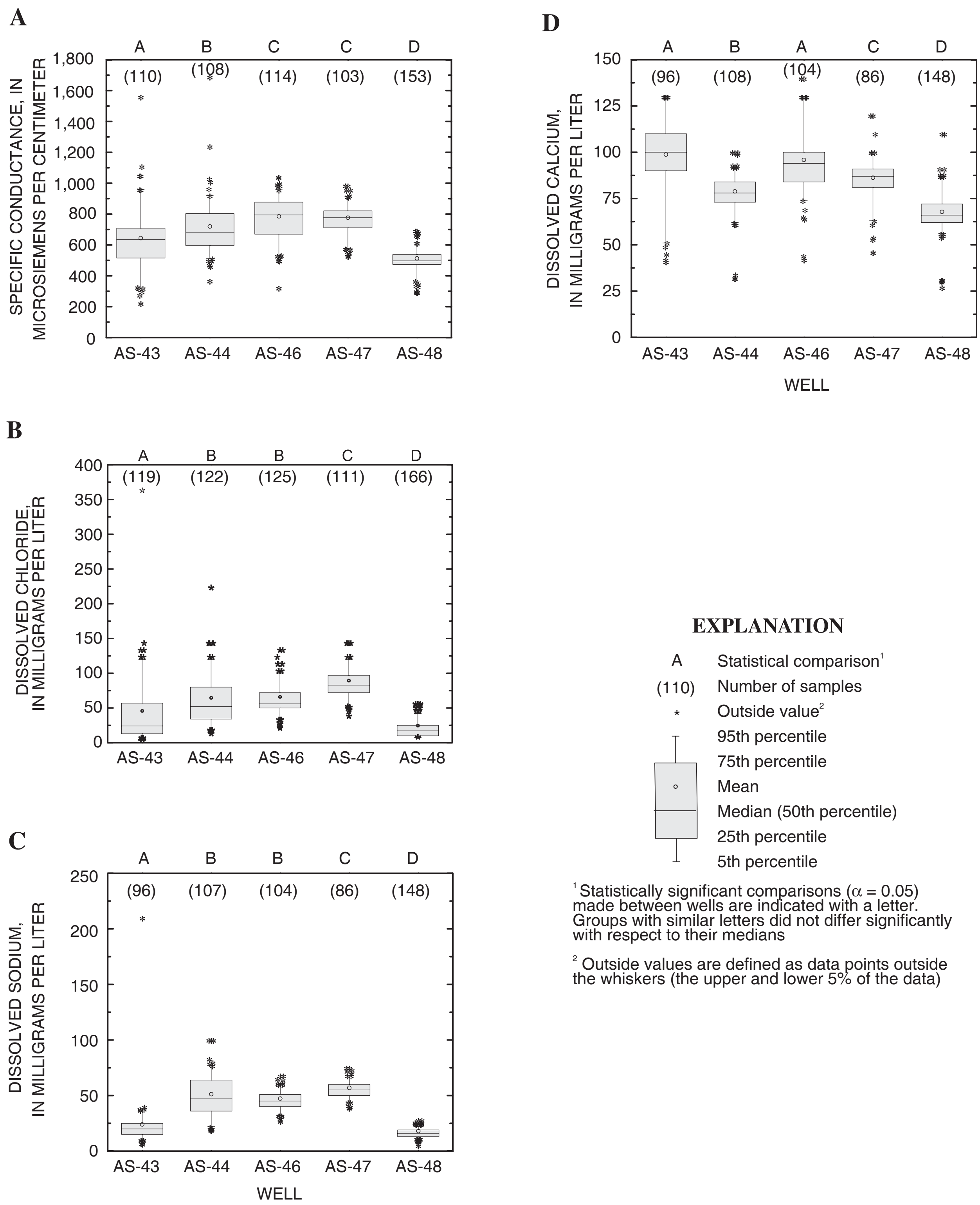


Figure 8. Distribution of (*A*) specific conductance and concentrations of dissolved (*B*) chloride, (*C*) sodium, and (*D*) calcium in ground-water samples, Ashland County, Ohio, study site, January 1991-September 1995. (Plots are shown in downgradient order from left to right. Far left plot is upgradient from the highway; others are downgradient.)

Table 5. Water-quality data for multilevel wells, Ashland County, Ohio, study site, water years 1991-95.

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
AS-43	Upgradient	Maximum	1,560	130	210	360
		Minimum	223	41	6	2
		Mean	632	98	22	41
		Median	638	100	20	24
		N	110	96	96	119
AS-44	1st downgradient	Maximum	1,690	100	100	220
		Minimum	368	32	19	10
		Mean	708	78	50	59
		Median	680	78	47	52
		N	108	108	107	122
AS-46	2nd downgradient	Maximum	1,040	140	68	130
		Minimum	322	42	27	18
		Mean	773	95	46	61
		Median	798	94	46	56
		N	114	104	104	125
AS-47	3rd downgradient	Maximum	986	120	75	140
		Minimum	528	46	39	35
		Mean	764	85	55	84
		Median	777	87	55	83
		N	103	86	86	111
AS-48	4th downgradient	Maximum	693	110	28	53
		Minimum	294	27	5	5
		Mean	501	67	16	20
		Median	497	66	16	17
		N	153	148	148	166

Air and Soil Temperature

During the study period, air temperature at this site ranged from a maximum of 35.5° C in 1991 to a minimum of -35.6° C in 1994.

Water year	Ashland County site: Air temperature, maximum (° C)	Air temperature, minimum (° C)
1991	[1]35.5	[1]-2.5
1992	31.7	-23.1
1993	34.8	-23.2
1994	34.9	-35.6
1995	33.1	-23.0

[1] No measurements made until May 1991.

During the study period, soil temperature ranged from a maximum of 35.5° C in 1991 to a minimum of -0.4° C in 1995.

Water year	Ashland County site: Soil temperature, maximum (° C)	Soil temperature, minimum (° C)
1991	[1]35.5	[1]16.0
1992	31.5	5.4
1993	31.3	3.8
1994	31.2	1.5
1995	27.7	-0.4

[1] No measurements made until May 1991.

Laboratory-Determined Characteristics

Deicing chemicals were not applied to the highway uniformly throughout a single winter or from year to year (table 4 and fig. 6). Snowfall and temperatures varied widely throughout each winter and, in some cases, sampling was discontinued temporarily when little or no deicing chemicals had been applied. Cold temperatures often created icy conditions, but large snowfalls were uncommon. Summary statistics of the water-quality data collected at upgradient and downgradient wells for all 5 years sampled during 1991–95 are listed in table 5. These same statistics for each year individually are listed in the appendix in table A-4. Boxplots of chloride concentration data collected at upgradient and downgradient wells for each of the 5 years individually are shown in figure 7. Boxplots of specific conductance, dissolved calcium, dissolved sodium, and dissolved chloride for water from all levels of the upgradient well and the four downgradient sampling wells for 1991–95 combined are shown in figure 8. Patterns that emerge from those data are noted below.

Specific Conductance

At the upgradient well, AS-43, the mean specific conductance was 632 µS/cm, and the maximum was 1,560 µS/cm (table 5, figure 8A). Values were generally higher at the first three downgradient wells (mean, 708–773 µS/cm; maximum, 986–1,690 µS/cm) than the fourth downgradient well (mean, 501 µS/cm; maximum, 693 µS/cm). Values remained fairly constant downgradient along the flowpath through the third downgradient well. Thus, 162 ft downgradient from the highway, the mean specific conductance at the fourth downgradient well was slightly lower than the upgradient or background concentration.

Chloride Concentration

At the upgradient well, AS-43, the mean concentration of chloride was 41 mg/L and the maximum was 360 mg/L (table 5, fig. 8B). This value could possibly include some contamination from salt spray, because the mean concentration of the upgradient well was higher than that of the fourth downgradient well. Concentrations were higher at the first three downgradient wells (mean, 59–84 mg/L; maximum, 130–220 mg/L) than the fourth downgradient well (mean, 20 mg/L; maximum 53 mg/L). Concentrations remained fairly constant downgradient along the flowpath through the third downgradient well. Thus, 162 ft downgradient from the highway, the mean concentration at the fourth downgradient well was lower than the upgradient or background concentration. Boxplots of chloride concentration data for each of 5 years are shown in figure 7. Patterns were similar except for 1995, which shows a wider range of values for all wells.

Dissolved-chloride concentrations at six sampling levels in each downgradient well at the site during a 12-month period in 1994–95 are represented as a series of chloride profiles in figure 9 (each color in the profile represents an additional 20 mg/L of chloride). This series of profiles shows how chloride moved through the aquifer after deicing chemicals were applied during winter 1993–94 at the site. The amount and frequency of precipitation and snowmelt recharge, as well as soil temperature, can also affect this movement during a specific time period. In figure 9A, the chloride concentrations in the aquifer are near background concentrations. In figure 9B, an area of higher chloride concentration enters the profile at the bottom of the first downgradient well, and by figure 9C, a stratified plume of higher chloride concentration is clearly evident. Destratification through dilution is indicated in figure 9D; a small amount of additional deicing-chemical input may be evident in figures 9E–9H, until in figure 9I, the concentration reaches a typical “between-winters” background concentration. In May, the most stratification and highest values are found at this site.

Soil samples were collected on four occasions at this site during 1993–95. The extract from the soil-sample preparation method was analyzed at the NWQL for dissolved-chloride concentration (table A-2). The chloride concentration of the samples collected from the ditch along the highway ranged from 3 to 210 mg/L and decreased to 5.8–47 mg/L 80 ft downgradient from the highway. The data are listed in the appendix in table A-2.

Sodium Concentration

At the upgradient well, AS-43, the mean concentration of sodium was 22 mg/L, and the maximum was 210 mg/L (table 5, fig. 8C). Concentrations were higher at the first three downgradient wells (mean, 46–55 mg/L; maximum, 68–100 mg/L) than the fourth downgradient well (mean, 16 mg/L; maximum, 28 mg/L). Thus, 162 ft downgradient from the highway, the mean concentration at the fourth downgradient well was about equal to the upgradient or background concentration.

Calcium Concentration

At the Ashland County site, no calcium chloride was applied. At the upgradient well, AS-43, the mean concentration of calcium was 98 mg/L, and the maximum was 130 mg/L (table 5, fig. 8D). Because no calcium chloride deicers were applied at this site, the amounts likely originated in the surrounding bedrock and glacial deposits. Concentrations were highest at the upgradient well and gradually declined as they reached the furthest downgradient well, AS-48. The mean concentration at this well was 67 mg/L with a maximum of 110 mg/L.

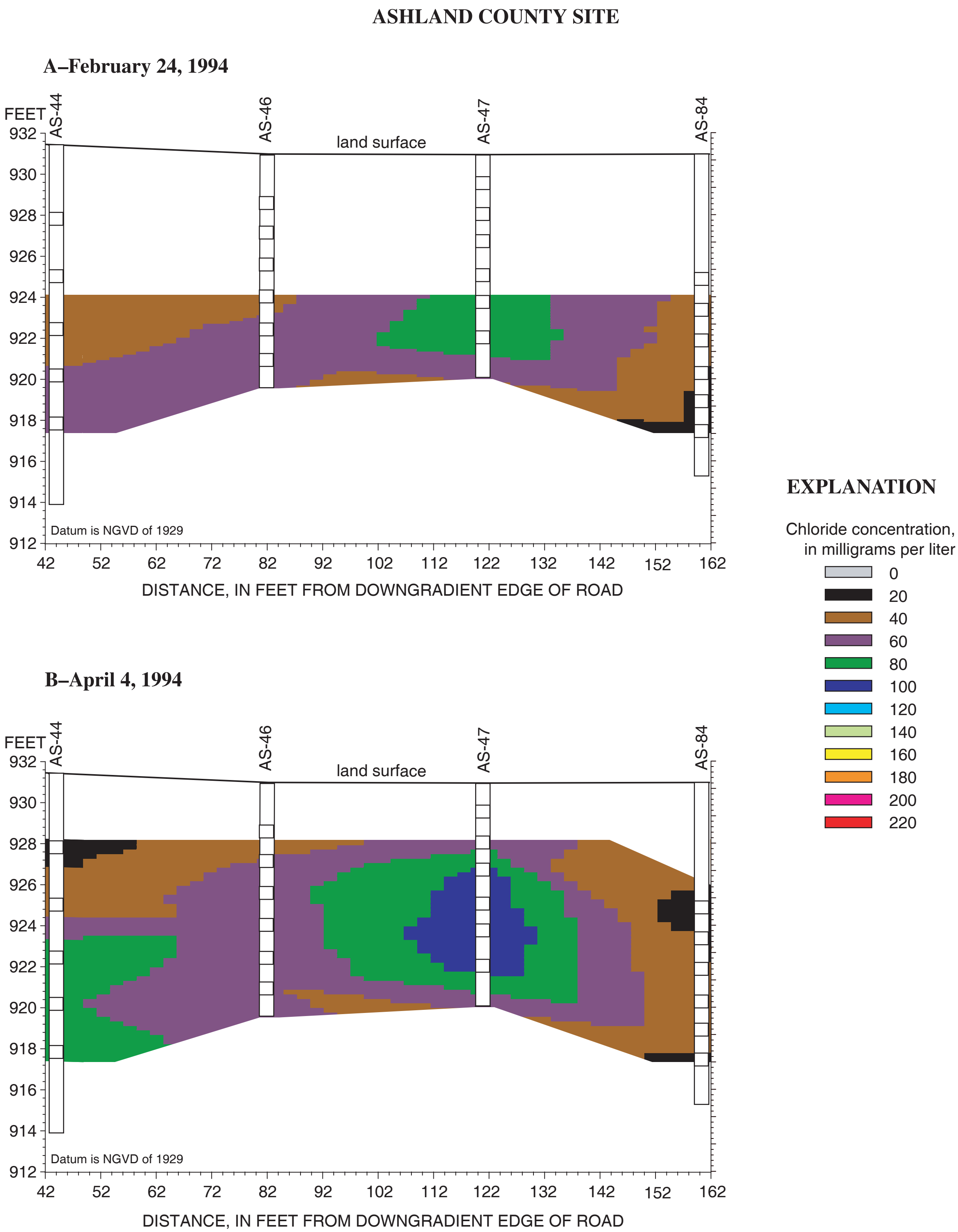


Figure 9. Profiles of chloride concentrations at study site in Ashland County, Ohio, February 24, 1994, through January 24, 1995.

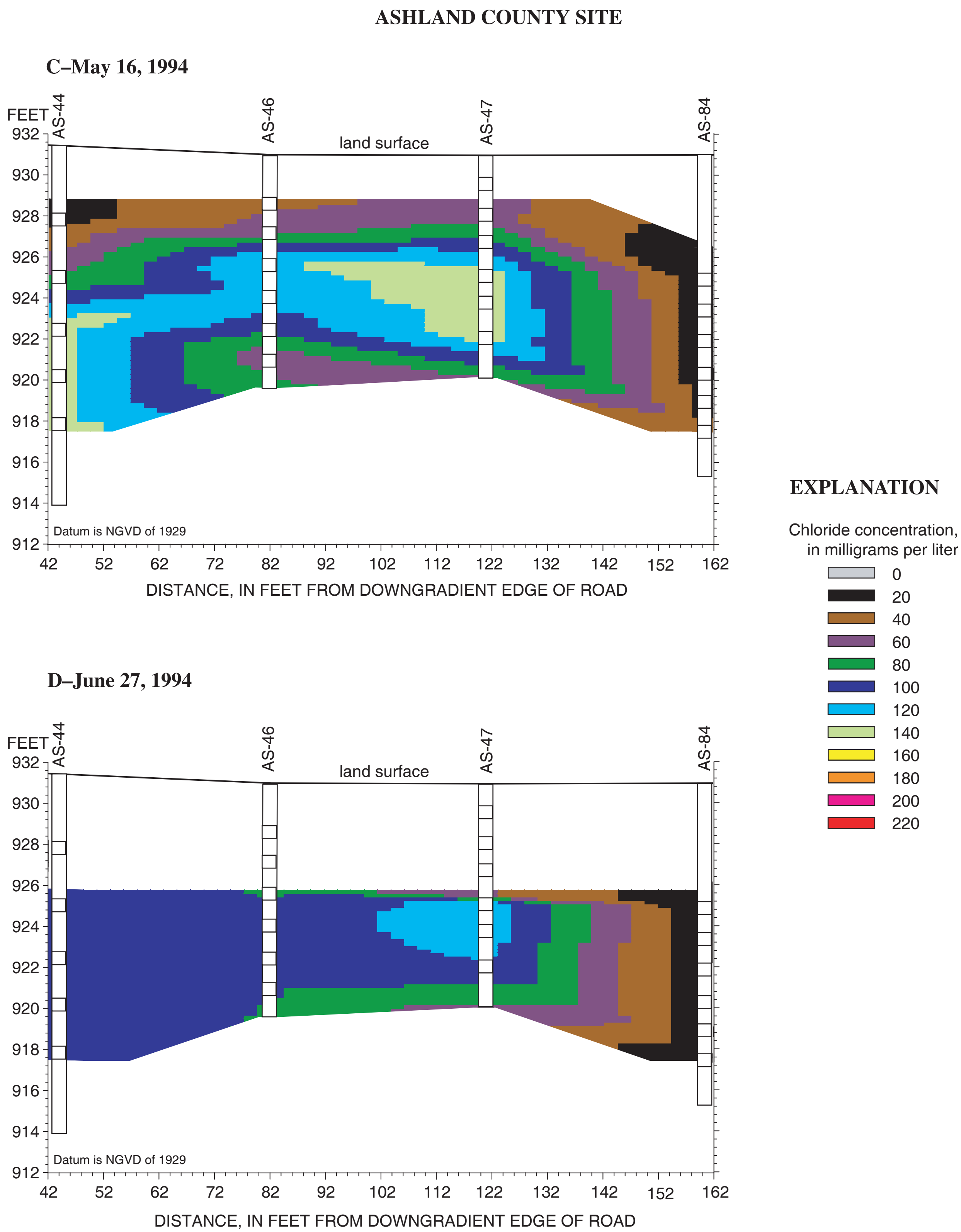


Figure 9. Profiles of chloride concentrations at study site in Ashland County, Ohio, February 24, 1994, through January 24, 1995.—Continued

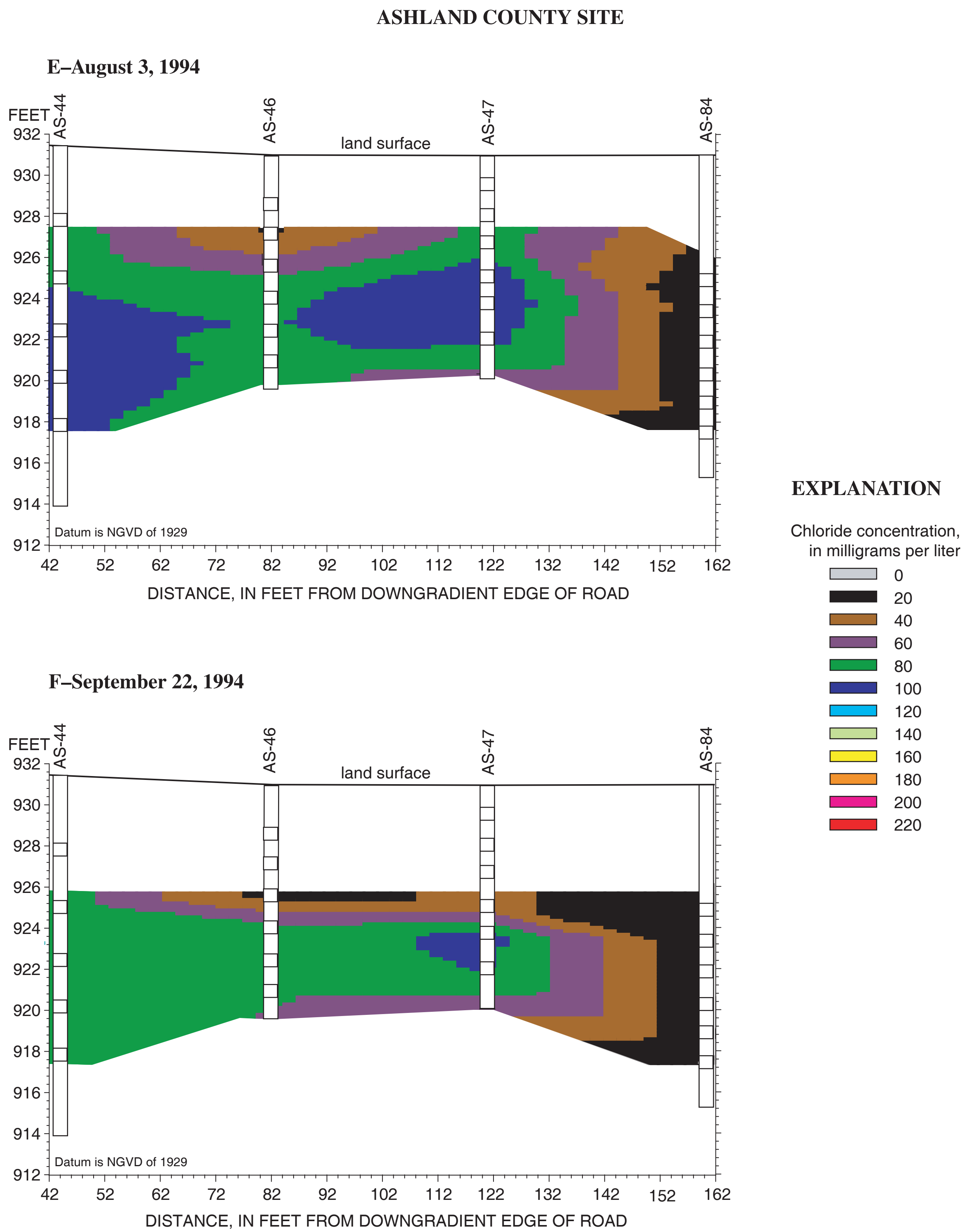


Figure 9. Profiles of chloride concentrations at study site in Ashland County, Ohio, February 24, 1994, through January 24, 1995.—Continued

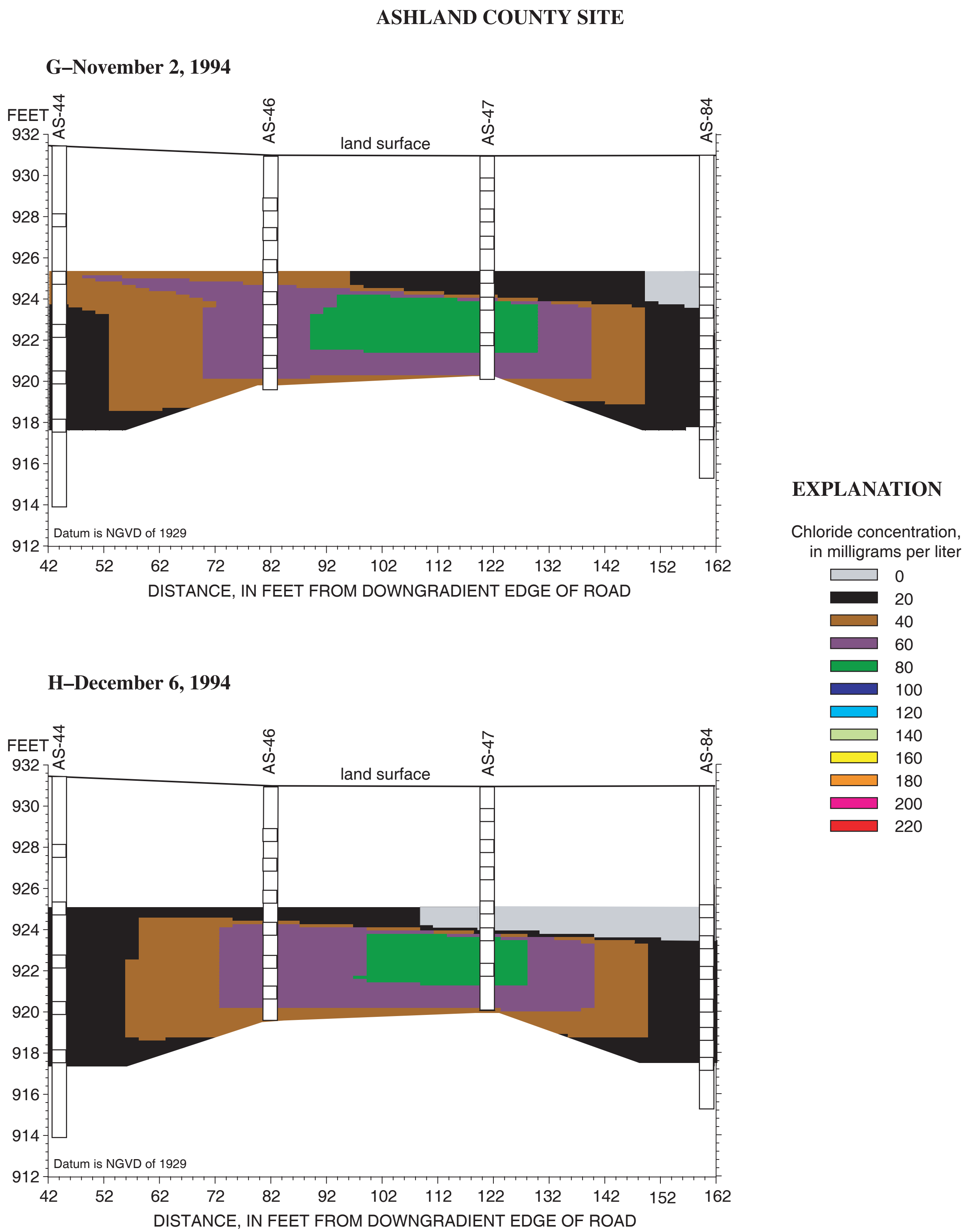


Figure 9. Profiles of chloride concentrations at study site in Ashland County, Ohio, February 24, 1994, through January 24, 1995.—Continued

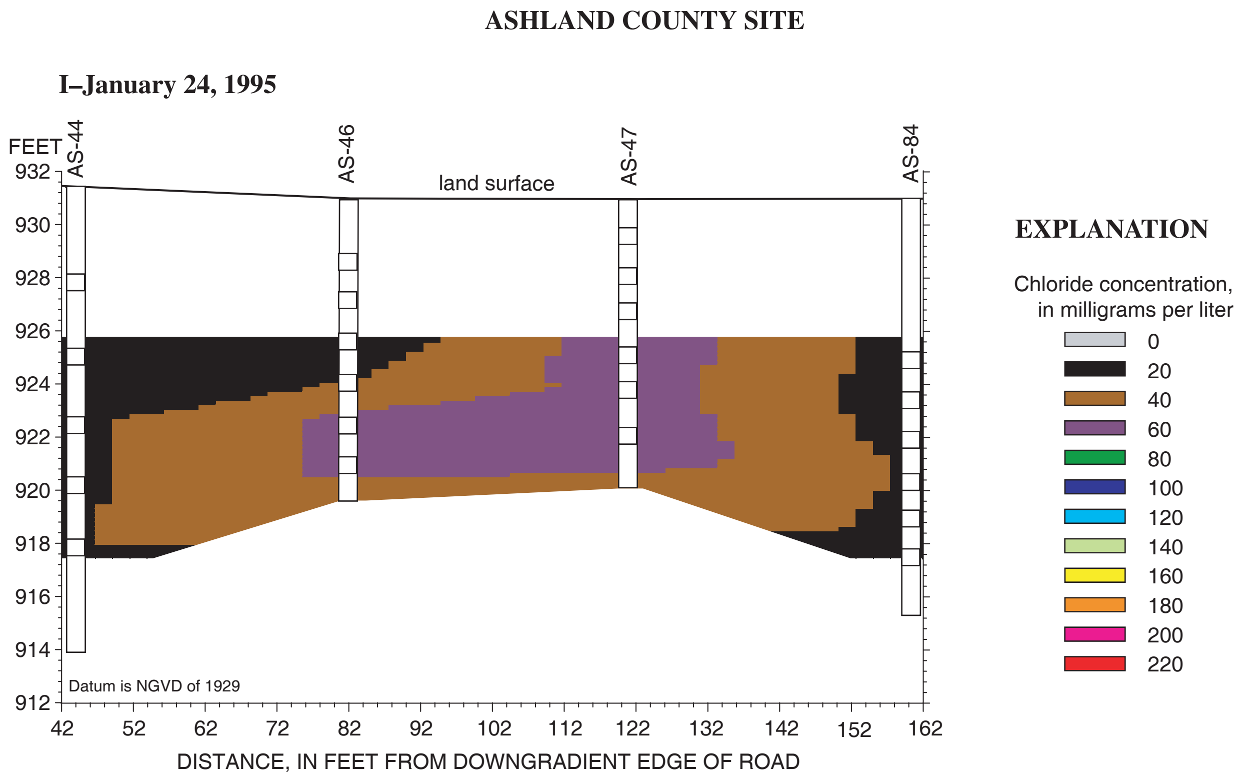


Figure 9. Profiles of chloride concentrations at study site in Ashland County, Ohio, February 24, 1994, through January 24, 1995.—Continued

Ashtabula County Site

Site Characteristics

The Ashtabula County site (fig. 10) is on SR 84, 1 1/4 mi west of the SR 193 junction in Kingsville Township near Kingsville, Ohio. SR 84 has second-priority designation for ODOT deicing. This location is the northernmost site in the study area. Of the eight sites, Ashtabula has the second highest average yearly snowfall and the highest average yearly salt use (table 3). This site is in the Eastern Lake Section of the Central Lowland Physiographic Province (Fenneman, 1946) and is part of an ancient lakebed and beach-ridge complex of post-glacial Lakes Warren and Whittlesey (enlarged stages of present-day Lake Erie), which formed during the retreat of Wisconsinan glaciers. The site is on the Whittlesey Beach Ridge, the higher and farther inland of the two ridges.

The topography of the site is a gently sloping hillside with an elevation drop of 14.7 ft from the upgradient well to the farthest downgradient well, 255 ft away, resulting in a surface slope of 0.058. Runoff flows toward the downgradient side of the highway in a generally north-northeasterly direction. About 200 ft to the east of the site is a drainage ditch flowing to the north-northwest. The downgradient side of the highway is a vacant, mowed, grass field owned by The Ohio State University's Ohio Agricultural Research and Development Center (OARDC) grape research farm. The upgradient side is a mowed grassy hillside owned by the County of Ashtabula Retirement Home. A row of trees lines about half of the upgradient side of the highway between the berm and the grassy area.

SR 84 is a two-lane highway that runs east and west. Drainage is by shallow, open ditches. Total pavement width, including shoulders, is 24 ft; the gravel berm is 3–4 ft wide. The highway is straight at this site, rising from east to west at a slight grade of about 0.03.

The soils are of the Otisville-Chenango association, the well-drained Colonie loamy fine sand predominating downgradient and the moderately well-drained Braceville loam predominating upgradient (U.S. Department of Agriculture, 1973). Beneath the soils layer, the surficial material at the site consists of layers of various combinations of sand, silt, clay, and gravel. Underlying this is a base of gray, silty-clay till (Ashtabula till) at a depth of 15–20 ft below land surface. Bedrock in the area is the Ohio Shale, which is about 20–30 ft below land surface (White and Totten, 1979). An individual well log was constructed for each of the wells. A geologic section of the site was constructed on the basis of these logs (fig. 11).

The nine-winter (1990–99) average annual use of sodium chloride in Ashtabula County, as a whole, was 26,012 tons

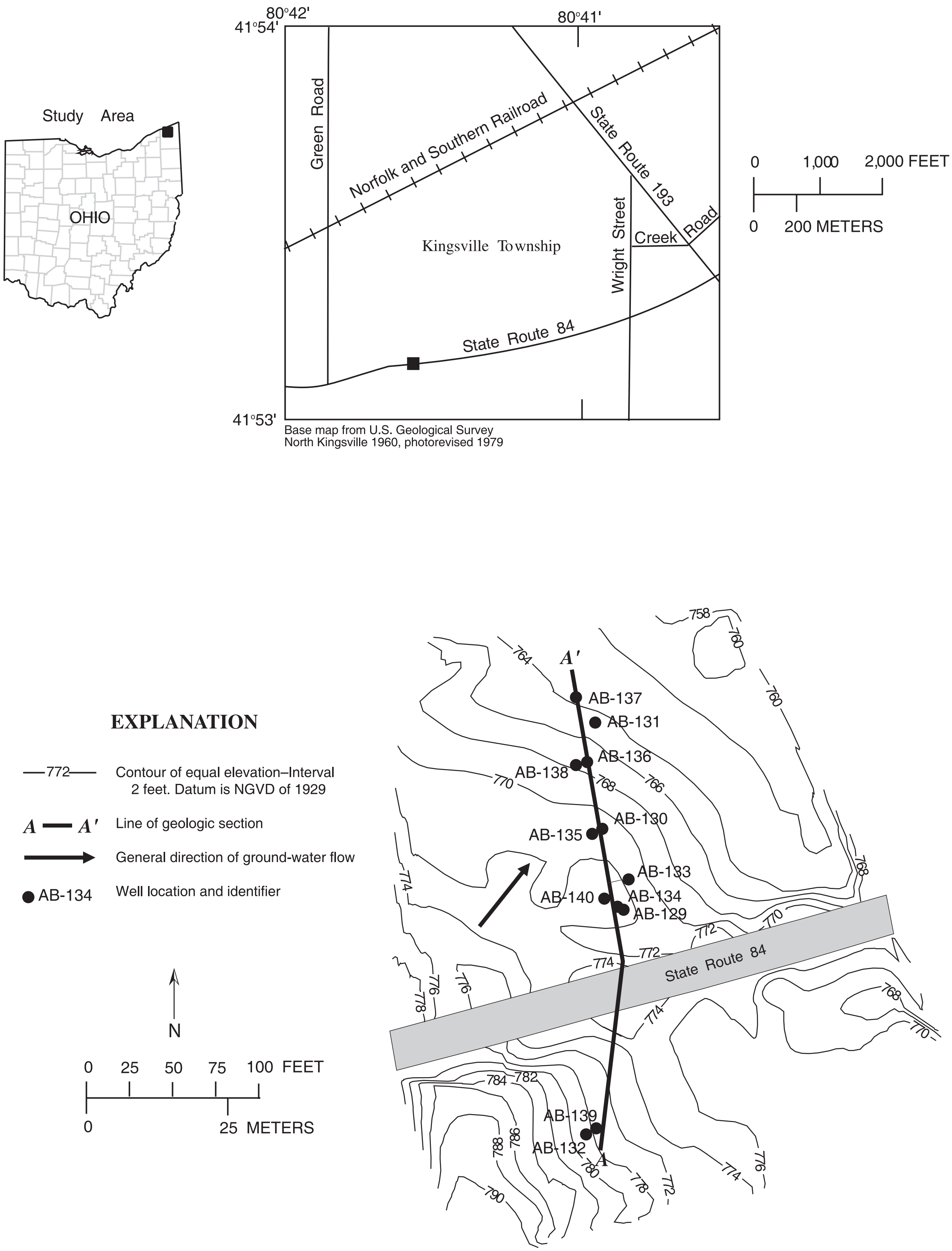
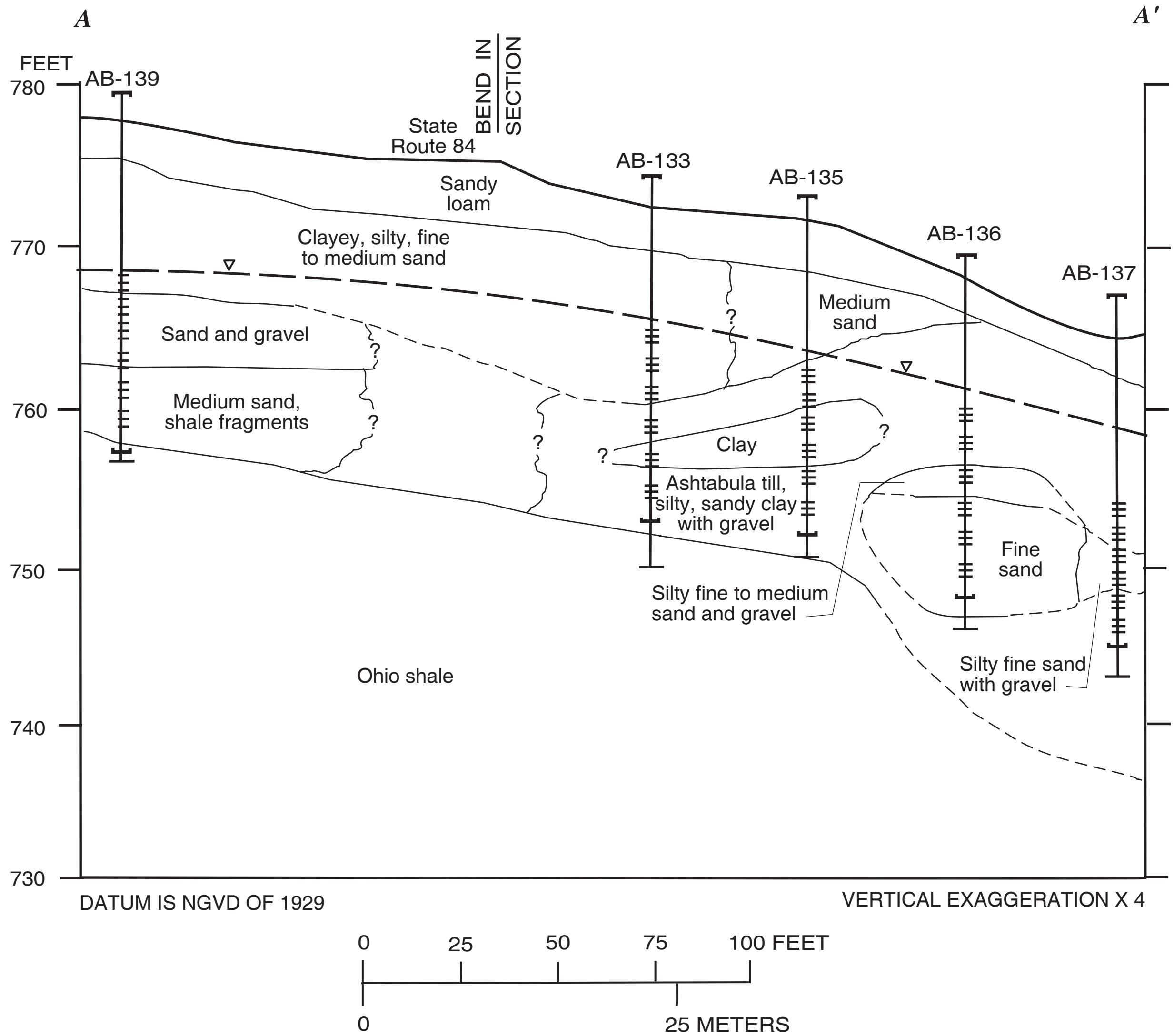


Figure 10. Topography, well locations, and ground-water flow direction at Ashtabula County, Ohio, study area.



EXPLANATION

AB-136 Well location and identifier–Well logs on file with the U.S. Geological Survey, Columbus, Ohio, office

Top of casing

Sampling interval–Wells with multiple sampling intervals are screened the full length of casing

Bottom of well

Bottom of boring–Wells in which the bottom of the boring extends below the bottom of the well were backfilled to the depth shown as the bottom of the well

Mean water level

Geologic contact–Dashed where approximately located

Figure 11. Geologic section *A-A′*, Ashtabula County study site, Ohio. (Section trace shown in fig. 10.)

(table 1). The maximum for this nine-winter period was 43,769 tons in 1995–96, and the minimum for this period was 15,000 tons in 1990–91. Data collected at this site (table 6) indicate the nine-winter average annual use of sodium chloride was 18.75 ton/2-ln mi (37,503 lb/2-ln mi), which is 94 percent greater than the State average of 9.7 ton/2-ln mi (19,380 lb/2-ln mi) (Ohio Department of Transportation, written commun., 1999). In addition to sodium chloride and abrasives, a small amount of liquid calcium chloride ($CaCl_2$) also was applied to the highway in 56 percent of the treatments during the study period.

Climate

Average annual precipitation for the area is 38.7 in. (table 3). Average annual temperature for the area is 9.3° C (48.7° F), with the monthly normal high of 27.0° C (80.7° F) in July and the monthly normal low of -8.3° C (17.1° F) in January (Midwestern Regional Climate Center, 2000). Annual precipitation based on data collected at the site, as well as precipitation at the nearest NOAA site, is listed by year in the table below. Average annual snowfall is 51.0 in. for nearby reporting areas; however, annual snowfall during the study period averaged 60.1 in. (Midwestern Regional Climate Center, 2000).

Ashtabula County site		
Water year	Onsite precipitation (inches)	Nearest NOAA site[1] precipitation (inches)
1991	[2]18.39	[2]19.72
1992	[3]35.33	[3]36.35
1993	36.87	[3]39.69
1994	38.57	44.98
1995	[3]26.74	[3]31.55
1996	49.62	[3]42.78
1997	[3]29.55	[3]52.16
1998	[3]24.40	34.23
1999	[3]28.52	37.44

[1] Refer to table 2 for site name.

[2] No measurements made until February 1991.

[3] Incomplete data.

Table 6. Sodium chloride application amounts by month and year, Ashtabula County, Ohio, study site.

[Amounts measured by pounds per 2-lane mile; e, estimated; NA, not available]

	October	November	December	January	February	March	April	Yearly total
1990-91	0	0	6,000	12,900	22,200	600	0	41,700
1991-92	0	3,300	8,700	10,200	6,500	2,700	300	31,700
1992-93	300	4,800	4,500	5,400	15,000	13,200	0	43,200
1993-94	0	0	15,270	21,600	7,200	5,700	0	49,770
1994-95	0	0	1,200	18,600	8,160	600	0	28,560
1995-96	0	8,400	28,200	12,300	5,000	2,200	200	56,300
1996-97	0	5,900	4,400	18,000	4,400	1,800	0	34,500
1997-98	0	6,500	3,000	6,700	0	6,000	0	22,200
1998-99	0	0	e5,400	e16,000	e3,400	e4,800	NA	e29,600
Total	300	28,900	e76,670	e121,700	e71,860	e37,600	500	e337,530
Average	33	3,211	8,519	13,522	7,984	4,178	56	37,503

Hydrogeology

The ground-water level ranged from 2.1 to 10.7 ft below land surface during the study period at this site (table 3). Average water-table gradient is about 0.036. At this site, the ground-water level responds to precipitation within 1 day, owing to the porous aquifer materials at the surface, the high permeability of the soils, and the shallow water table. Additional data regarding water-table gradient and flow direction can be found in the appendix in table A-3.

Results of single-well aquifer tests (slug tests) on the aquifer indicate that the hydraulic conductivity is 2.3 ft/d. Assuming an average gradient of 0.036 and an effective porosity of 42 percent, the ground-water velocity was computed to be 0.20 ft/d.

Ground-water velocity and bulk hydraulic conductivity also were computed by use of water-quality data. Peaks of dissolved-chloride concentration were noted at sites where enough road salt was applied to result in obvious peaks over at least a 4-year period. Using the procedure described in the "Methods" section of this report, the median of the computed average ground-water velocities and the median bulk hydraulic conductivity were computed. At the Ashtabula County site, the computation was done 10 times, resulting in a median of the average ground-water velocities of 0.325 ft/d (s= 0.225) and a median bulk hydraulic conductivity of 3.86 ft/d (s= 2.69).

Effects of Highway Deicing Chemicals on Water Quality

Field-monitored characteristics (rainfall, specific conductance, and ground-water levels recorded from dedicated instrumentation at well AB-140 near the first downgradient sampling well) and the amounts of sodium chloride applied to the highway are shown in figure 12. The amounts of sodium chloride applied to the highway adjacent to the site, as recorded by each ODOT outpost driver, are listed in table 6. Plots of these characteristics can be used to help compare the events that resulted in increased specific conductance with ambient site conditions and deicer applications. Movement of chloride and other deicing-related constituents from the highway, with time, is indicated by boxplots of laboratory-determined data (figs. 13 and 14).

Field-Monitored Characteristics

Specific Conductance

Specific conductance of ground water near the highway varied greatly during the study period (fig.12). As is evident from the table that follows this paragraph, specific conductance recorded continuously in well AB-140 near the first downgradient water-quality sampling well at this site ranged from a maximum of 4,550 µS/cm in 1999 to a minimum of 241 µS/cm, both in 1999. For comparison, the mean specific conductance of the upgradient well for the study period was 514 µS/cm. Fluctuations in specific conductance seem to occur fairly quickly (within weeks) at this site, possibly because of the relatively steep gradient of the terrain and rapid fluctuations in the water table at this site (table 7).

Ashtabula County site, well AB-140		
Water year	Specific conductance, maximum (µS/cm)	Specific conductance, minimum (µS/cm)
1991	[1]2,560	[1]948
1992	2,880	615
1993	2,660	308
1994	3,460	461
1995	2,330	317
1996	3,540	254
1997	3,670	378
1998	3,480	728
1999	4,550	241

[1] No measurements made until February 1991.

Air and Soil Temperature

During the study period, air temperature at this site ranged from 34.9° C in 1999 to a minimum of -29.6° C in the winter of 1994.

Ashtabula County site		
Water year	Air temperature, maximum (° C)	Air temperature, minimum (° C)
1991	[1]33.0	[1]-12.5
1992	30.7	-18.8
1993	33.0	-19.8
1994	31.8	-29.6
1995	33.1	-17.0
1996	31.4	-25.0
1997	31.6	-19.7
1998	33.3	-10.3
1999	34.9	-22.2

[1] No measurements made until February 1991.

During the study period, the soil-temperature record was often incomplete, but recorded data ranged from a maximum of 31.8° C in 1993 to a minimum of -3.1° C in 1996.

Ashtabula County site		
Water year	Soil temperature, maximum (° C)	Soil temperature, minimum (° C)
1992	[1]27.9	[1]12.9
1993	31.8	-0.7
1994	[2] -	1.7
1995	27.9	17.4
1996	26.3	-3.1
1997	23.3	-0.4
1998	23.3	0.4
1999	24.9	0.4

[1] No measurements made until July 1992.

[2] No measurement, temperature probe defective.

Laboratory-Determined Characteristics

The Ashtabula County site was the site most heavily treated with deicing materials during the study period (table 6). Summary statistics of the water-quality data collected at upgradient and downgradient wells for all 9 years sampled during 1991–99 are listed in table 7. These same statistics for each year individually are listed in the appendix in table A-5. Boxplots of chloride concentration data collected at upgradient and downgradient wells for each of the 9 years individually are shown in figure 13. Boxplots of specific conductance, dissolved calcium, dissolved sodium, and dissolved chloride for water from all levels of the upgradient well and the four downgradient sampling wells for 1991–99 combined are shown in figure 14. Patterns that emerge from those data are noted below.

Table 7. Water-quality data for multilevel wells, Ashtabula County, Ohio, study site, water years 1991-99.

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
AB-139	Upgradient	Maximum	2,130	163	284	544
		Minimum	82	14	3	1
		Mean	514	64	24	37
		Median	448	62	8	6
		N	319	254	254	341
AB-133	1st downgradient	Maximum	4,960	260	770	1,500
		Minimum	748	23	100	120
		Mean	2,461	92	381	652
		Median	2,270	80	350	590
		N	352	332	331	372
AB-135	2nd downgradient	Maximum	2,800	180	330	844
		Minimum	575	64	32	62
		Mean	1,204	101	100	255
		Median	1,105	97	92	230
		N	392	386	387	415
AB-136	3rd downgradient	Maximum	2,590	153	349	705
		Minimum	989	48	120	106
		Mean	1,596	81	211	373
		Median	1,510	76	200	340
		N	417	393	393	432
AB-137	4th downgradient	Maximum	936	120	173	280
		Minimum	456	19	2	10
		Mean	744	82	46	100
		Median	744	82	46	100
		N	336	330	330	359

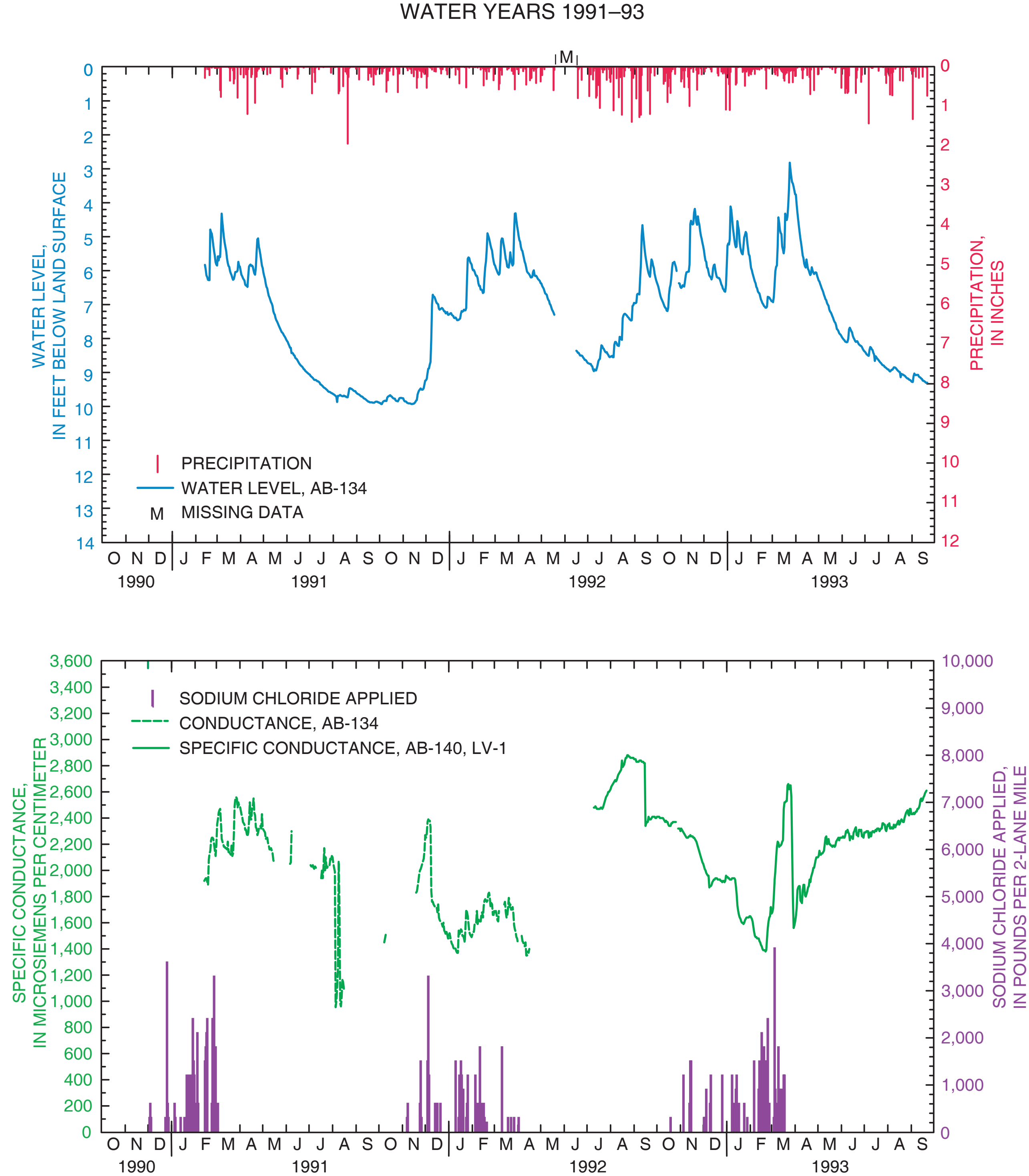


Figure 12. Ground-water levels, precipitation, specific conductance, and sodium chloride application, Ashtabula County, Ohio, study site, water years 1991-99.

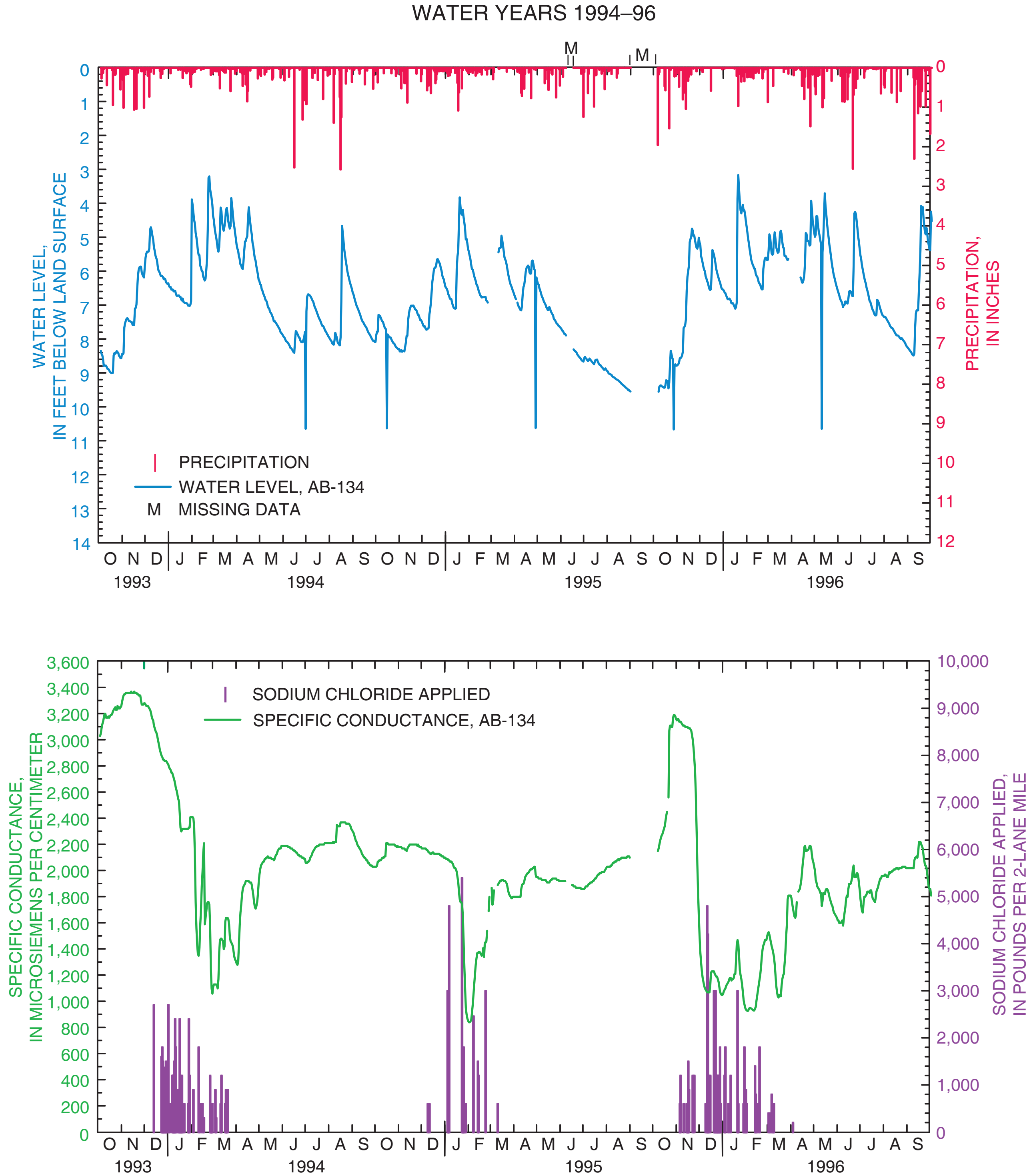


Figure 12. Ground-water levels, precipitation, specific conductance, and sodium chloride application, Ashtabula County, Ohio, study site, water years 1991-99.—Continued

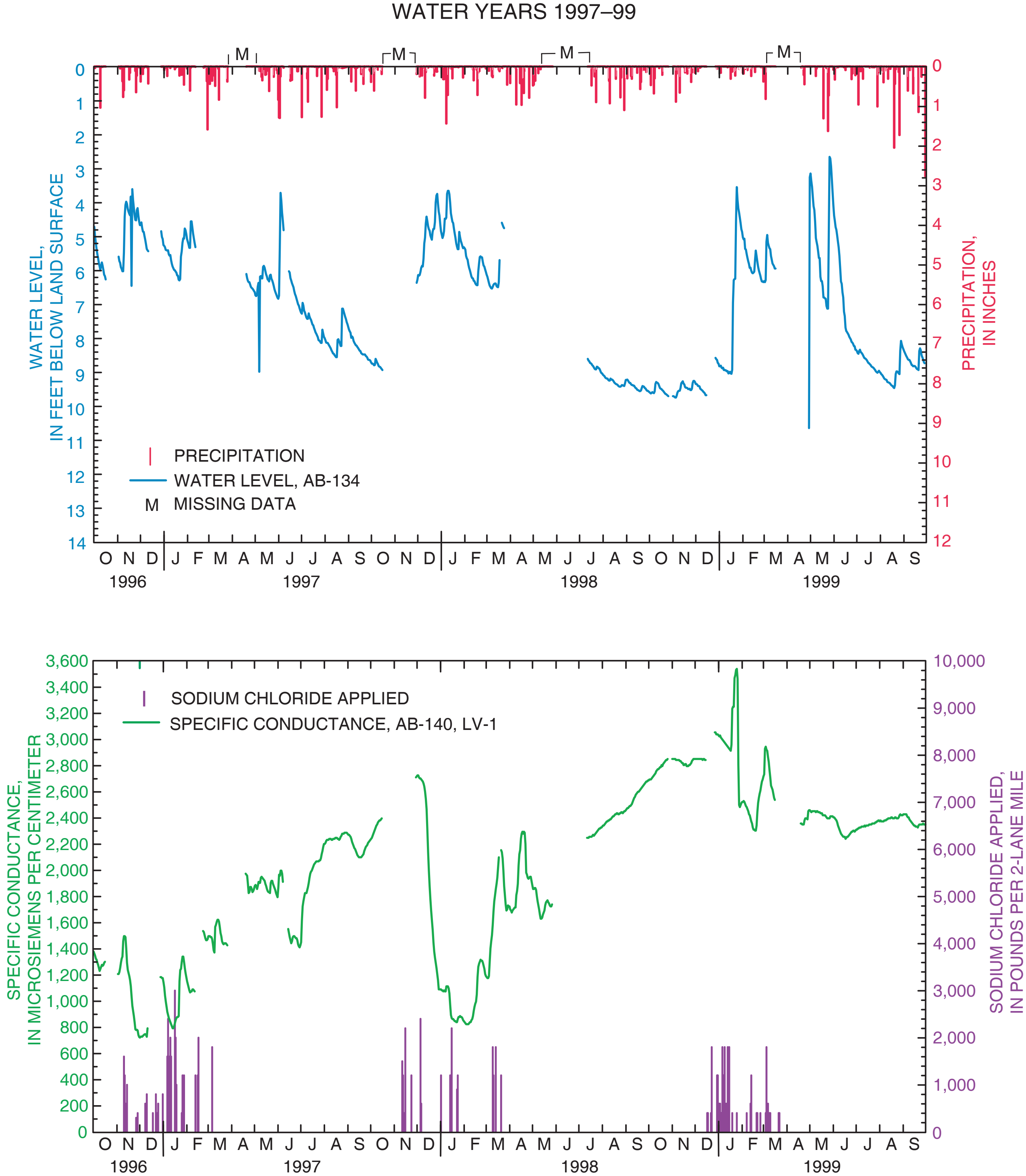


Figure 12. Ground-water levels, precipitation, specific conductance, and sodium chloride application, Ashtabula County, Ohio, study site, water years 1991-99.—Continued

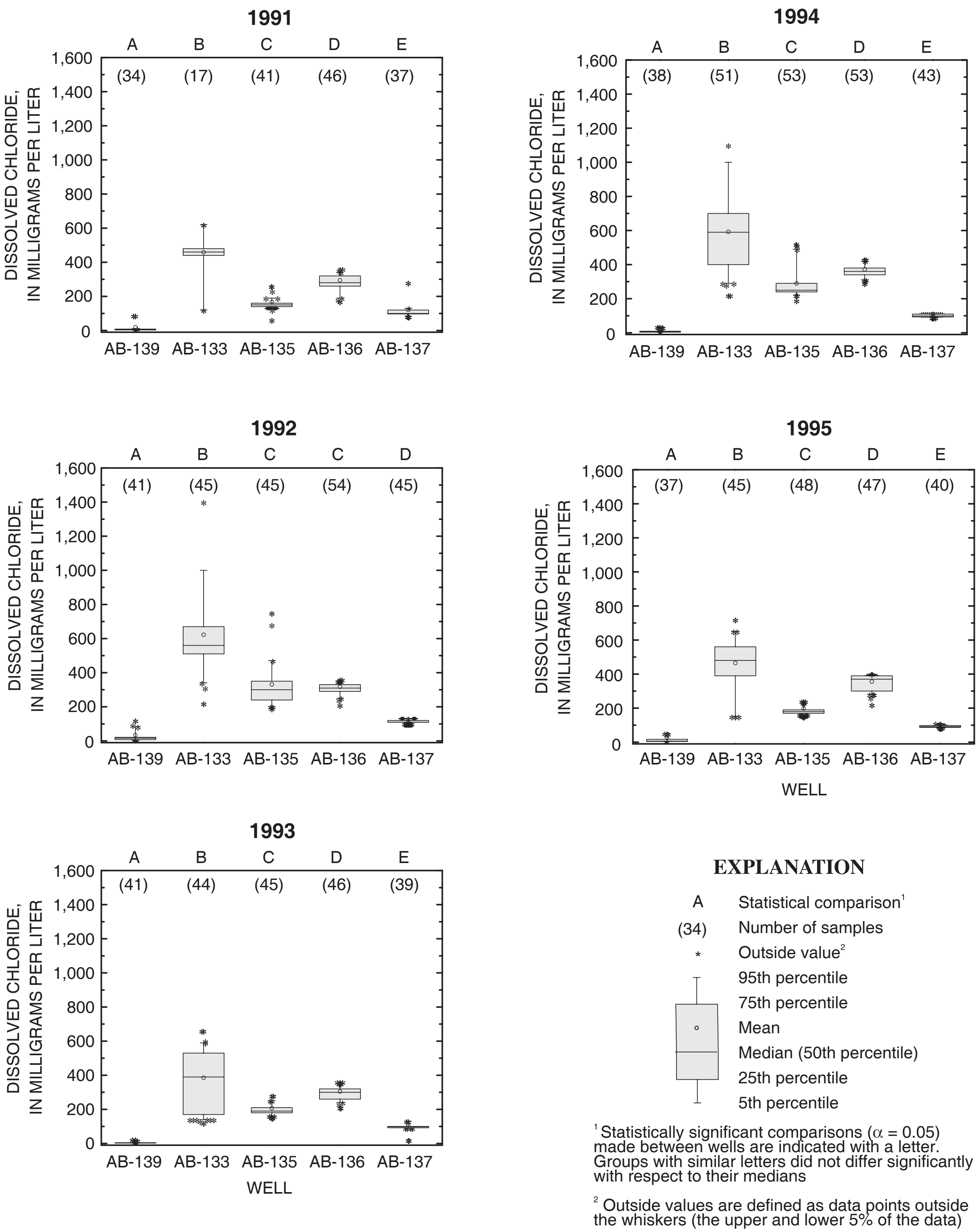


Figure 13. Distribution of concentrations of dissolved chloride in ground-water samples, Ashtabula County, Ohio, study site, January 1991-September 1999. (Plots are shown in downgradient order from left to right. Far left plot is upgradient from highway; others are downgradient.)

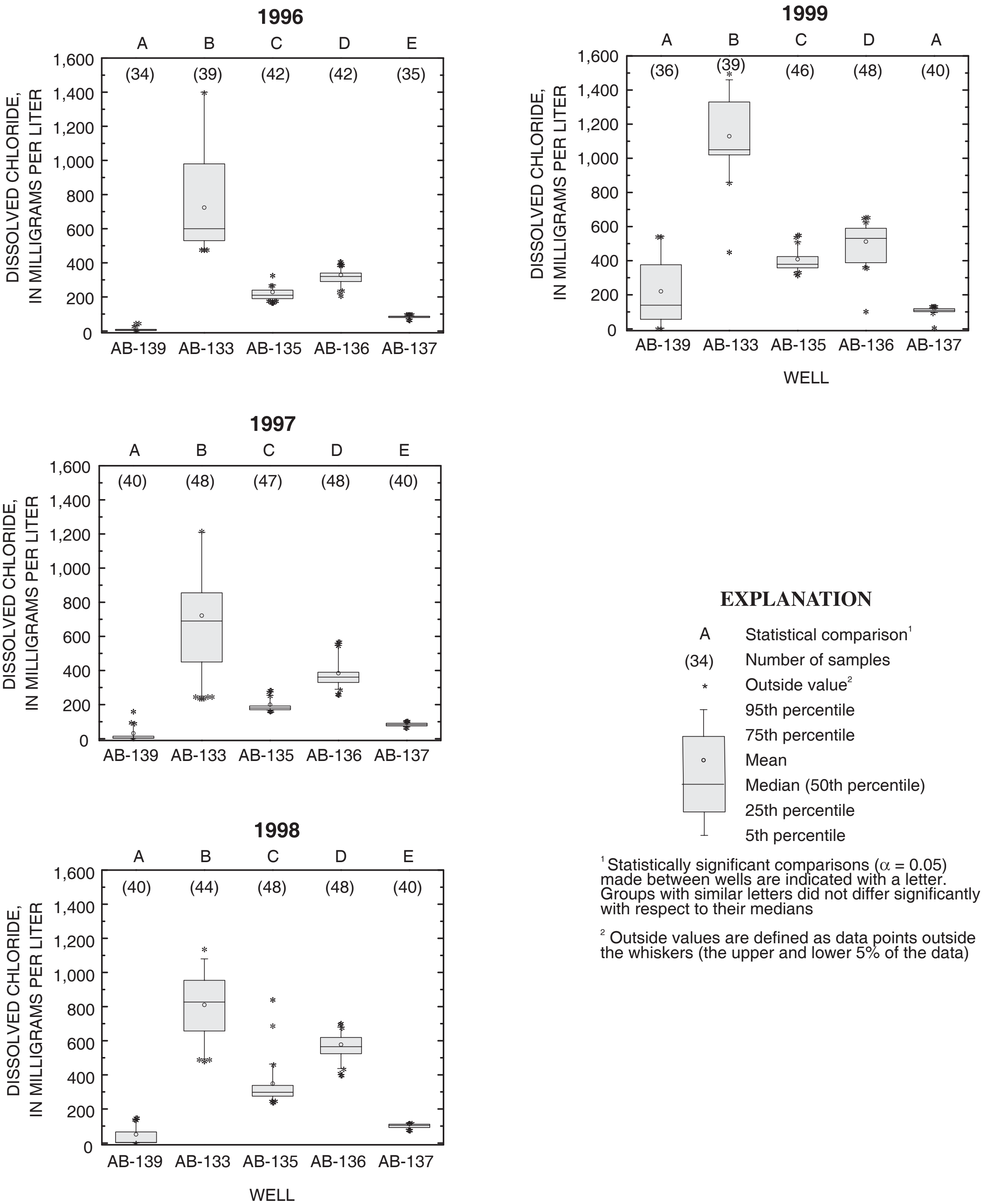


Figure 13. Distribution of concentrations of dissolved chloride in ground-water samples, Ashtabula County, Ohio, study site, January 1991-September 1999. (Plots are shown in downgradient order from left to right. Far left plot is upgradient from highway; others are downgradient.)—Continued

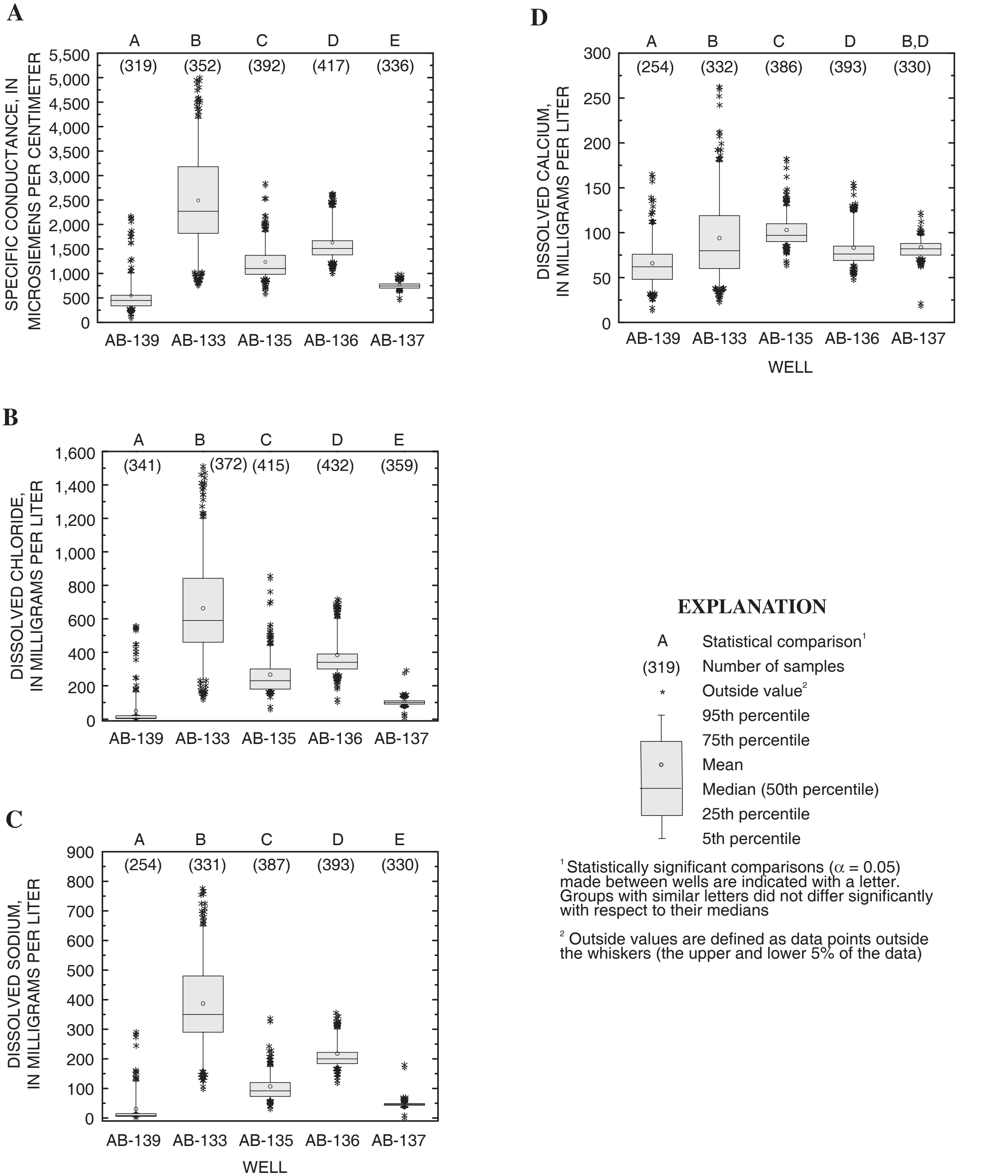


Figure 14. Distribution of (*A*) specific conductance and concentrations of dissolved (*B*) chloride, (*C*) sodium, and (*D*) calcium in ground-water samples, Ashtabula County, Ohio, study site, January 1991-September 1999. (Plots are shown in downgradient order from left to right. Far left plot is upgradient from the highway; others are downgradient.)

Specific Conductance

At the upgradient well, AB-139, the mean specific conductance was 514 µS/cm, and the maximum was 2,130 µS/cm (table 7, fig. 14A). Values were highest at the first downgradient well, AB-133 (mean, 2,461 µS/cm; maximum, 4,960 µS/cm). Values generally decreased downgradient along the flowpath through the second and third downgradient wells. At the fourth downgradient well, AB-137, the mean specific conductance was 744 µS/cm, and the maximum was 936 µS/cm. Thus, 158 ft downgradient from the highway, the mean value at the fourth downgradient well was about 1 1/2 times the upgradient or background value.

Chloride Concentration

At the upgradient well, AB-139, the mean concentration of chloride was 37 mg/L, and the maximum was 544 mg/L (table 7, fig. 14B). Concentrations were highest at the first downgradient well, AB-133 (mean, 652 mg/L; maximum, 1,500 mg/L). Concentrations generally decreased downgradient along the flowpath through the second and third downgradient well (table 7, fig. 14B). At the fourth downgradient well, AB-137, the mean concentration was 100 mg/L, and the maximum was 280 mg/L. Thus, 158 ft downgradient from the highway, mean concentration at the fourth downgradient well was about 3 times the upgradient or background concentration.

Dissolved-chloride concentrations at six sampling levels in each downgradient well at the site during a 20-month period in 1998–99 are represented as a series of chloride profiles in figure 15. (Each color in the profile represents an additional 150 mg/L of chloride.) This series of profiles shows how chloride moved through the aquifer in several waves after deicing chemicals were applied at the site during the winter 1997–98 and again in winter 1998–99 (heaviest during January 1999) at the site. The amount and frequency of precipitation and snowmelt recharge and the soil temperature can also affect this movement during a specific time period. During winter 1997–98, deicing material application was spread out relatively evenly from November 1997 through March 1998; however, during winter 1998–99, deicing material application was heavily concentrated in January 1999. Figure 15 shows this pattern in the profile plots. Plumes of chloride in the 900-mg/L maximum range can be seen moving through the ground-water flow system in summer and fall 1998 (figs. 15E, F, G), but a single plume of chloride in the 1,600-mg/L range can be seen moving through the system as soon as February 1999 (fig. 15I) after the large input of deicing chemicals in January. This large input of chloride was accompanied by several large precipitation events, which facilitated movement of the chemicals into the aquifer more quickly than in the previous winter.

Soil samples were collected on eight occasions at this site during 1993–99 (table A-2). The range of chloride concentration of the samples collected from the ditch along the highway was 65–806 mg/L and decreased to 6–310 mg/L by 80 ft downgradient from the highway. The data are listed in the appendix in table A-2.

Sodium Concentration

At the upgradient well, AB-139, the mean concentration of sodium was 24 mg/L, and the maximum was 284 mg/L (table 7, fig. 14C). Concentrations were highest at the first downgradient well, AB-133 (mean, 381 mg/L; maximum, 770 mg/L) (table 7, fig 14C). At the fourth downgradient well, AB-137, the mean concentration was 46 mg/L, and the maximum was 173 mg/L. Thus, 158 ft downgradient from the highway, mean concentration at the fourth downgradient well was about twice the upgradient or background concentration.

Calcium Concentration

In addition to sodium chloride and abrasives, varying amounts of liquid calcium chloride ($CaCl_2$) were applied to the highway during the study period. From a mean concentration of 64 mg/L and a maximum of 163 mg/L at the upgradient well (AB-139), the concentrations increased to a mean of 92 mg/L and a maximum of 260 mg/L at the first downgradient well, AB-133, (table 7, fig 14D). These concentrations decreased slightly to the last downgradient well (AB-137), with a mean concentration of 82 mg/L and maximum of 120 mg/L.

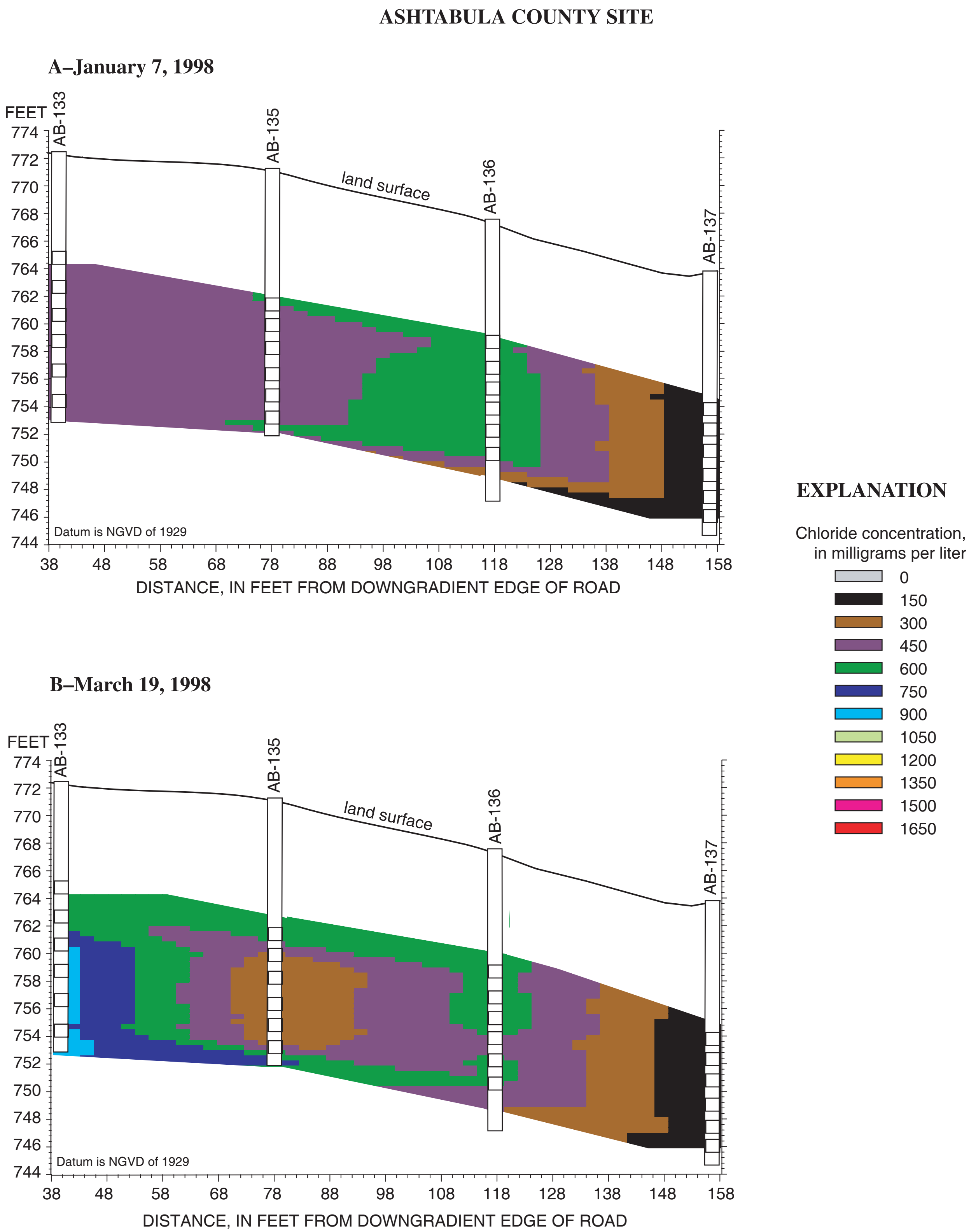


Figure 15. Profiles of chloride concentrations at the study site in Ashtabula County, Ohio, January 7, 1998, through September 8, 1999.

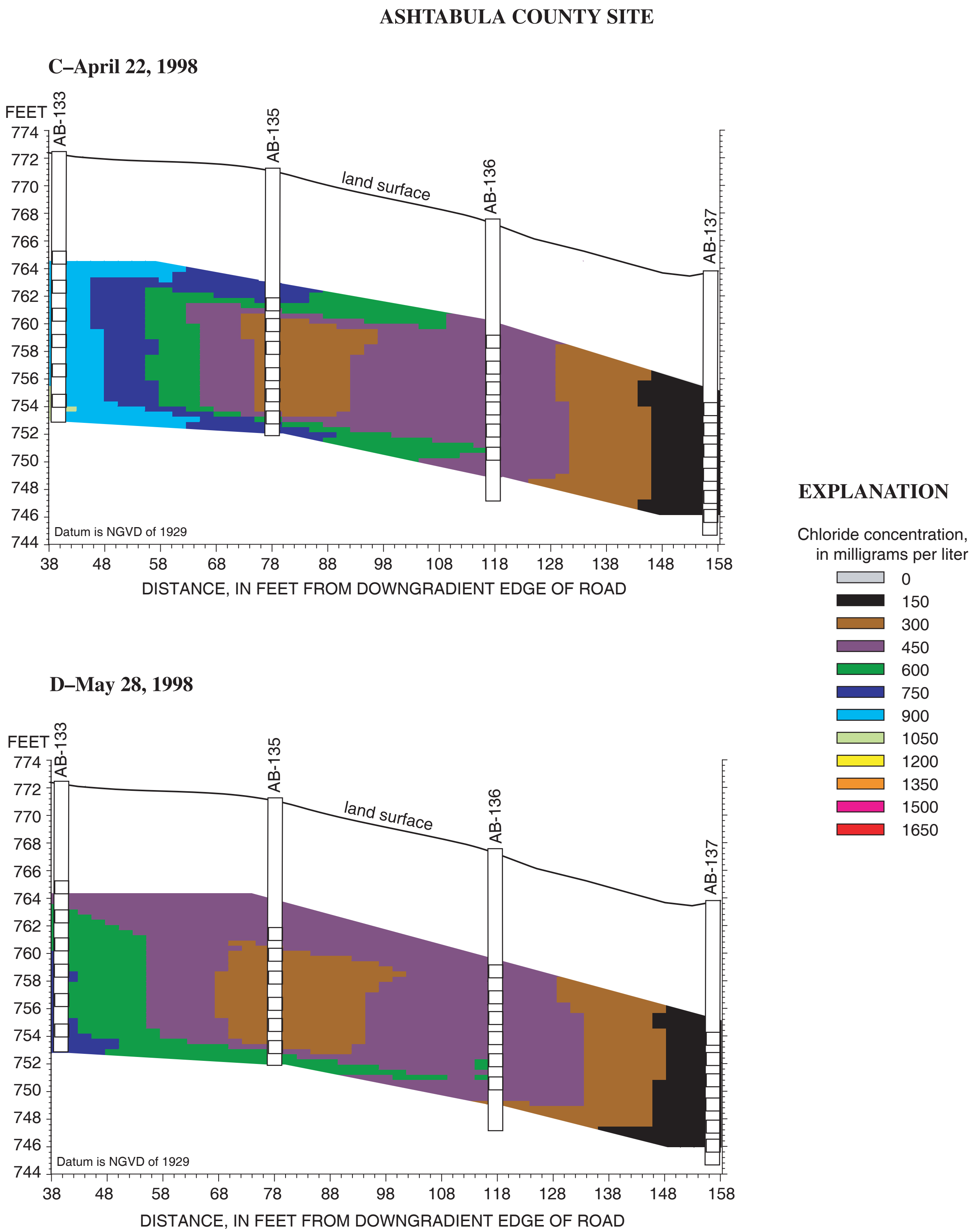


Figure 15. Profiles of chloride concentrations at the study site in Ashtabula County, Ohio, January 7, 1998, through September 8, 1999.—Continued

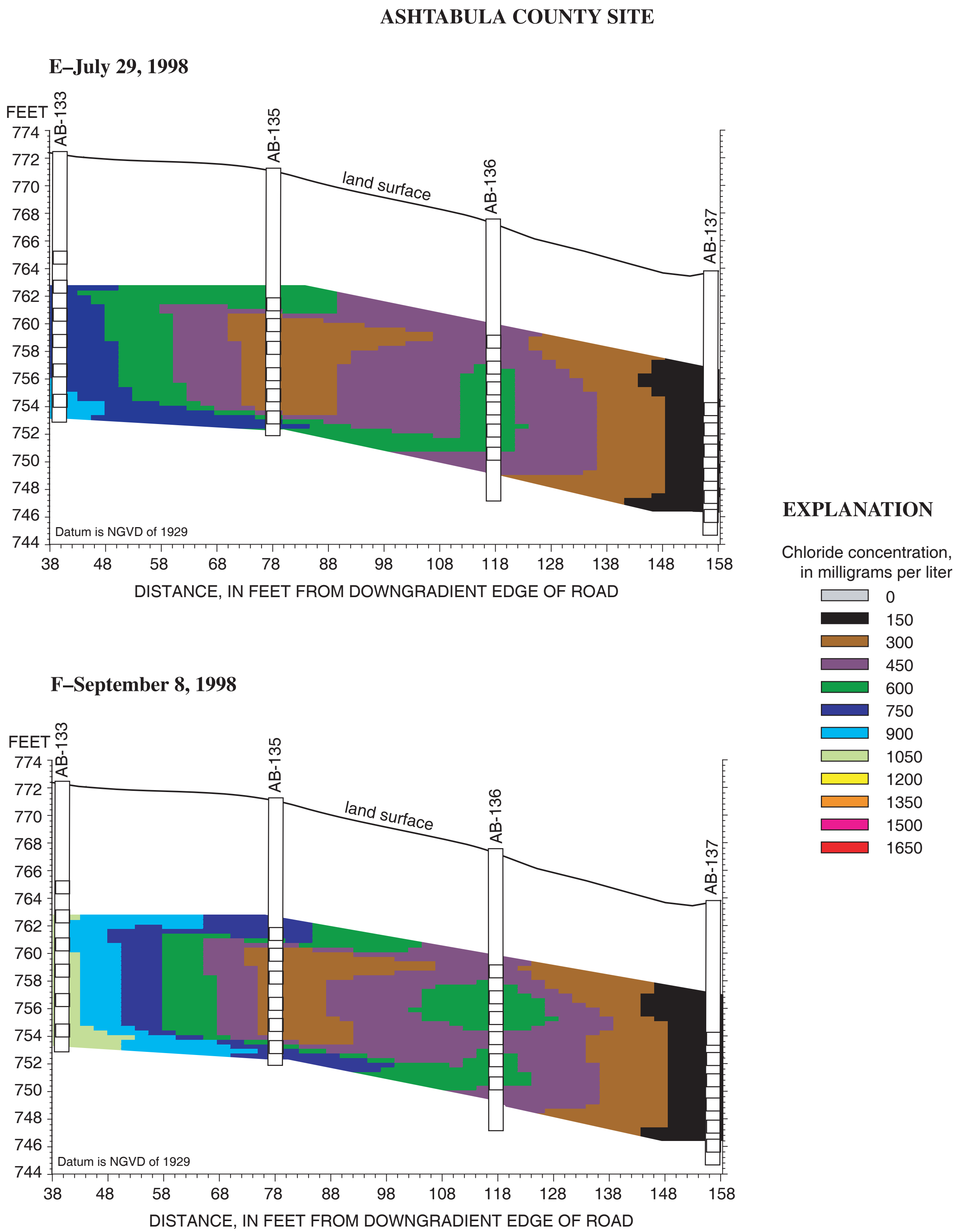


Figure 15. Profiles of chloride concentrations at the study site in Ashtabula County, Ohio, January 7, 1998, through September 8, 1999.—Continued

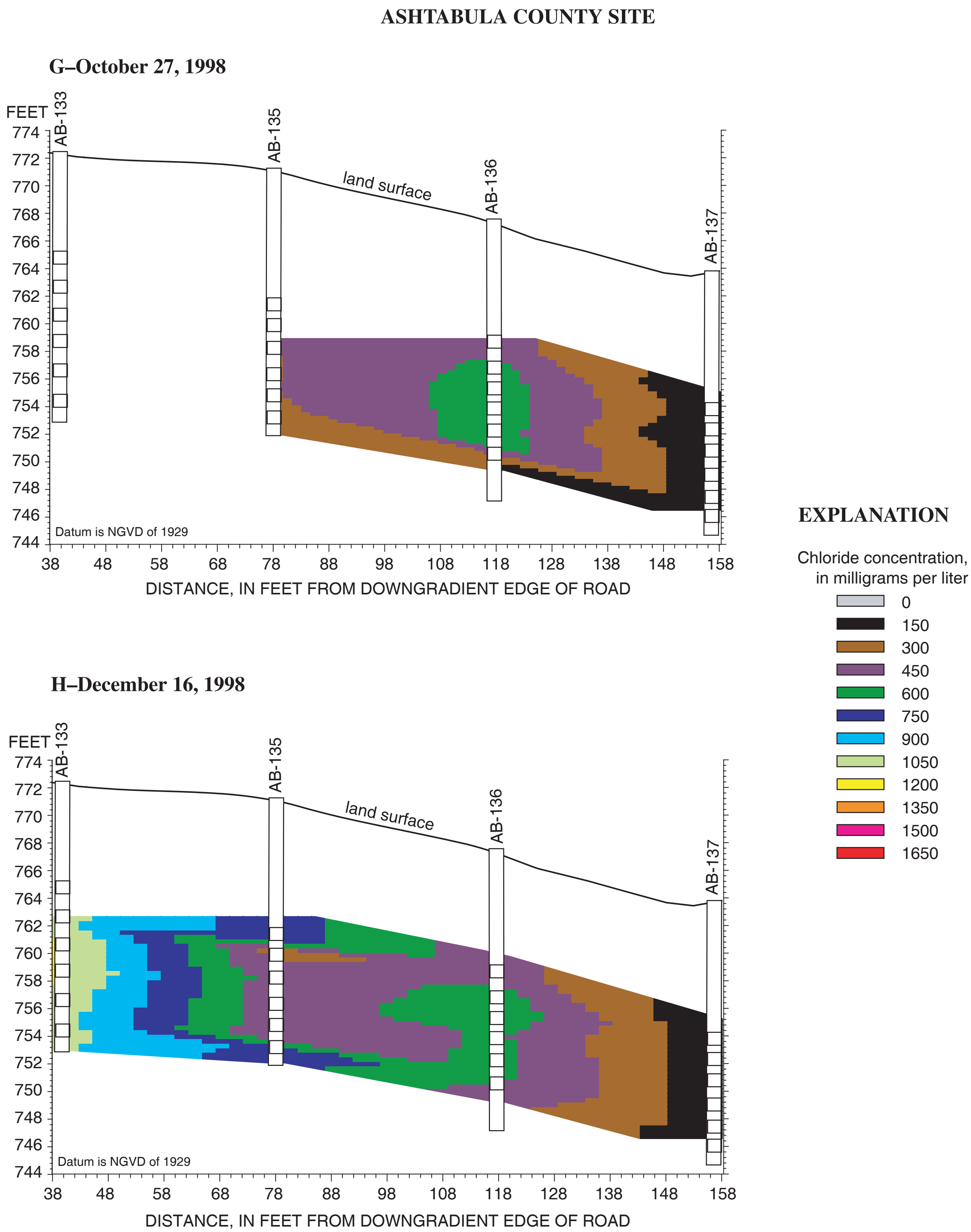
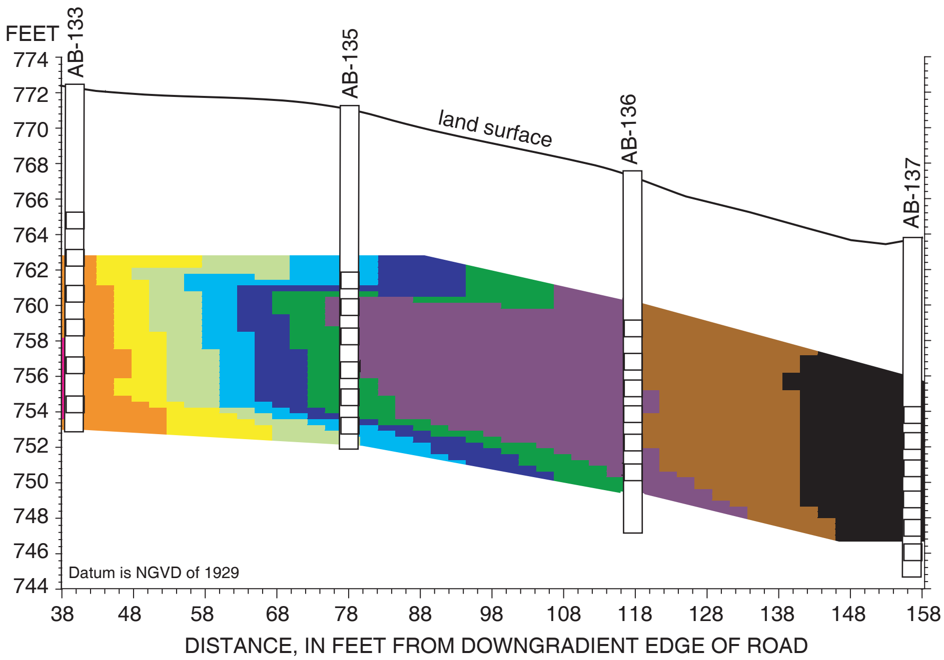


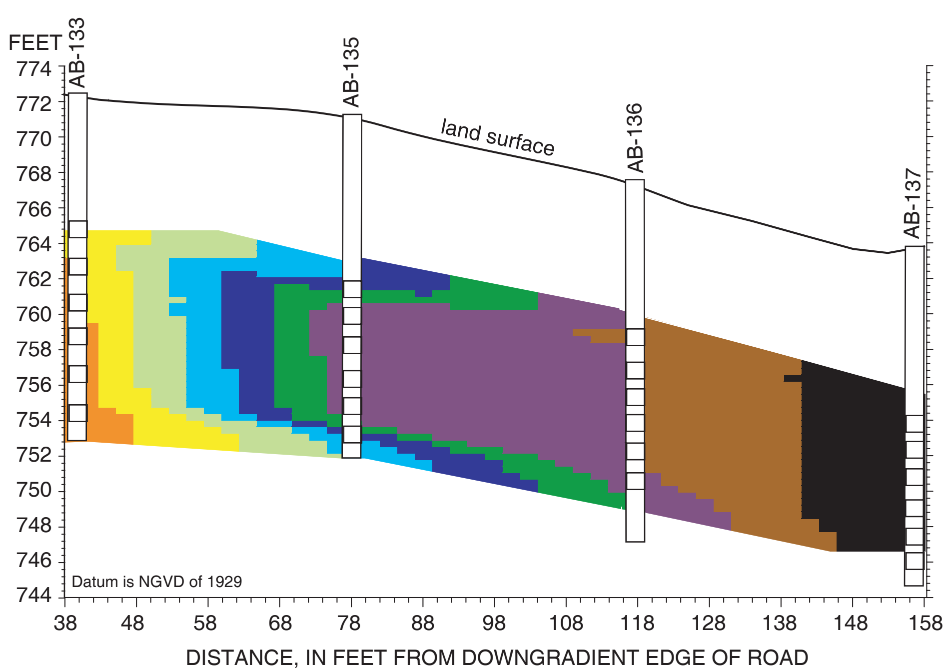
Figure 15. Profiles of chloride concentrations at the study site in Ashtabula County, Ohio, January 7, 1998, through September 8, 1999.—Continued

ASHTABULA COUNTY SITE

I–February 17, 1999



J–March 17, 1999



EXPLANATION

Chloride concentration, in milligrams per liter

- 0
- 150
- 300
- 450
- 600
- 750
- 900
- 1050
- 1200
- 1350
- 1500
- 1650

Figure 15. Profiles of chloride concentrations at the study site in Ashtabula County, Ohio, January 7, 1998, through September 8, 1999.—Continued

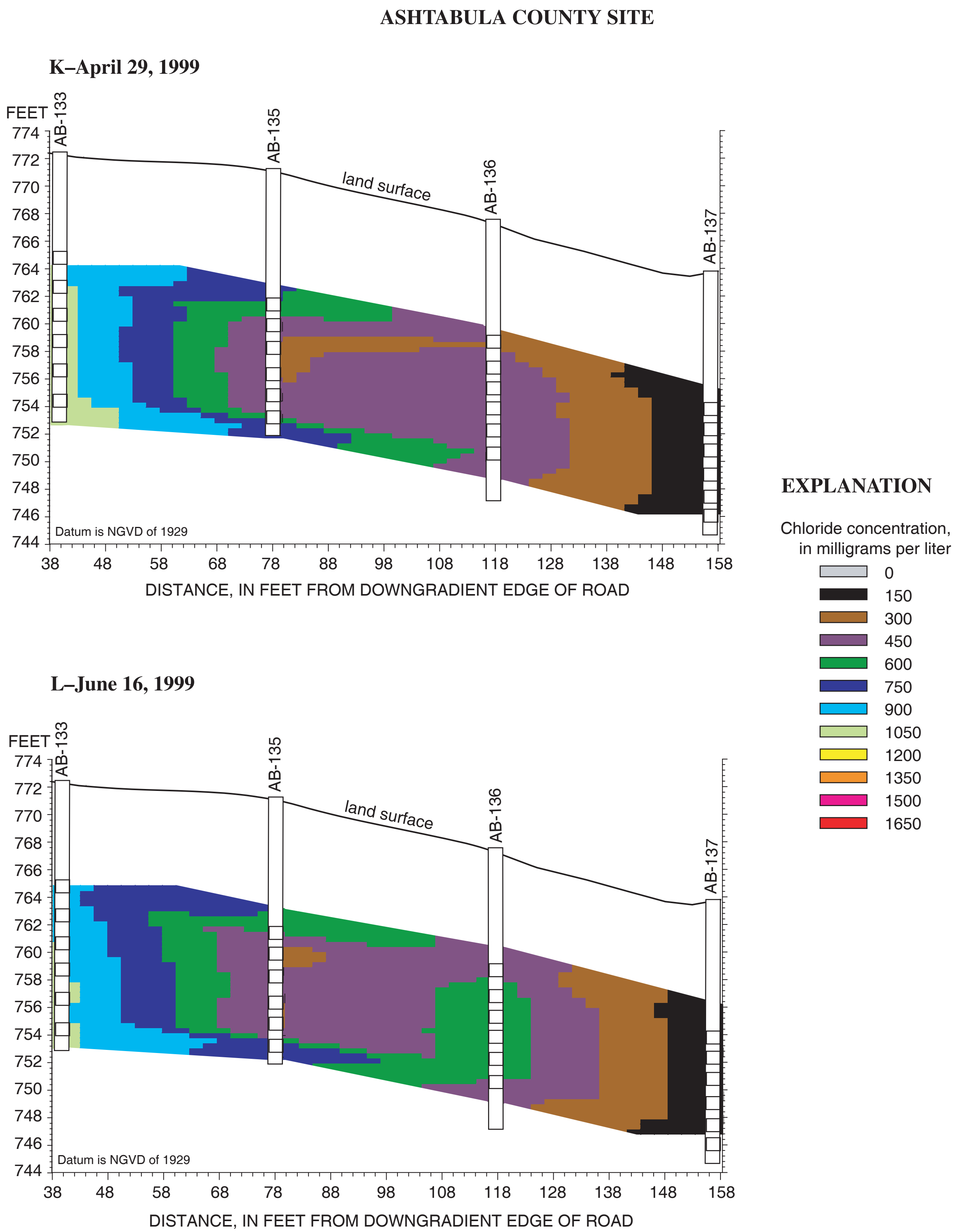


Figure 15. Profiles of chloride concentrations at the study site in Ashtabula County, Ohio, January 7, 1998, through September 8, 1999.—Continued

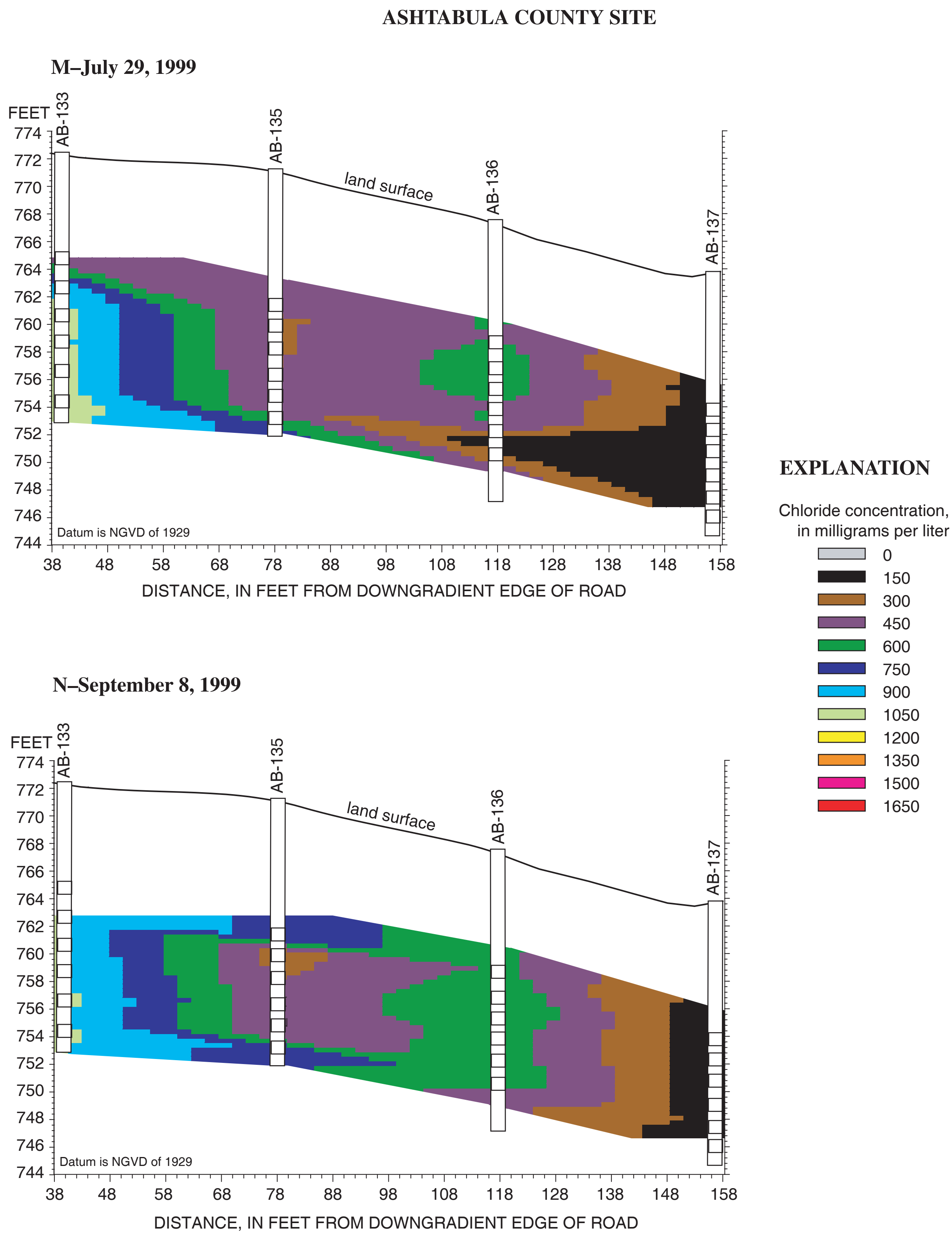


Figure 15. Profiles of chloride concentrations at the study site in Ashtabula County, Ohio, January 7, 1998, through September 8, 1999.—Continued

Champaign County Site

Site Characteristics

The Champaign County site (fig. 16) is on SR 29, 1 mi northwest of the SR 296 junction in Concord Township and 4.5 mi north-northwest of Urbana, Ohio. SR 29 has second-priority designation for ODOT deicing. This site is in the glacial Till Plains Section of the Central Lowland Physiographic Province (Fenneman, 1946). The site lies in an outwash plain of the Mad River, about 0.4 mi west of the river. Terrain at the site is fairly flat; slope of the area is only 1.4 ft over 170 ft, or 0.008. On the upgradient side, there is a slight depression about 300 ft from the highway. The upgradient side of the highway is in continual crop rotation of either corn or soybeans. The downgradient side also is in crops and is adjacent to a rural home surrounded by mowed lawn and a hog farm about 150 ft to the north.

SR 29 is a two-lane, undivided highway that runs northwest to southeast. Drainage is by shallow, open ditches. Total pavement width, including shoulders, is 25.5 ft; the gravel berm is 3-4 ft wide. The highway is very flat and straight at this site, but it begins a bend about 0.1 mi north of the site.

The soil type is the Homer silt loam upgradient and near the road downgradient, and the Lippincott Silty Clay loam farther downgradient (U.S. Department of Agriculture, 1971). Underlying material consists of fine to coarse sand with small gravel and medium to large cobbles. Bedrock consists of Silurian limestone with some shale. No well logs in the area could be found to help verify the elevation of the bedrock surface specifically at this site; however, seismic surveys done in the county by Feulner (1960) indicate a bedrock-surface elevation about 240 ft below land surface. Both loams are fairly poorly drained soils. An individual well log was constructed for each of the wells. A geologic section of the site was constructed on the basis of these logs (fig. 17).

The nine-winter (1990–99) average annual use of sodium chloride in Champaign County, as a whole, was 2,229 tons (table 1). The maximum for this nine-winter period was 3,882 tons in 1998–99, and the minimum for this period was 1,289 tons in 1994–95. Data collected at this site (table 8) indicate the nine-winter average annual use of sodium chloride was 2.55 ton/2-ln mi (5,094 lb/2-ln mi), which is 74 percent less than the State average of 9.7 ton/2-ln mi (19,380 lb/2-ln mi) (Ohio Department of Transportation, written commun., 1999). In addition to sodium chloride and abrasives, a small amount of liquid calcium chloride ($CaCl_2$) also was applied to the highway in approximately 2.4 percent of the treatments during the study period.

Climate

Average annual precipitation for the area is 38.4 in. (table 3). Average annual temperature for the area is 9.6° C (49.3° F), with the monthly normal high of 28.9° C (84.0° F) in July and the monthly normal low of -9.6° C (14.7° F) in January (Midwestern Regional Climate Center, 2000). Annual precipitation based on data collected at the site, as well as precipitation at the nearest NOAA site, is listed by water year in the table below. Average annual normal snowfall is 13.4 in., whereas the annual snowfall during the study period averaged 22.9 in. for nearby reporting areas (Midwestern Regional Climate Center, 2000).

Champaign County site		
Water year	Onsite precipitation (inches)	Nearest NOAA site[1] precipitation (inches)
1991	[2]13.13	[2]23.29
1992	[3]32.50	42.83
1993	25.41	45.06
1994	14.12	30.09
1995	[3]14.50	46.07
1996	[3]6.33	51.84
1997	[3]32.71	[3]43.82
1998	[3]18.16	40.71
1999	29.17	40.25

[1] Refer to table 2 for site name.

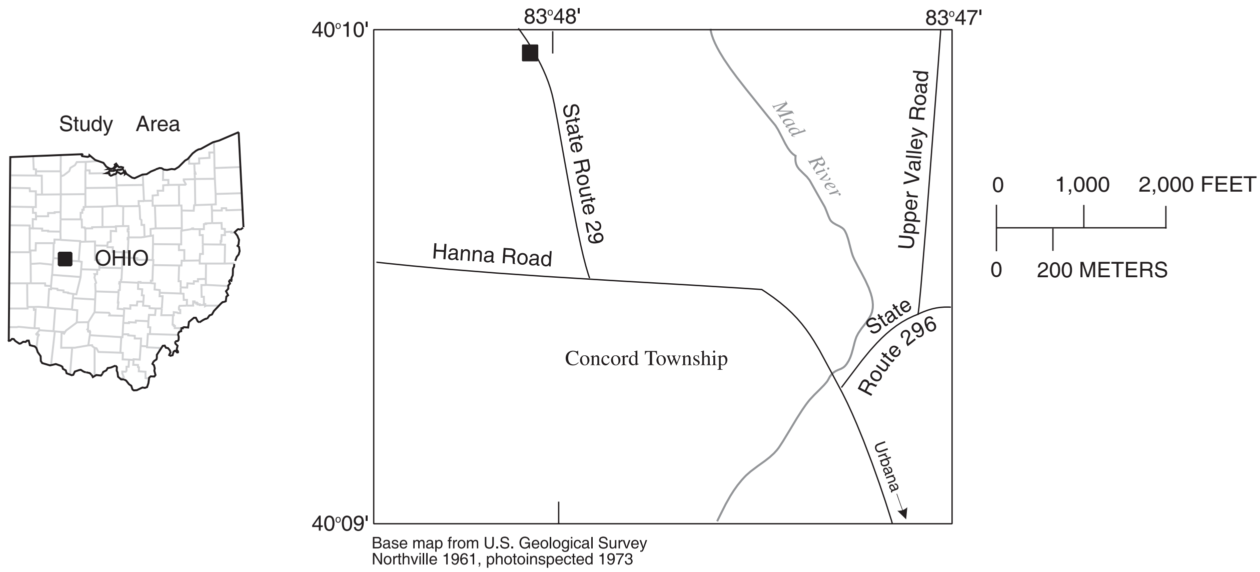
[2] No measurements made until February 1991.

[3] Incomplete data.

Hydrogeology

The ground-water level ranged from 4.6 to 10.6 ft below land surface during the study period at this site (table 3). During the study period, the direction of flow varied from approximately 19° to 27° to the alignment of the highway, as determined by the triangulation method using available wells; average water-table gradient is about 0.002. Additional data regarding water-table gradient and flow direction can be found in the appendix in table A-3.

Results of single-well aquifer tests (slug tests) on the aquifer indicate that the hydraulic conductivity is 47.4 ft/d. Assuming an average gradient of 0.002 and an effective porosity of 35 percent, the ground-water velocity was computed to be 0.27 ft/d. At this site, the ground-water level responds to precipitation within 1 day, a result of the porous aquifer materials at the surface.



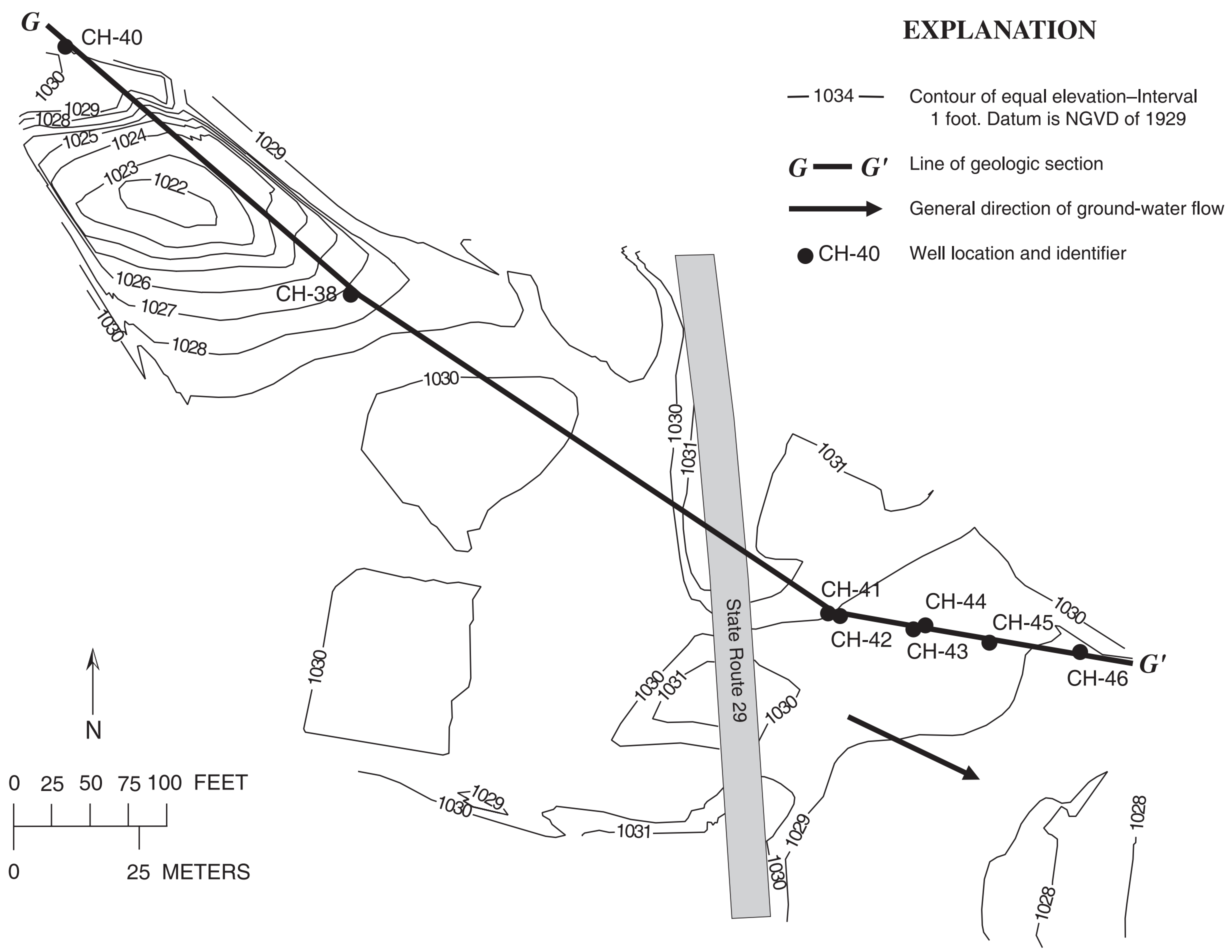


Figure 16. Topography, well locations, and ground-water flow direction at Champaign County, Ohio, study site.

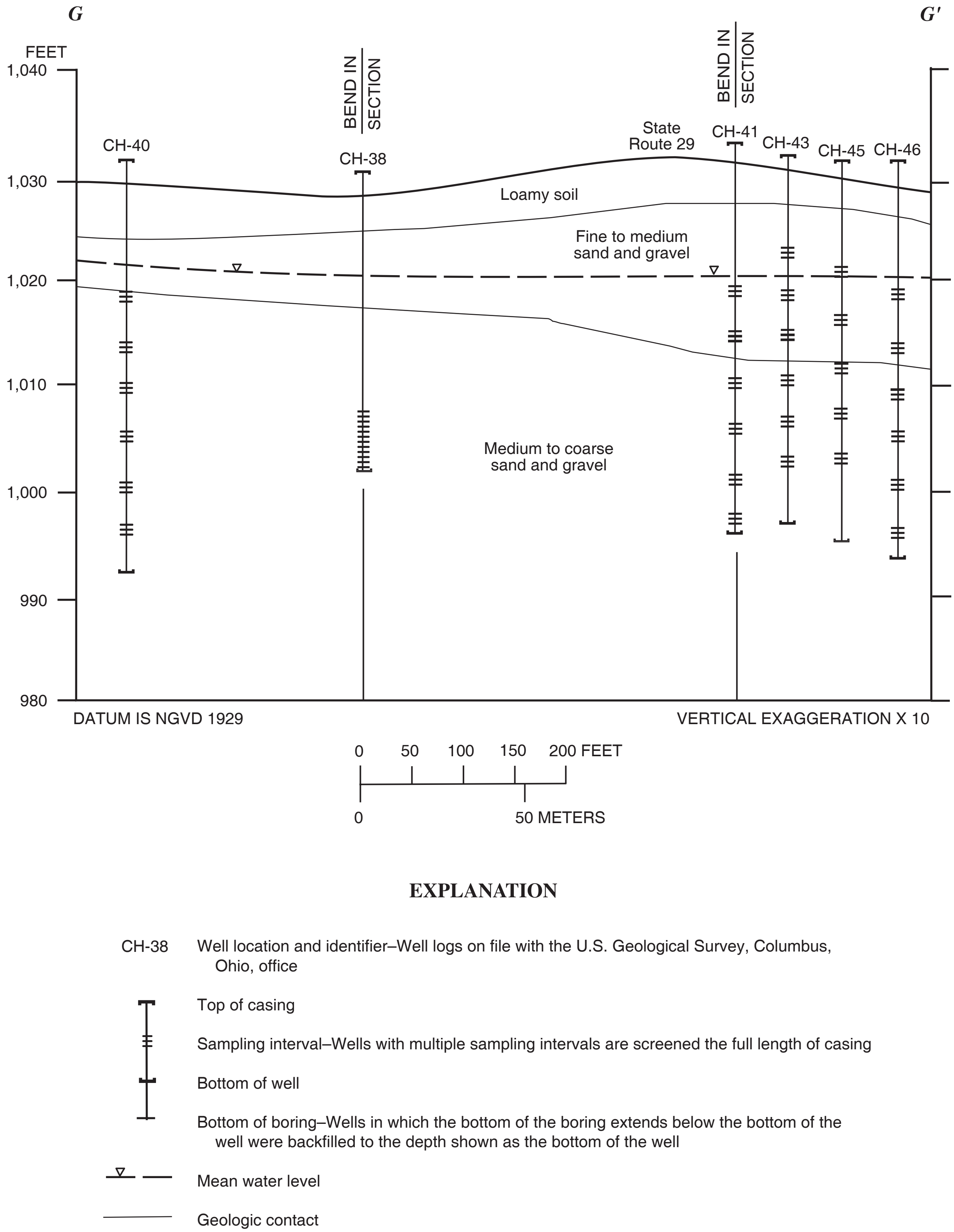


Figure 17. Geologic section *G-G′*, Champaign County, Ohio, study site. (Section trace shown in fig. 16.)

Table 8. Sodium chloride application amounts by month and year, Champaign County, Ohio, study site.

[Amounts measured by pounds per 2-lane mile]

	October	November	December	January	February	March	April	Yearly total
1990-91	0	0	1,330	6,350	1,190	150	0	9,020
1991-92	0	475	0	2,600	0	0	0	3,075
1992-93	0	0	500	928	1,505	200	0	3,133
1993-94	0	0	400	2,133	400	0	0	2,933
1994-95	0	0	0	2,150	1,000	0	0	3,150
1995-96	0	200	3,300	2,800	200	2,800	0	9,300
1996-97	0	400	907	2,800	1,007	0	0	5,114
1997-98	0	400	0	1,125	195	0	0	1,720
1998-99	0	0	1,000	6,800	600	0	0	8,400
Total	0	1,475	7,437	27,686	6,097	3,150	0	45,845
Average	0	164	826	3,076	677	350	0	5,094

Effects of Highway Deicing Chemicals on Water Quality

Field-monitored characteristics (rainfall, specific conductance, and ground-water levels recorded from dedicated instrumentation at a well near the first downgradient sampling well) and the amount of sodium chloride applied to the highway are shown in figure 18. The amount of sodium chloride applied to the highway adjacent to the site, as recorded by each ODOT outpost driver, is listed in table 8. Plots of these characteristics can be used to help compare application events that resulted in increased specific conductance with ambient site conditions and deicer applications. Movement of chloride and other deicing-related constituents from the highway, with time, is indicated by boxplots of laboratory-determined data (figs. 19 and 20).

Field-Monitored Characteristics

Specific Conductance

Specific conductance of ground water varied only slightly during the study period (fig. 18). As is evident from the table to the right, specific conductance recorded continuously in well CH-42 near the first downgradient water-quality sampling well at this site ranged from a maximum of 919 μS/cm in 1994 to a minimum of 712 μS/cm in 1997 (range, 207 μS/cm). For comparison, the mean specific conductance at the upgradient well for the study period was 693 μS/cm (table 9).

Champaign County site; well CH-42		
Water year	Specific conductance, maximum (μS/cm)	Specific conductance, minimum (μS/cm)
1991	[1]852	1,735
1992	846	759
1993	918	780
1994	919	831
1995	854	765
1996	911	746
1997	862	712
1998	846	721
1999	865	780

[1] No measurements made until February 1991.

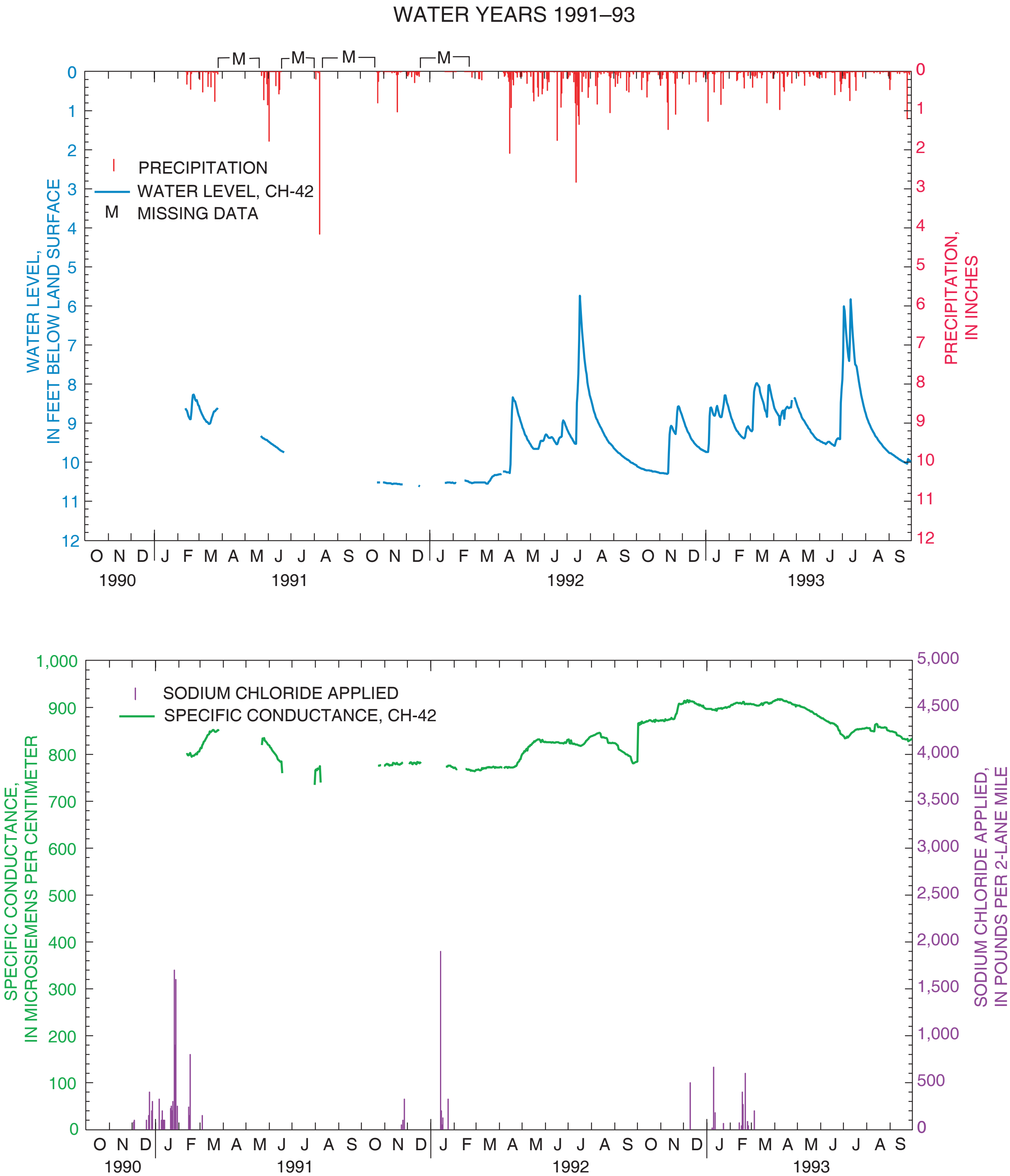


Figure 18. Ground-water levels, precipitation, specific conductance, and sodium chloride application, Champaign County, Ohio, study site, water years 1991-99.

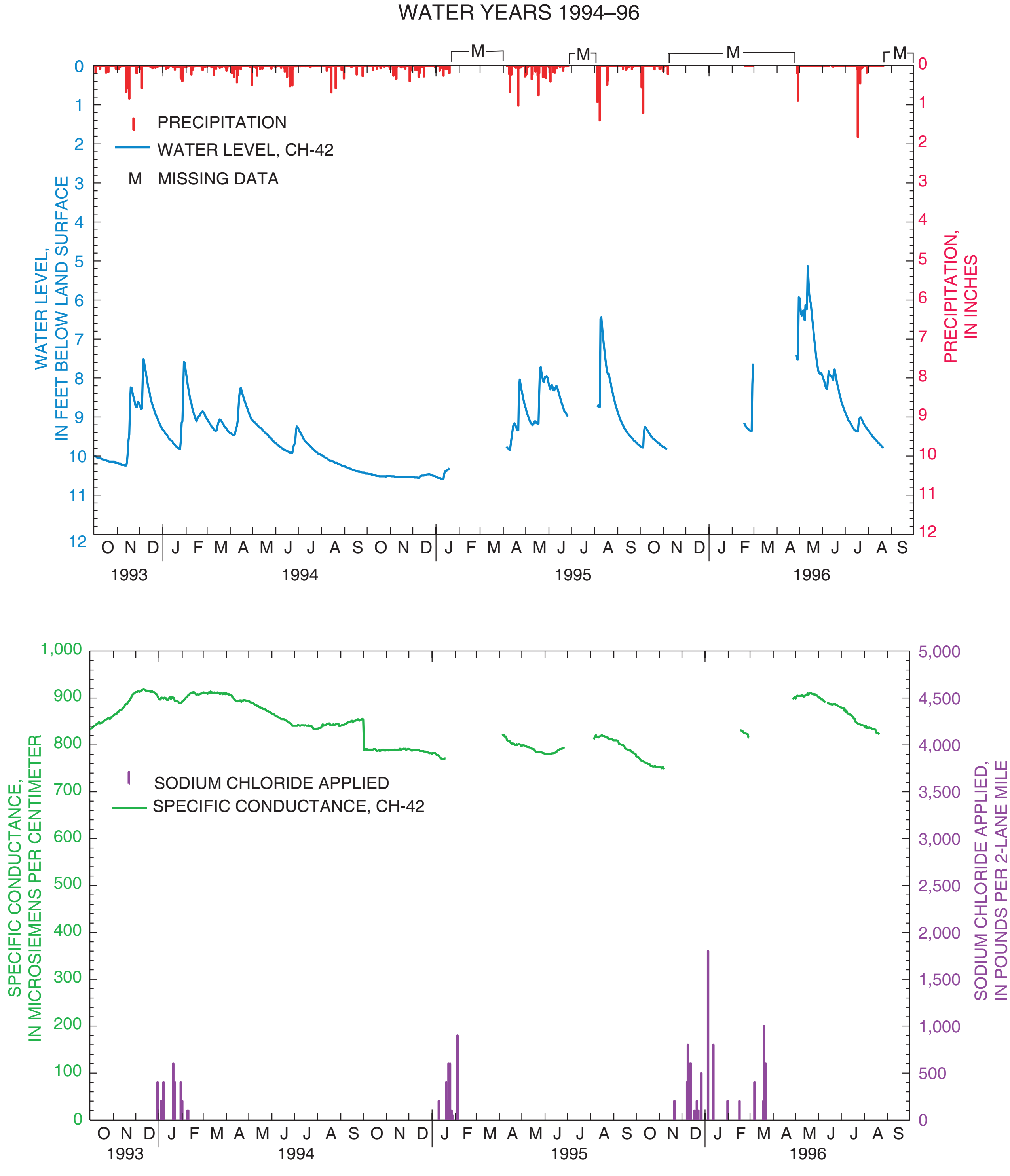


Figure 18. Ground-water levels, precipitation, specific conductance, and sodium chloride application, Champaign County, Ohio, study site, water years 1991-99.—Continued

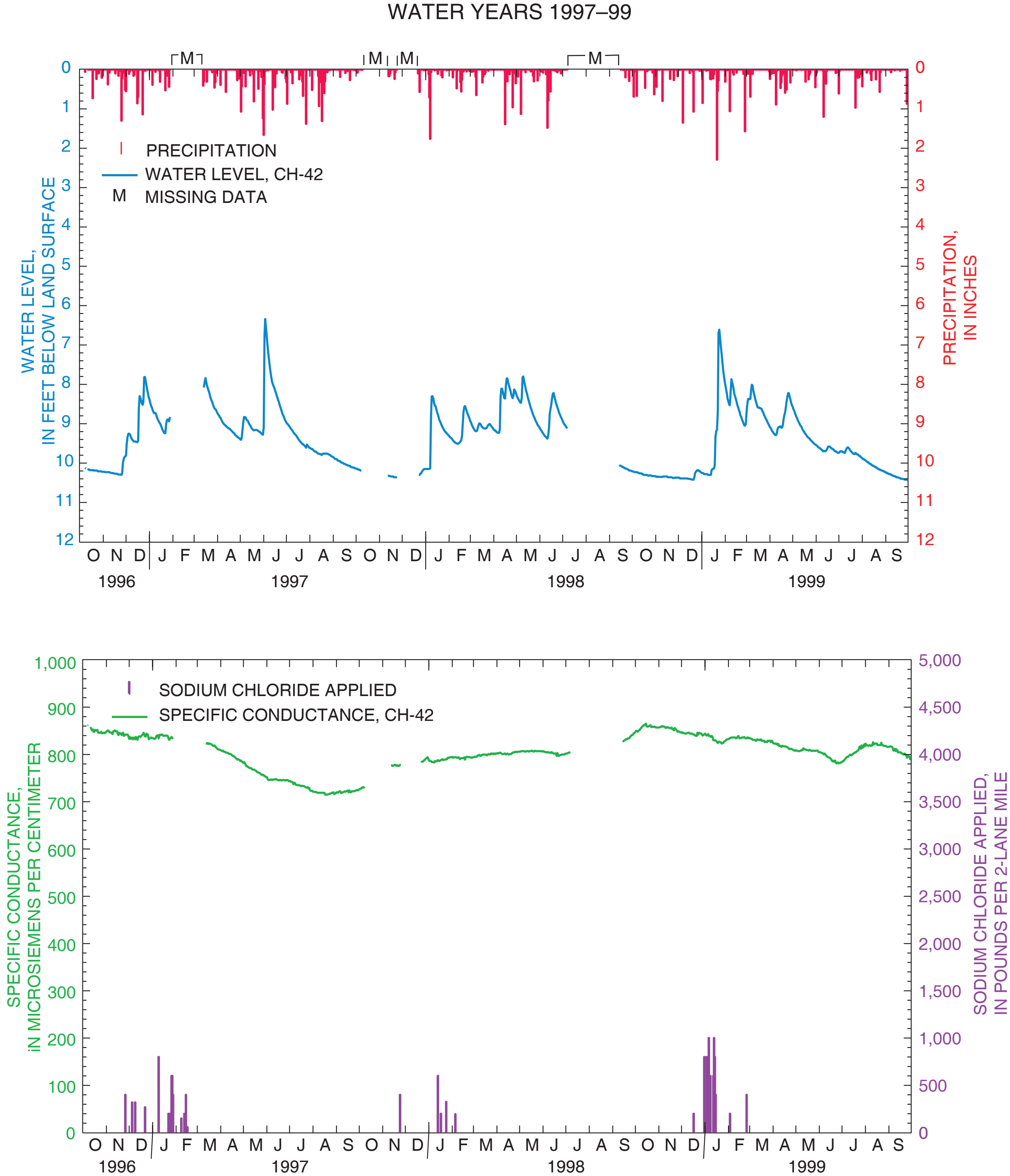


Figure 18. Ground-water levels, precipitation, specific conductance, and sodium chloride application, Champaign County, Ohio, study site, water years 1991-99.—Continued

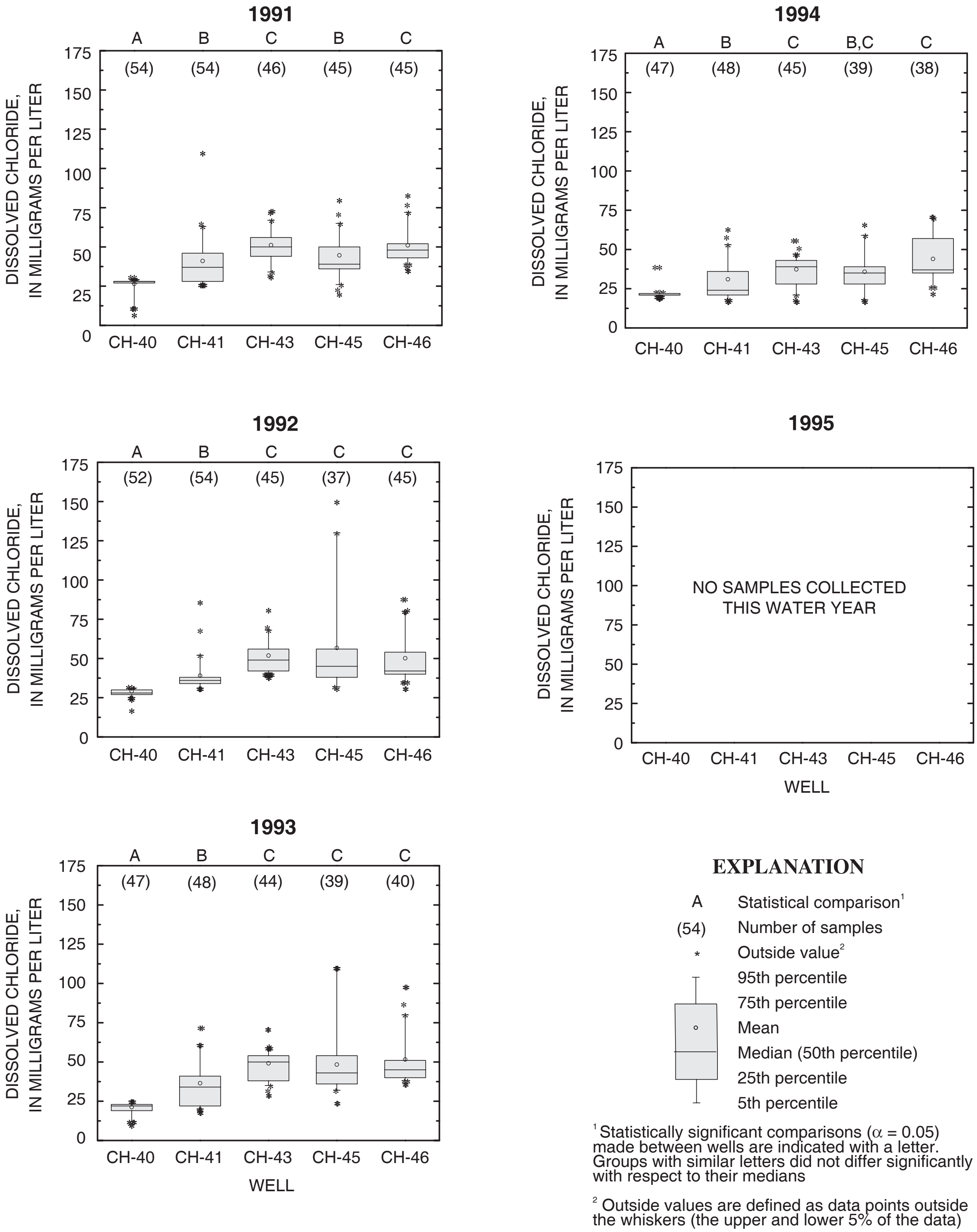


Figure 19. Distribution of concentrations of dissolved chloride in ground-water samples, Champaign County, Ohio, study site, January 1991-September 1999. (Plots are shown in downgradient order from left to right. Far left plot is upgradient from highway; others are downgradient.)

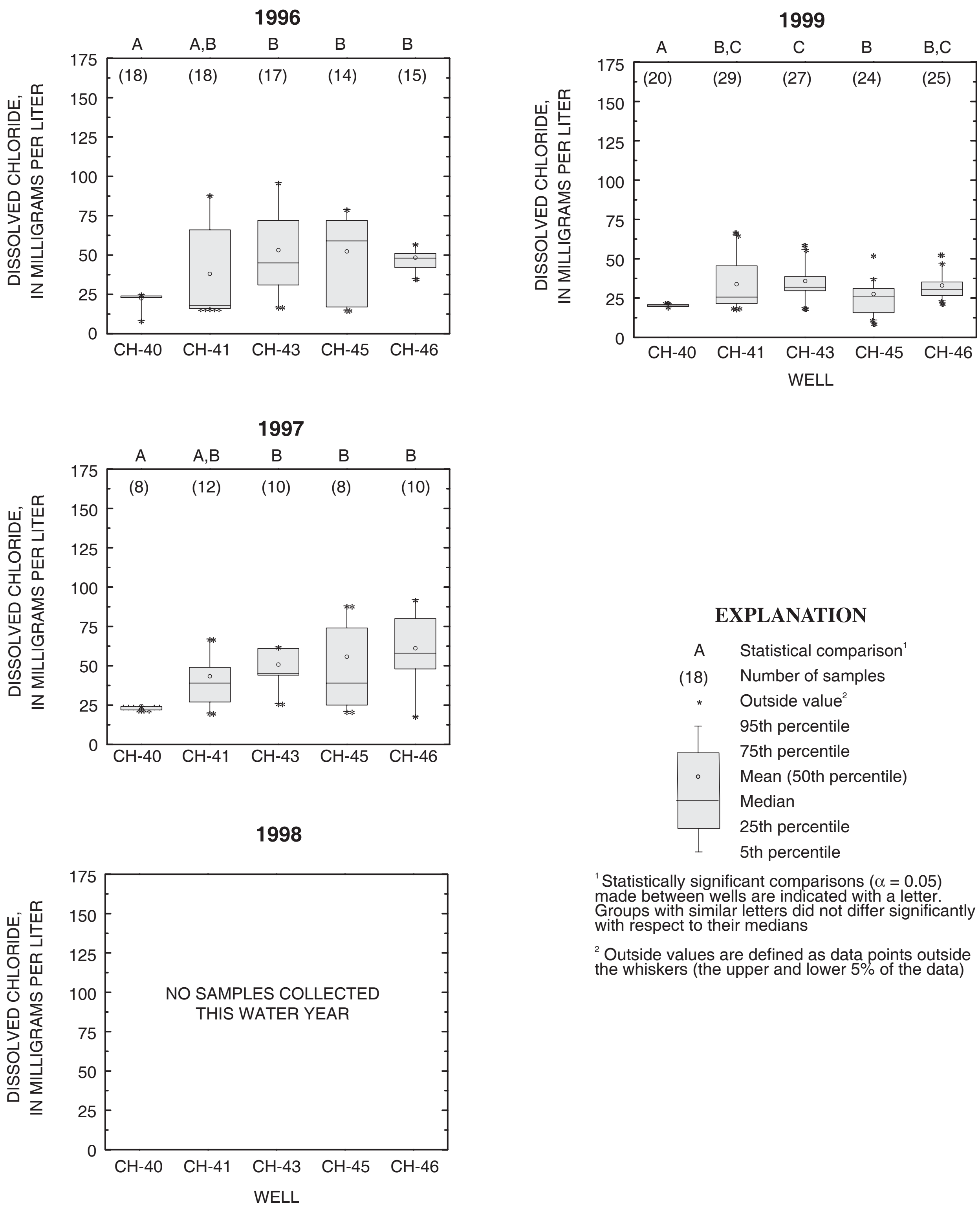


Figure 19. Distribution of concentrations of dissolved chloride in ground-water samples, Champaign County, Ohio, study site, January 1991-September 1999. (Plots are shown in downgradient order from left to right. Far left plot is upgradient from highway; others are downgradient.)—Continued

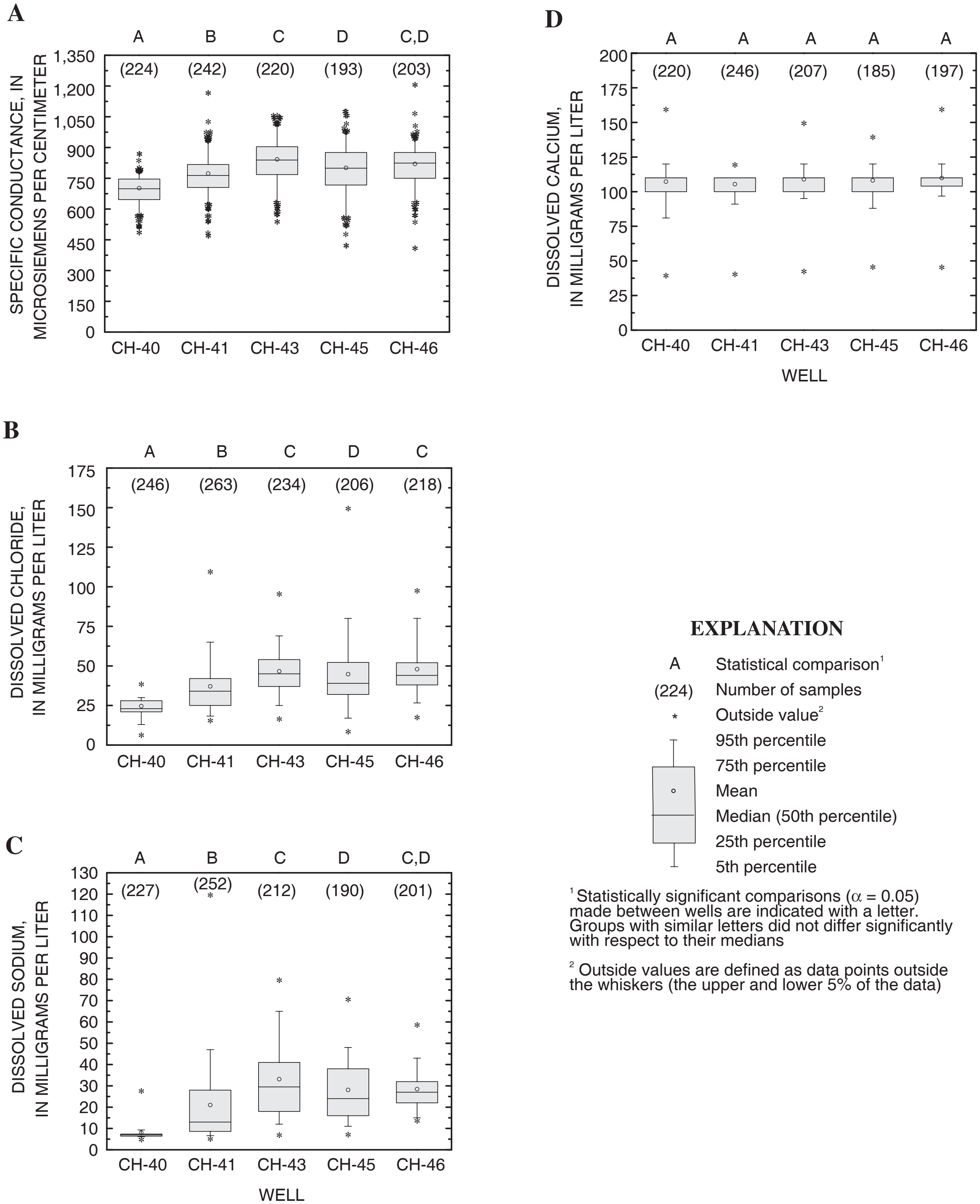


Figure 20. Distribution of (*A*) specific conductance and concentrations of dissolved (*B*) chloride, (*C*) sodium, and (*D*) calcium in ground-water samples, Champaign County, Ohio, study site, January 1991-September 1999. (Plots are shown in downgradient order from left to right. Far left plot is upgradient from the highway; others are downgradient.)

Table 9. Water-quality data for multilevel wells, Champaign County, Ohio, study site, water years 1991-99.

[μS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (μS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
CH-40	Upgradient	Maximum	873	160	28	39
		Minimum	490	40	5	7
		Mean	693	106	7	23
		Median	700	110	7	23
		N	224	220	227	246
CH-41	1st downgradient	Maximum	1,170	120	120	110
		Minimum	474	41	6	16
		Mean	764	104	20	36
		Median	764	110	13	34
		N	242	246	252	263
CH-43	2nd downgradient	Maximum	1,060	150	80	96
		Minimum	542	43	7	17
		Mean	833	108	32	45
		Median	840	110	30	45
		N	220	207	212	234
CH-45	3rd downgradient	Maximum	1,080	140	71	150
		Minimum	426	46	8	9
		Mean	792	107	27	44
		Median	799	110	24	39
		N	193	185	190	206
CH-46	4th downgradient	Maximum	1,210	160	59	98
		Minimum	413	46	14	18
		Mean	811	108	23	47
		Median	824	110	27	44
		N	203	197	201	218

Air and Soil Temperature

During the study period, air temperature at this site varied from 39.9° C in 1999 to a minimum of -33.6° C in 1994.

Champaign County site		
Water year	Air temperature, maximum (° C)	Air temperature, minimum (° C)
1991	[1]37.0	[1]0.0
1992	30.7	-14.8
1993	35.0	-22.2
1994	37.6	-33.6
1995	37.1	-19.3
1996	33.2	-20.1
1997	33.8	-22.2
1998	33.6	-15.0
1999	39.9	-24.6

[1] No measurements made until February 1991.

During the study period, soil temperature ranged from a maximum of 30.5° C in 1991 to a minimum of -1.8° C in 1994.

Champaign County site		
Water year	Soil temperature, maximum (° C)	Soil temperature, minimum (° C)
1991	[1]30.5	[1]0.0
1992	24.3	0.7
1993	24.8	0.3
1994	28.0	-1.8
1995	23.9	-0.3
1996	23.9	-0.2
1997	25.2	0.4
1998	24.7	2.5
1999	29.9	1.6

[1] No measurements made until February 1991.

Laboratory-Determined Characteristics

At the Champaign County site, deicing chemicals were applied in relatively small amounts compared to other sites (table 8). Snowfall was generally light and winters mild and, in some cases, sampling was discontinued temporarily when little or no deicing chemicals were applied. Cold temperatures sometimes created icy conditions, but large snowfalls were uncommon. Summary statistics of the water-quality data collected at upgradient and downgradient wells for all 7 years sampled during 1991–99 are listed in table 9. These same statistics for each year individually are listed in the appendix in table A-6. Boxplots of chloride concentration data collected at upgradient and downgradient wells for each of the 7 years individually are shown in figure 19. Boxplots of specific conductance, dissolved calcium, dissolved sodium, and dissolved chloride for water from all levels of the upgradient well and the four downgradient sampling wells for 1991–99 combined are shown in figure 20. Patterns that emerge from those data are noted below.

Specific Conductance

At the upgradient well, CH-40, the mean specific conductance was 693 µS/cm, and the maximum was 873 µS/cm (table 9, fig. 20A). Of the downgradient wells, mean values were lowest at the first downgradient well (764 µS/cm), increased slightly at the second downgradient well (833 µS/cm), decreased at the third (792 µS/cm), and increased slightly again at the fourth (811 µS/cm) downgradient well. Therefore, 228 ft downgradient from the highway, the mean specific conductance at the fourth downgradient well was about 1.2 times the upgradient or background concentration.

Chloride Concentration

At the upgradient well, CH-40, the mean concentration of chloride was 23 mg/L, and the maximum was 39 mg/L (table 9, fig. 20B). Mean concentrations were 1.5 to 2 times greater at the downgradient wells (36–47 mg/L). Maximum concentrations at the four downgradient wells ranged from 96 to 150 mg/L. Thus, 228 ft downgradient from the highway, the mean concentration at the fourth downgradient well (47 mg/L) was about twice the upgradient or background concentration.

Dissolved-chloride concentrations at six sampling levels in each downgradient well at the site during a 6-month period in 1992 are represented as a series of chloride profiles in figure 21. (Each color in the profile represents an additional 15 mg/L of chloride.) This series of profiles shows how chloride moved through the aquifer after deicing chemicals were applied in January 1992 (fig. 18). The amount and frequency of precipitation and snowmelt recharge and the soil temperature also affected chloride movement during this time period. In general, only minor amounts of deicing materials were applied at this site. For a short time in January 1992, however, deicing material application was relatively concentrated. Increased precipitation in the following months corresponded to increased water level. The resulting pattern of chloride concentrations is shown in the profile plots on figure 21. The surficial material at this site is a fine to coarse sand with small to large gravel and cobbles that may contribute to a preferential flowpath between the highway and the third and fourth downgradient wells, but the vertical distribution of chloride concentration is clearly evident with the multilevel wells. From April through June 1992 (figs. 21C, D, E), a distinct plume with a maximum chloride concentration of 150 mg/L can be seen; the plume is then diluted as it moves through the aquifer.

Soil samples were collected on eight occasions at this site during 1993–99 (table A-2). The range of chloride concentration of the samples collected from the ditch along the highway was 5–230 mg/L and decreased to 3.5–17.5 mg/L by 80 ft downgradient from the highway. The data are listed in the appendix in table A-2.

Sodium Concentration

At the upgradient well, CH-40, the mean concentration of sodium was 7 mg/L, and the maximum was 28 mg/L (table 9, fig. 20C). Concentrations were generally higher at the four downgradient wells (mean, 20–32 mg/L; maximum, 59–120 mg/L). Concentrations increased slightly along the flowpath to the second downgradient well and then decreased slightly at the third and fourth downgradient wells. At the third and fourth downgradient wells, CH-45 and CH-46, the mean concentration was 27 mg/L and 23 mg/L, respectively, and the maximum concentrations were 71 mg/L and 59 mg/L, respectively. Thus, 228 ft downgradient from the highway, the mean concentration at the fourth downgradient well was about 3 times the upgradient or background concentration.

Calcium Concentration

During the study period, liquid calcium chloride ($CaCl_2$) was applied to the highway during two applications in addition to sodium chloride and abrasives. The calcium concentration at the upgradient well, CH-40, (mean, 106 mg/L, table 9, fig, 20D) stayed about the same downgradient to the furthest well, CH-46, (mean, 108 mg/L) (table 9, fig. 20D), with little concentration change along the way. The calcium present is likely due to natural presence in the glacial aquifer.

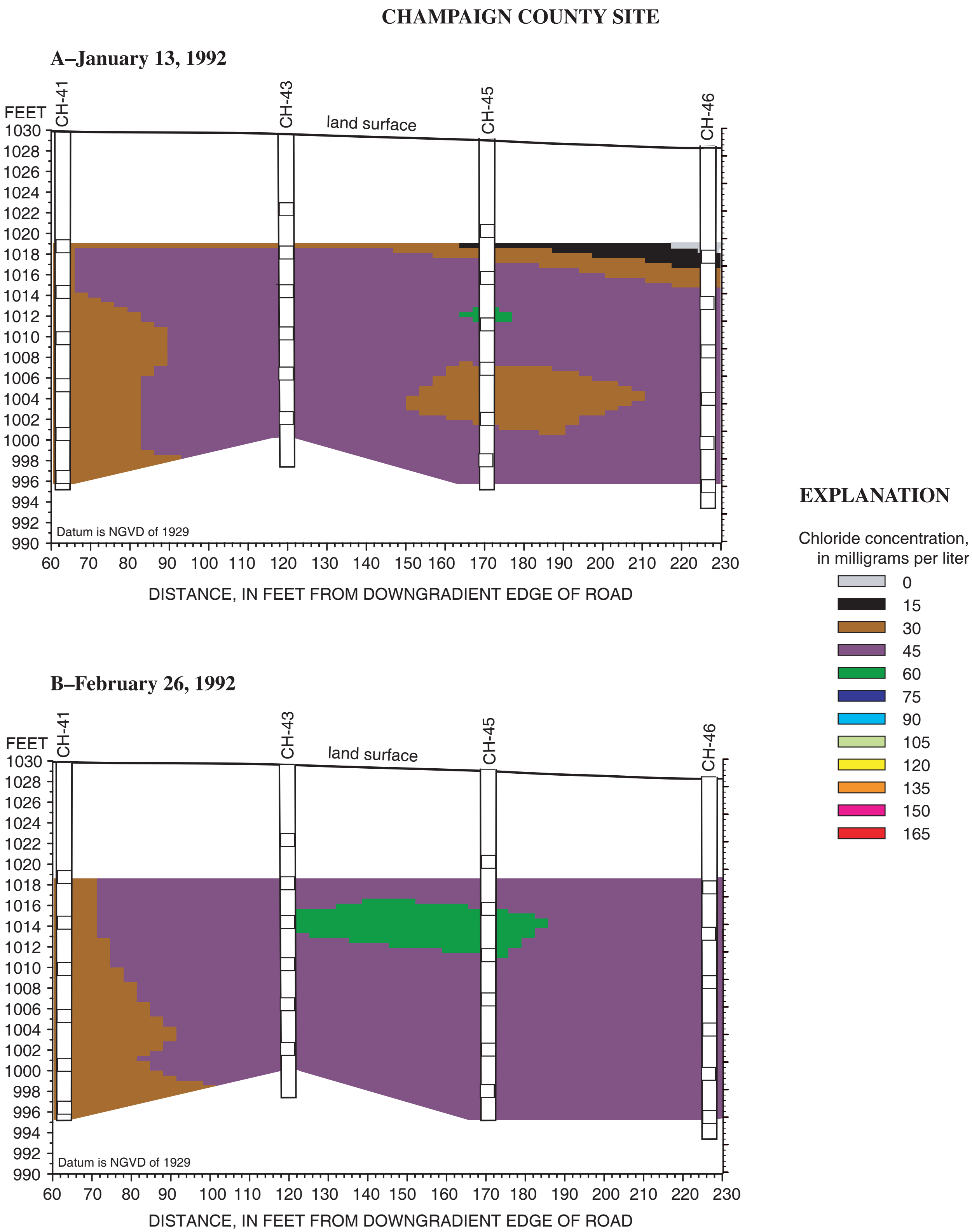


Figure 21. Profiles of chloride concentrations at the study site in Champaign County, Ohio, January 13, 1992, through June 30, 1992.

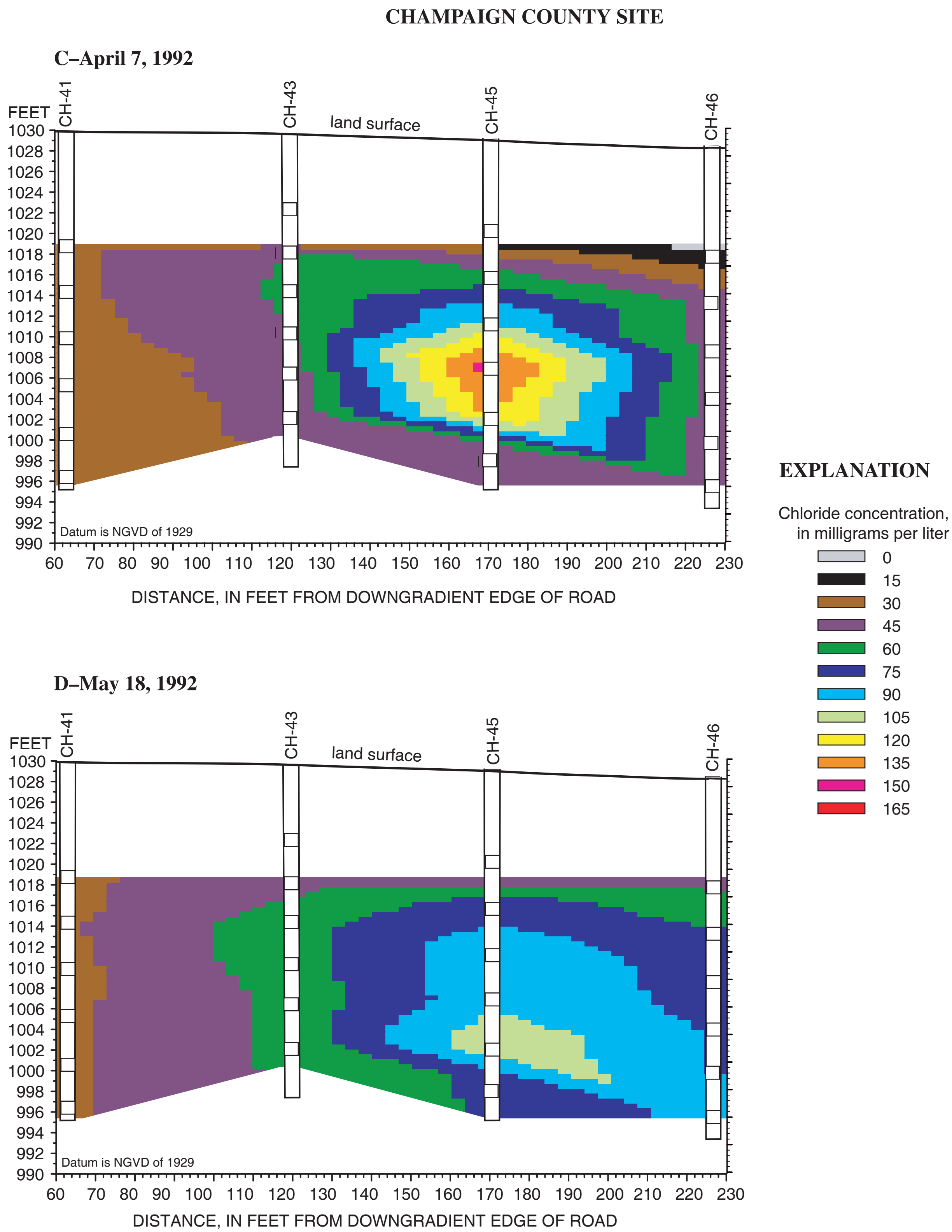


Figure 21. Profiles of chloride concentrations at the study site in Champaign County, Ohio, January 13, 1992, through June 30, 1992.—Continued

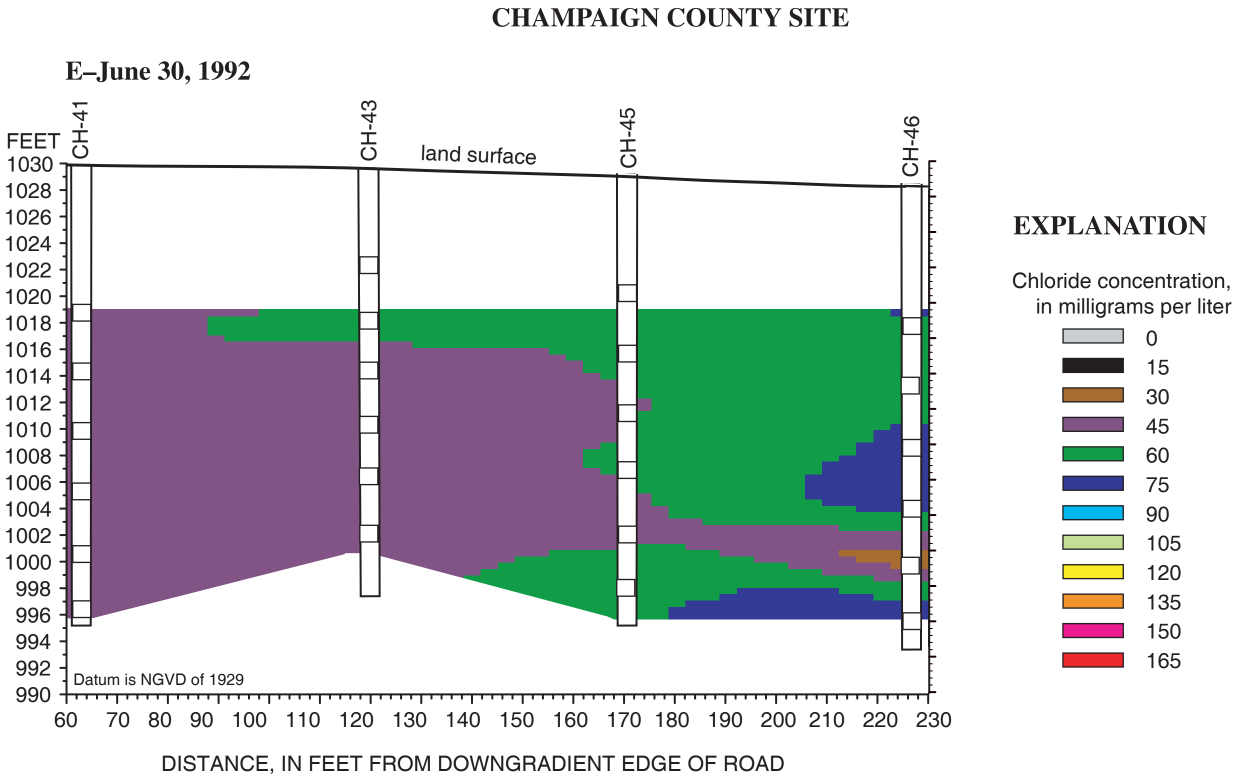


Figure 21. Profiles of chloride concentrations at the study site in Champaign County, Ohio, January 13, 1992, through June 30, 1992.—Continued

Clark County Site

Site Characteristics

The Clark County site (fig. 22) is on SR 4, near a fisherman's access road at Buck Creek State Park, 0.8 mi north of SR 334 in Moorefield Township near Springfield, Ohio. SR 4 has first-priority designation for ODOT deicing. This site is in the Till Plains Section of the Central Lowland Physiographic Province (Fenneman, 1946) and lies in a glacial outwash valley of a tributary (Buck Creek) of the Mad River. The slope of the area is 2.6 ft over 280 ft or 0.009. The downgradient side of the highway is an unused field (weeds and brush) that is part of Buck Creek State Park. The upgradient side is a mowed lawn near a private residence surrounded by woods.

SR 4 is a two-lane, undivided highway that runs southwest to northeast. Drainage is by shallow open ditches. Total pavement width, including shoulders, is 25.5 ft; the gravel berm is 3–4 ft wide. The highway is flat and straight at this site.

The soil type at this site is the poorly drained Sloan silt loam upgradient and the well-drained Fox silt loam downgradient (U.S. Department of Agriculture, 1958). Beneath the soil layer is medium to coarse sand with gravel and large cobbles. The bedrock is Cedarville Dolomite (Norris and others, 1952) at a depth of at least 160 ft below land surface, as inferred from well logs obtained by ODNR from an area within 0.4 mi of the site. Individual well logs were constructed for each of the wells. A geologic section of the site was constructed on the basis of these logs (fig. 23).

The nine-winter (1990–99) average annual use of sodium chloride in Clark County as a whole was 3,261 tons (table 1). The maximum for this nine-winter period was 4,971 tons in 1998–99, and the minimum for this period was 1,733 tons in 1993–94. Data collected at this site (table 10) indicate the nine-winter average annual use of sodium chloride was 2.74 ton/2-ln mi (5,478 lb/2-ln mi), which is 72 percent less than the State average of 9.7 ton/2-ln mi (19,380 lb/2-ln mi) (Ohio Department of Transportation, written commun., 1999). During the study period at this site, no calcium chloride ($CaCl_2$) was applied to the highway, although calcium chloride was applied in other areas of the county.

Climate

Average annual precipitation for the area is 38.4 in. (table 3). Average annual temperature for the area is 9.6° C (49.3° F), with the monthly normal high of 28.9° C (84.0° F) in July and the monthly normal low of -9.6° C (14.7° F) in January (Midwestern Regional Climate Center, 2000). Annual

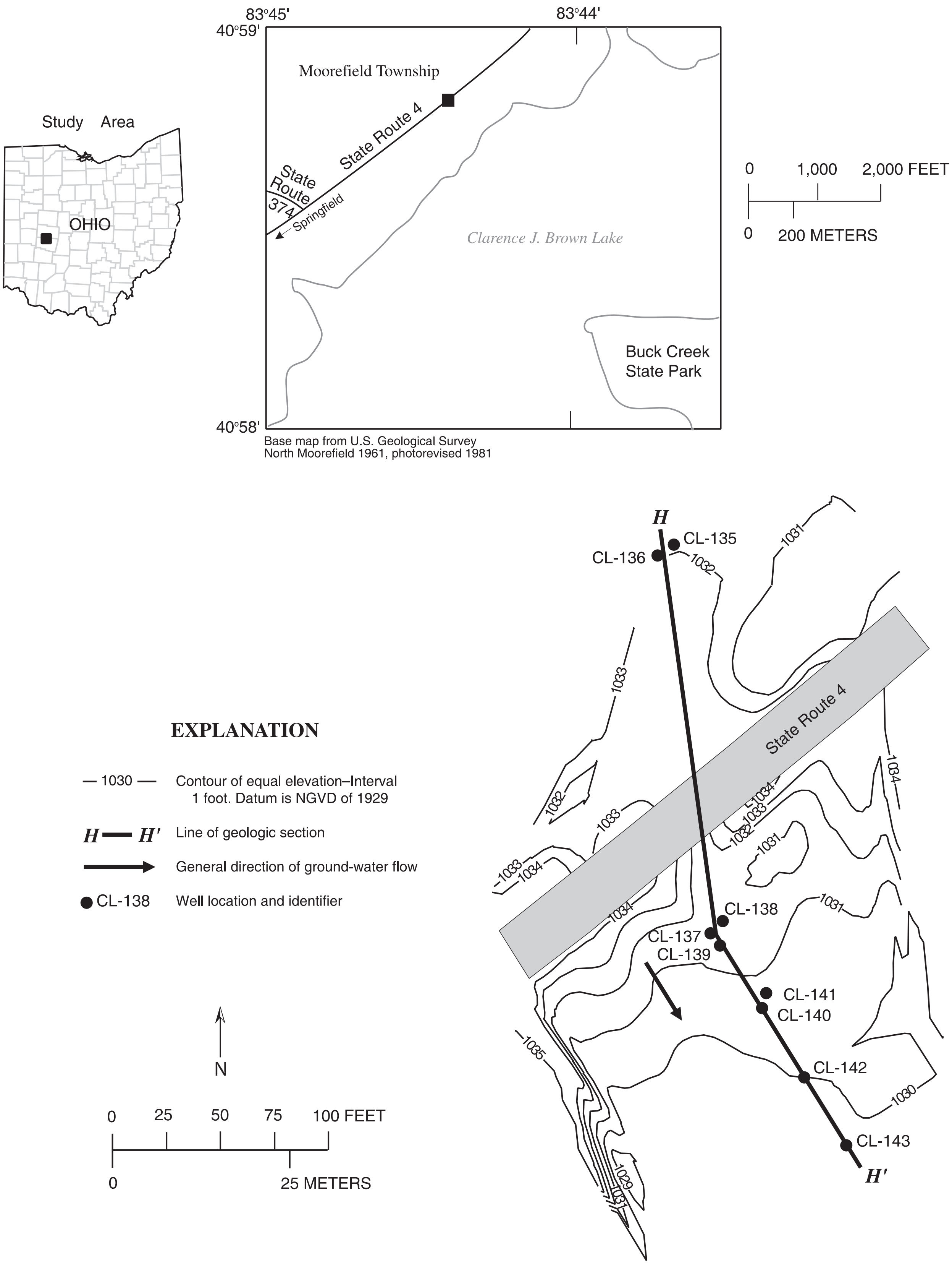
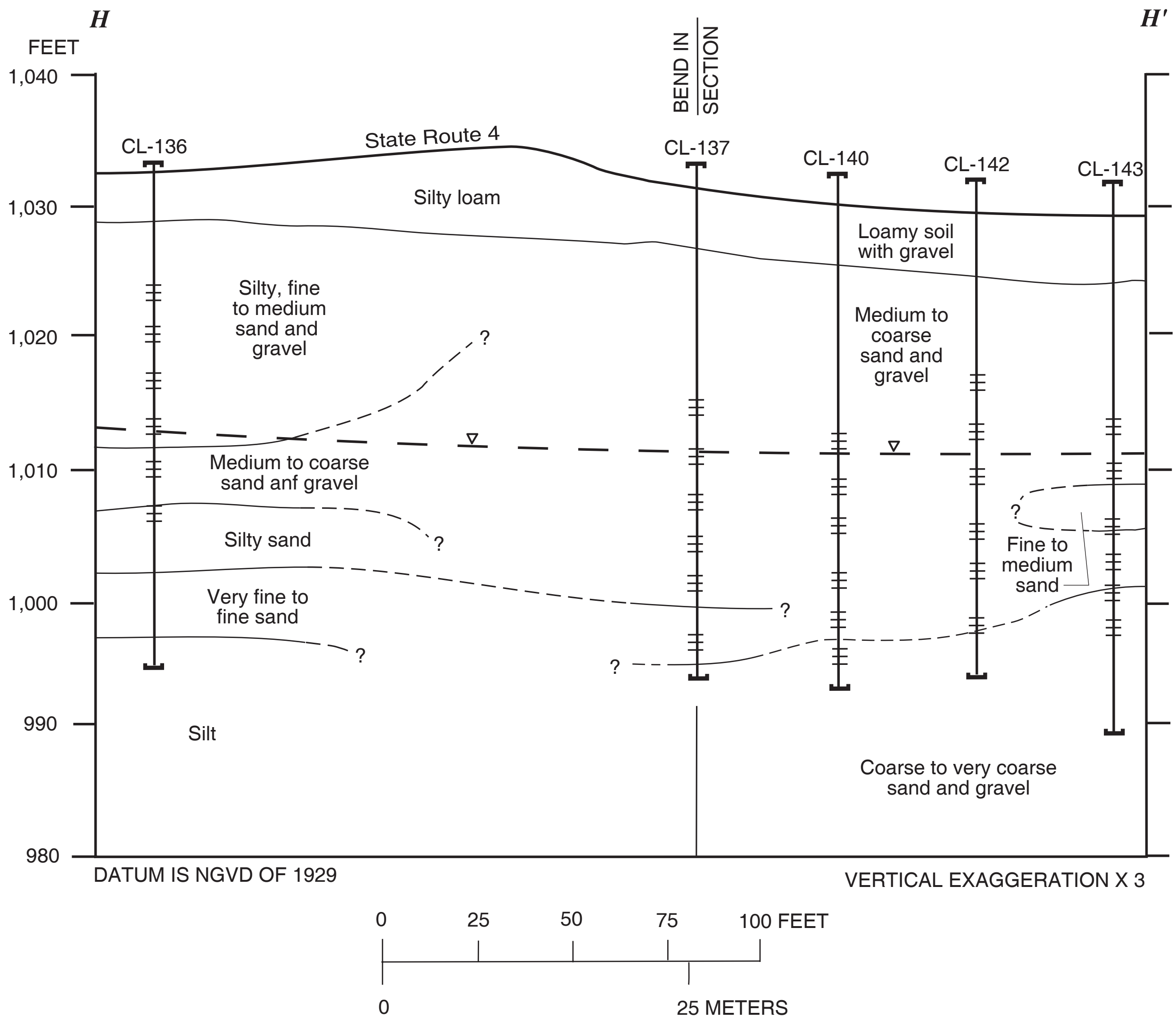


Figure 22. Topography, well locations, and ground-water flow direction, Clark County, Ohio, study site.



EXPLANATION

CL-136 Well location and identifier–Well logs on file with the U.S. Geological Survey, Columbus, Ohio, office

Top of casing

Sampling interval–Wells with multiple sampling intervals are screened the full length of casing

Bottom of well

Bottom of boring–Wells in which the bottom of the boring extends below the bottom of the well were backfilled to the depth shown as the bottom of the well

Mean water level

Geologic contact–Dashed where approximately located

Figure 23. Geologic section *H-H′*, Clark County, Ohio, study site. (Section trace shown in fig. 22.)

Table 10. Sodium chloride application amounts by month and year, Clark County, Ohio, study site.

[Amounts measured by pounds per 2-lane mile]

	October	November	December	January	February	March	April	Yearly total
1990-91	0	0	1,975	2,315	1,225	525	0	6,040
1991-92	0	750	300	3,975	750	1,225	0	7,000
1992-93	0	0	825	700	3,750	0	0	5,275
1993-94	0	0	3,225	4,475	300	0	0	8,000
1994-95	0	0	300	4,100	900	300	0	5,600
1995-96	0	320	3,680	1,560	640	840	0	7,040
1996-97	0	1,150	840	1,600	1,350	0	0	4,940
1997-98	0	480	0	400	266	800	0	1,946
1998-99	0	0	560	1,800	500	600	0	3,460
Total	0	2,700	11,705	20,925	9,681	4,290	0	49,301
Average	0	300	1,301	2,325	1,076	477	0	5,478

precipitation based on data collected at the site, as well as precipitation at the nearest NOAA site, is listed by year in the table below. Average annual snowfall is 13.4 in. for nearby reporting areas. The annual snowfall during the study period averaged 14.1 in. (Midwestern Regional Climate Center, 2000).

Clark County site		
Water year	Onsite precipitation (inches)	Nearest NOAA site[1] precipitation (inches)
1991	[2]2.54	[2]19.57
1992	[3]24.11	[3]33.92
1993	[3]34.73	[3]35.99
1994	[3]17.95	[3]28.27
1995	41.96	[3]36.35
1996	[3]46.21	[3]47.73
1997	[3]29.77	[3]36.32
1998	[3]35.33	[3]34.99
1999	32.26	29.01

[1] Refer to table 2 for site name.

[2] No measurements made until February 1991.

[3] Incomplete data.

Hydrogeology

The ground-water level ranged from 17 to 23 ft below land surface during the study period at this site (table 3). The direction of flow was relatively constant, varying from 84° to 88° to the alignment of the highway, as determined by the triangulation method using available wells; average water-table gradient is about 0.003. At this site, the ground-water level responds to precipitation within 1 day, a result of the porous aquifer materials at the surface. Additional data regarding water-table gradient and flow direction can be found in the appendix in table A-3.

Results of single-well aquifer tests (slug tests) on the aquifer indicate that the hydraulic conductivity is 36 ft/d. Assuming an average gradient of 0.003 and an effective porosity of 35 percent, the ground-water velocity was computed to be 0.31 ft/d.

Effects of Highway Deicing Chemicals on Water Quality

Field-monitored characteristics (rainfall, specific conductance, and ground-water levels recorded from dedicated instrumentation at a well near the first downgradient sampling well) and the amount of sodium chloride applied to the highway are shown in figure 24. The amounts of sodium chloride applied to the highway adjacent to the site, as recorded by each ODOT outpost driver, are listed in table 10. Plots of these characteristics can be used to help compare the events that resulted in increased specific conductance with ambient site conditions and deicer applications. Movement of chloride and other deicing-related constituents from the highway, with time, is indicated by boxplots of laboratory-determined data (figs. 25 and 26).

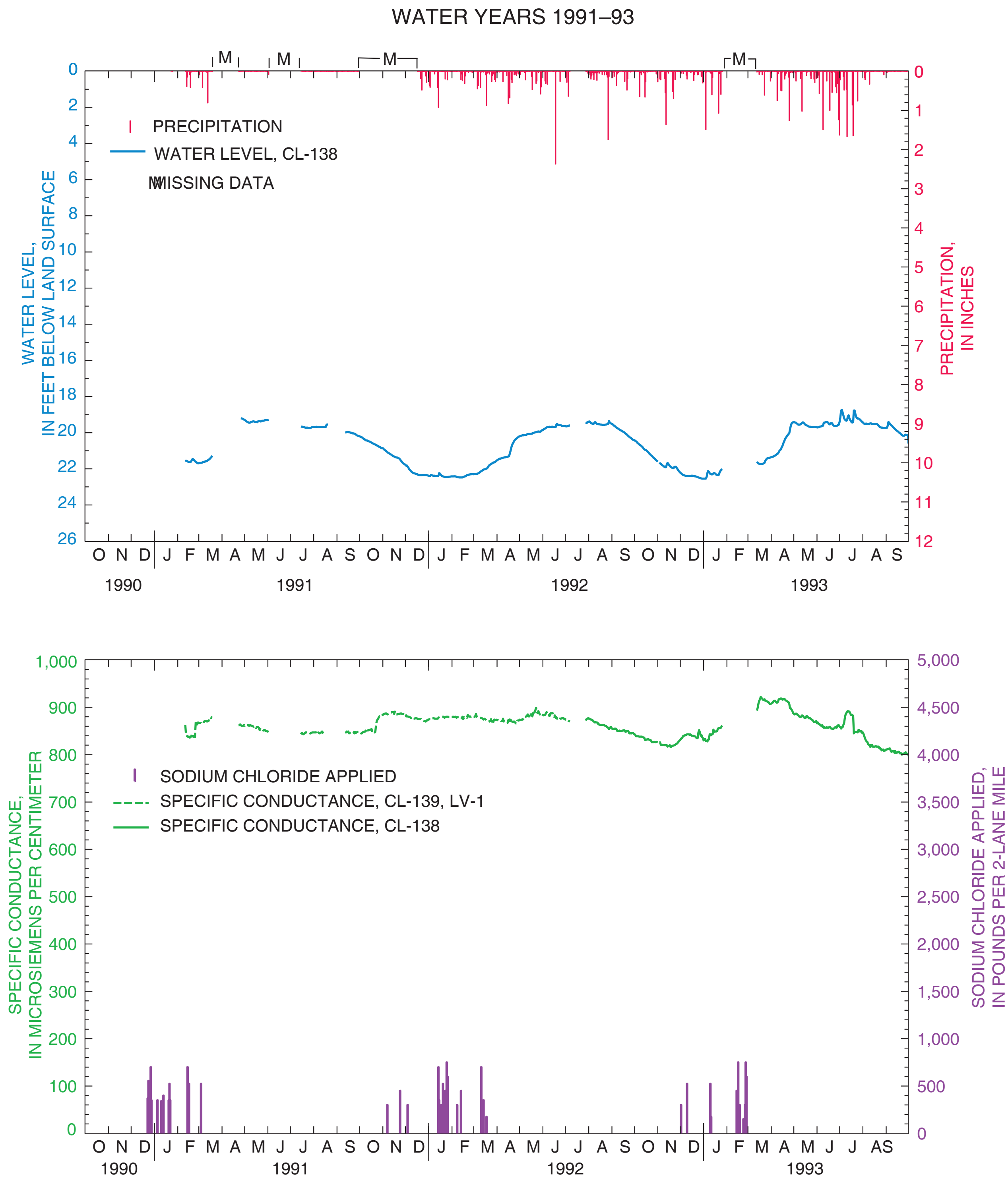


Figure 24. Ground-water levels, precipitation, specific conductance, and sodium chloride application, Clark County, Ohio, study site, water years 1991-99.

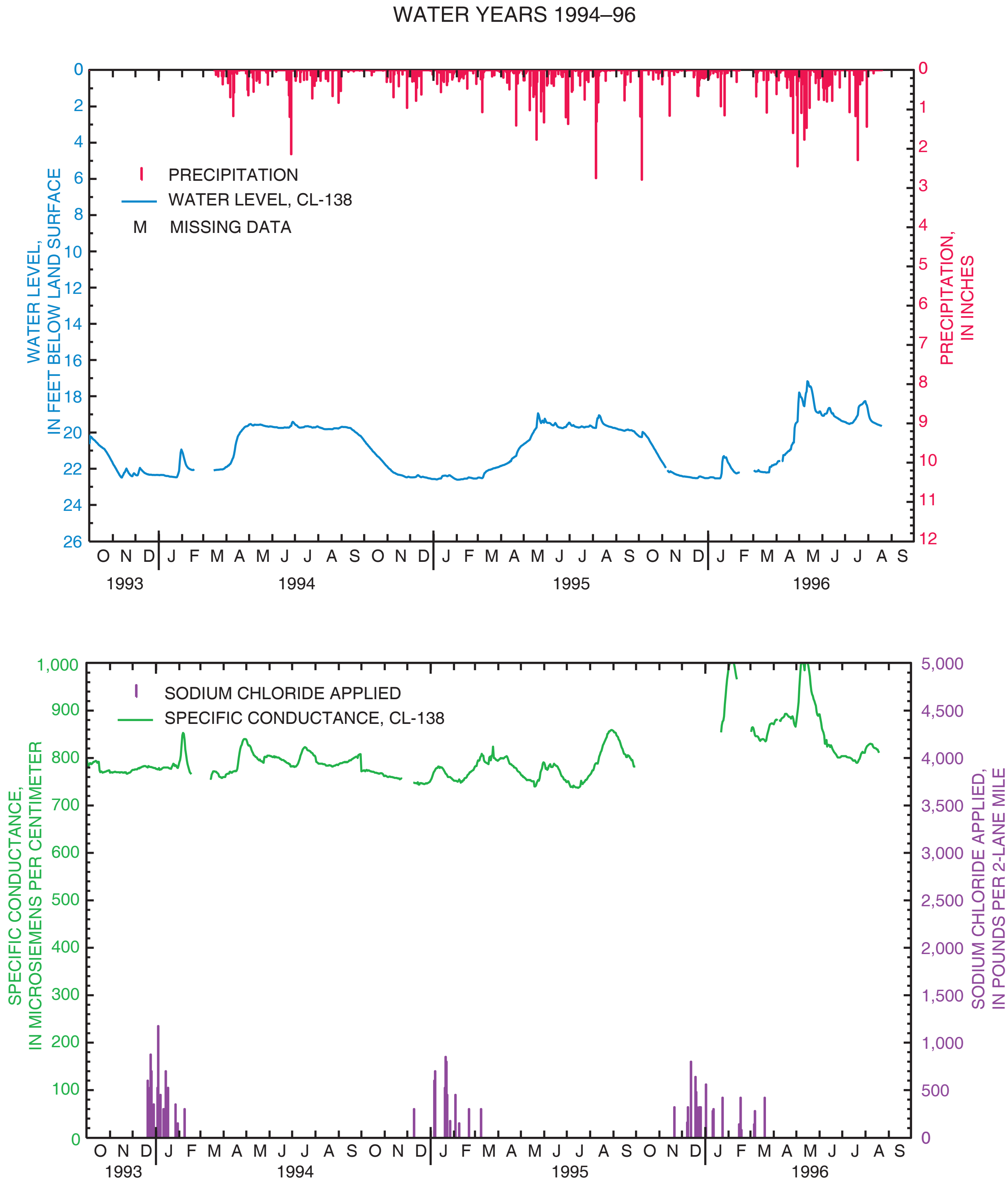


Figure 24. Ground-water levels, precipitation, specific conductance, and sodium chloride application, Clark County, Ohio, study site, water years 1991-99.—Continued

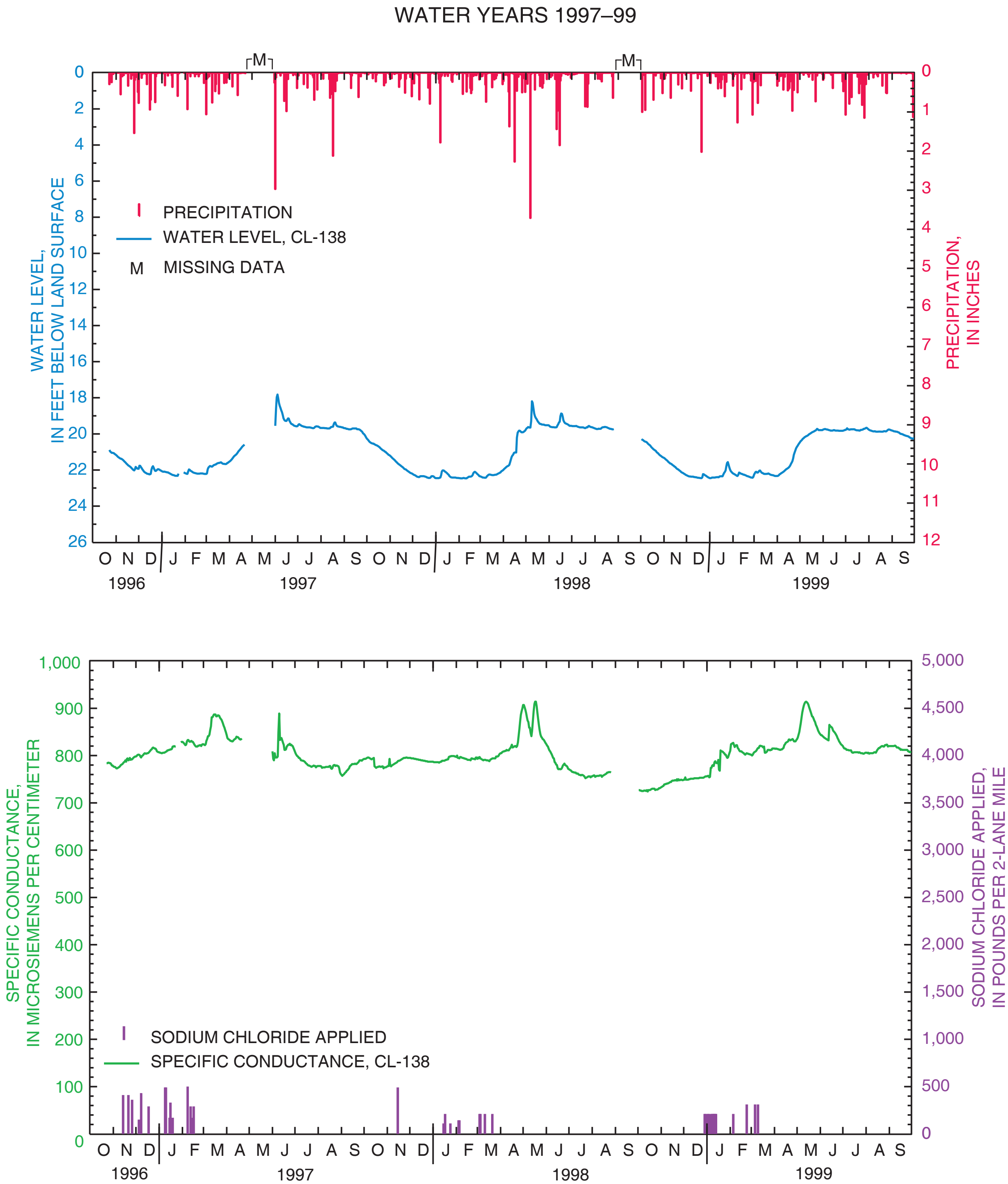


Figure 24. Ground-water levels, precipitation, specific conductance, and sodium chloride application, Clark County, Ohio, study site, water years 1991-99.—Continued

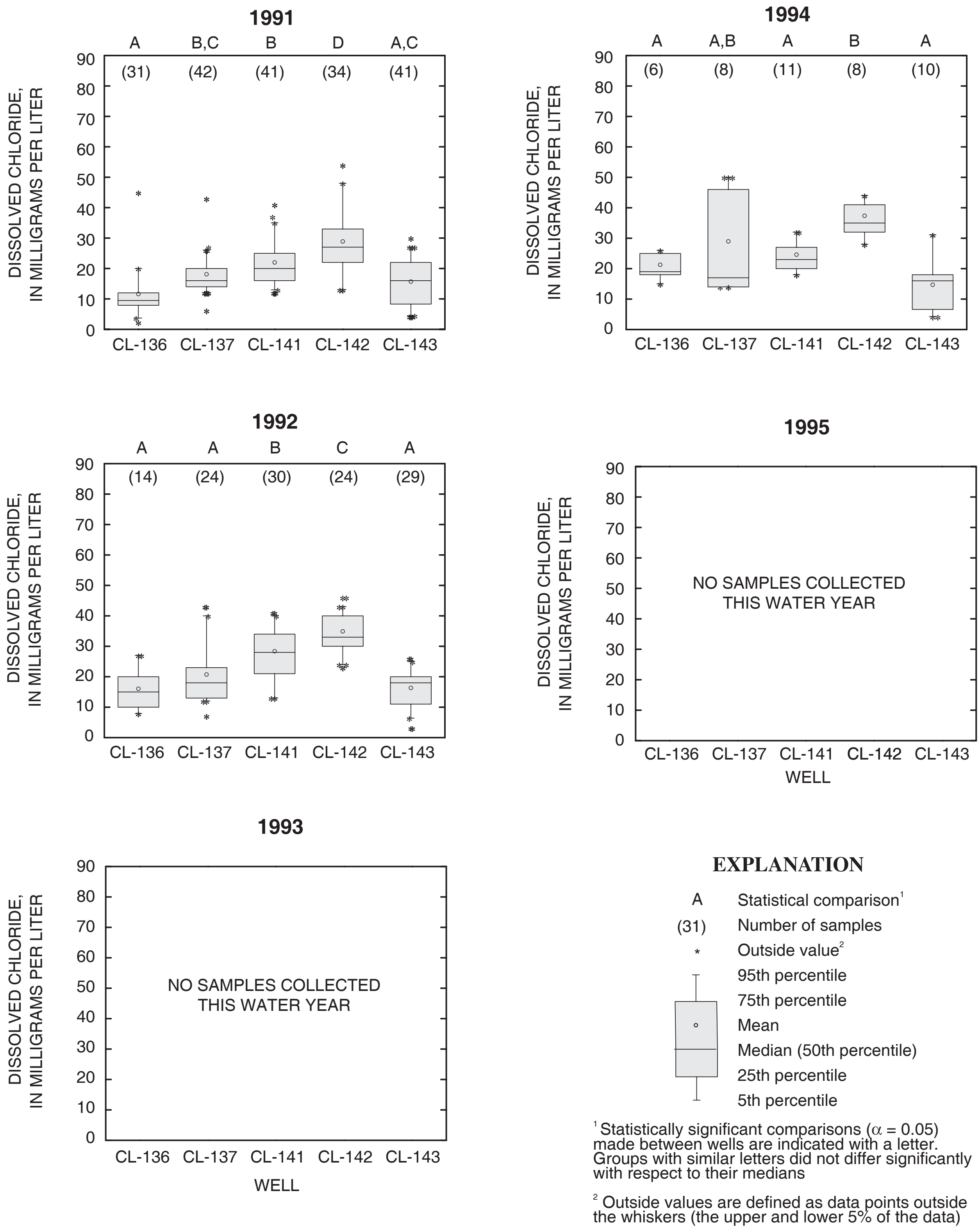


Figure 25. Distribution of concentrations of dissolved chloride in ground-water samples, Clark County, Ohio, study site, January 1991-September 1999. (Plots are shown in downgradient order from left to right. Far left plot is upgradient from highway; others are downgradient.)

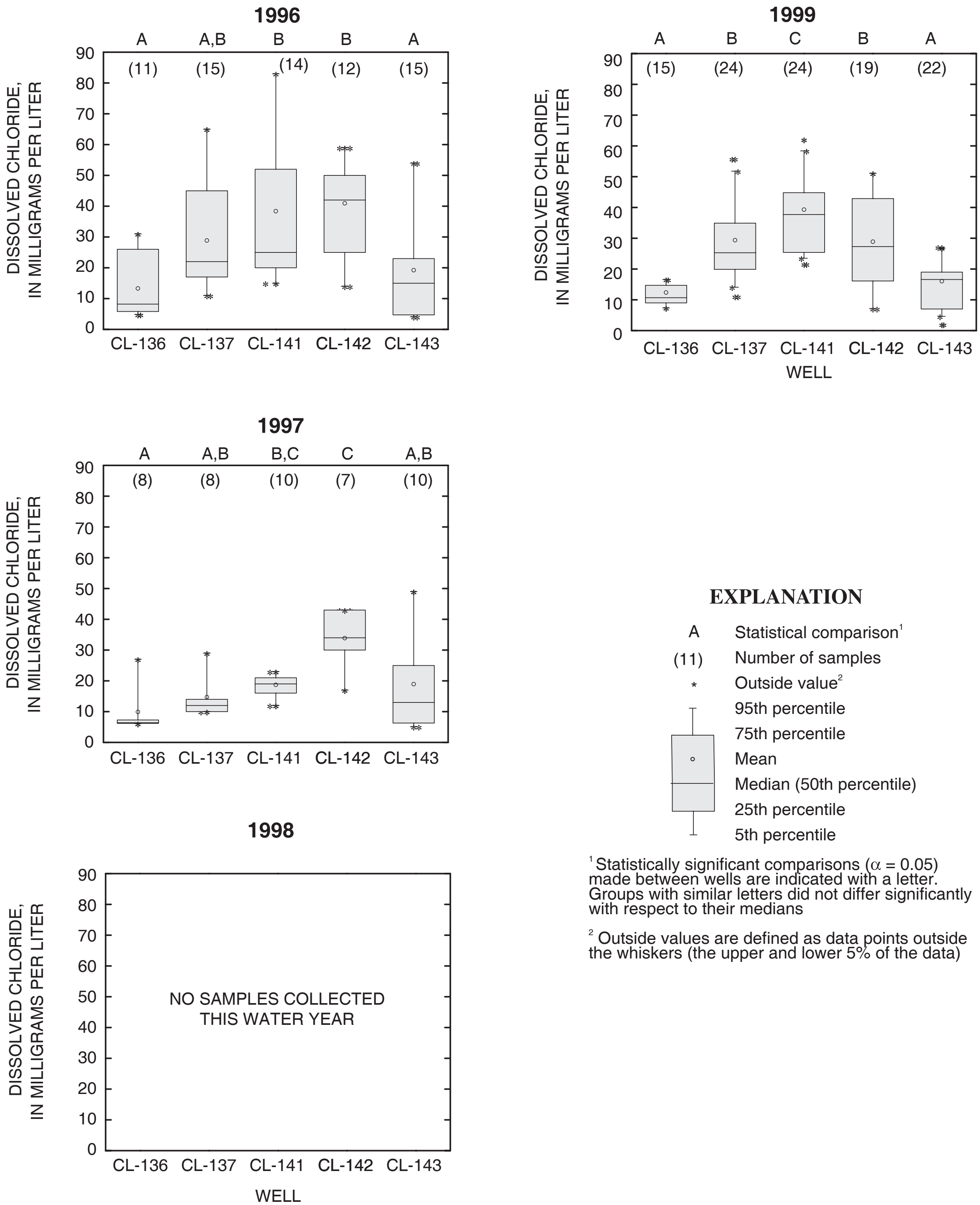


Figure 25. Distribution of concentrations of dissolved chloride in ground-water samples, Clark County, Ohio, study site, January 1991-September 1999. (Plots are shown in downgradient order from left to right. Far left plot is upgradient from highway; others are downgradient.)—Continued

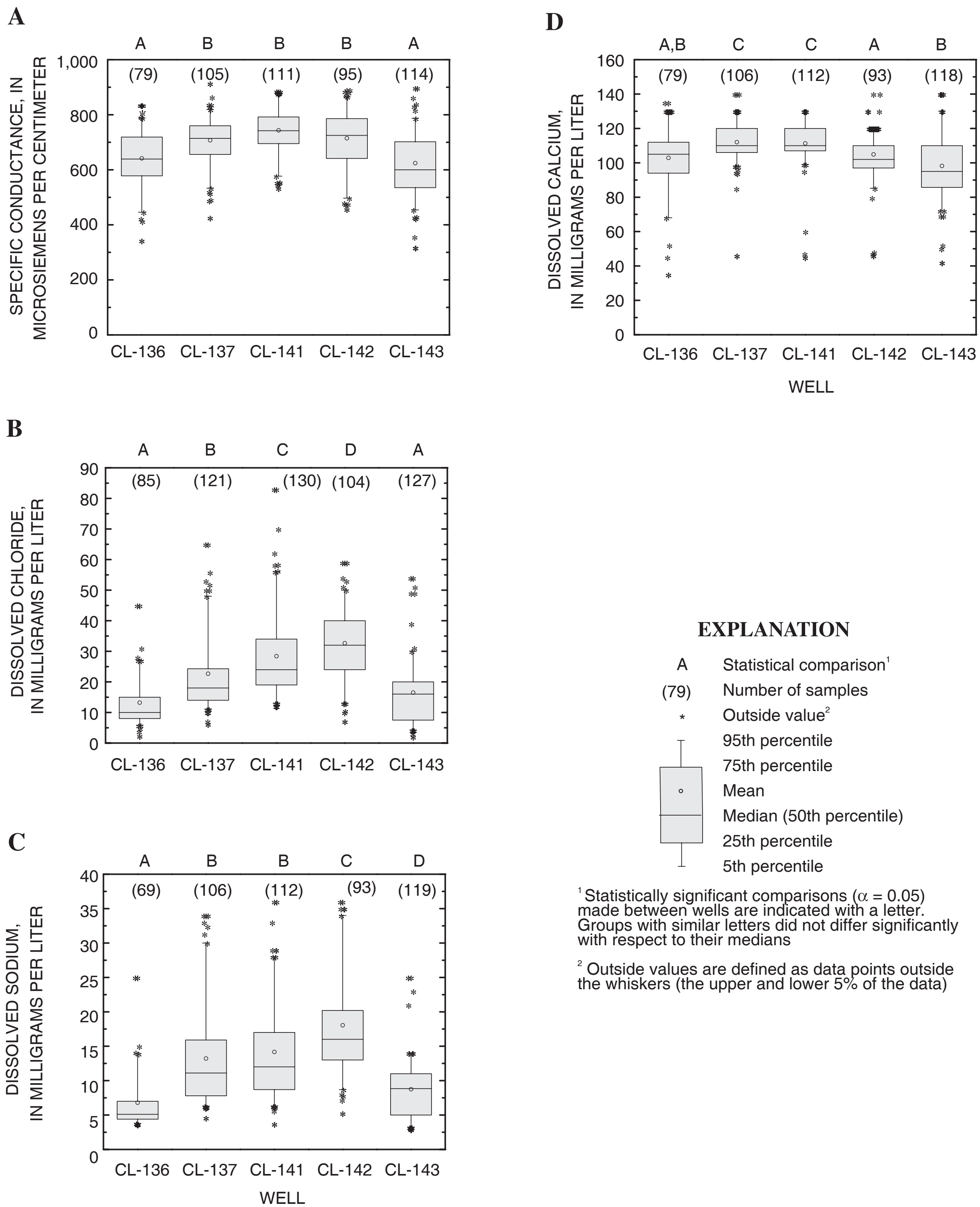


Figure 26. Distribution of (*A*) specific conductance and concentrations of dissolved (*B*) chloride, (*C*) sodium, and (*D*) calcium in ground-water samples, Clark County, Ohio, study site, January 1991-September 1999. (Plots are shown in downgradient order from left to right. Far left plot is upgradient from the highway; others are downgradient.)

Field-Monitored Characteristics

Specific conductance

Specific conductance of ground water varied only slightly during the study period (fig. 24). As is evident from the table at the right, specific conductance recorded continuously in well CL-138 near the first downgradient water-quality sampling well at this site ranged from a maximum of 1,010 µS/cm in 1996, to a minimum of 716 µS/cm in 1999 (a range of 294 µS/cm). For comparison, the mean specific conductance of the upgradient well for the study period was 635 µS/cm (table 11). The small amount of variation in specific conductance of the ground water at this site, as reflected in the small, infrequent spikes in the record, may be due partly to the small amounts of deicing chemicals applied at this site.

Clark County site; well CL-138		
Water year	Specific conductance, maximum (µS/cm)	Specific conductance, minimum (µS/cm)
1991	[1]879	[1]792
1992	899	783
1993	922	795
1994	853	751
1995	859	733
1996	1,010	783
1997	889	754
1998	914	750
1999	914	716

[1] No measurements made until February 1991.

Table 11. Water-quality data for multilevel wells, Clark County, Ohio, study site, water years 1991-99.

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
CL-136	Upgradient	Maximum	832	135	25	45
		Minimum	343	35	4	2
		Mean	635	102	6	13
		Median	639	105	5	10
		N	79	69	69	85
CL-137	1st downgradient	Maximum	914	140	34	65
		Minimum	426	46	5	6
		Mean	700	111	13	22
		Median	714	110	11	18
		N	105	106	106	121
CL-141	2nd downgradient	Maximum	885	150	36	83
		Minimum	533	45	4	12
		Mean	736	110	14	28
		Median	742	110	12	24
		N	111	112	112	130
CL-142	3rd downgradient	Maximum	890	140	36	59
		Minimum	457	46	5	7
		Mean	708	104	18	32
		Median	725	102	16	32
		N	95	93	93	104
CL-143	4th downgradient	Maximum	897	140	25	54
		Minimum	317	42	3	2
		Mean	617	97	8	16
		Median	602	96	9	16
		N	114	118	119	127

Air and Soil Temperature

During the study period, air temperature at this site ranged from 37.5° C in 1991 to a minimum of -30.7° C in 1994.

Clark County site		
Water year	Air temperature, maximum (° C)	Air temperature, minimum (° C)
1991	[1]37.5	[1]0.0
1992	33.3	-21.2
1993	35.0	-14.8
1994	37.1	-30.7
1995	36.5	-20.1
1996	34.2	-22.3
1997	35.7	-20.3
1998	34.2	-11.8
1999	36.6	-24.0

[1] No measurements made until February 1991.

During the study period, soil temperature ranged from a maximum of 39.5° C in 1991 to a minimum of -2.7° C in 1992.

Clark County site		
Water year	Soil temperature, maximum (° C)	Soil temperature, minimum (° C)
1991	39.5	[1]0.0
1992	29.9	9.4
1993	26.9	-2.7
1994	30.6	1.2
1995	28.1	-0.4
1996	26.8	-2.5
1997	32.6	-0.7
1998	29.8	0.9
1999	32.4	0.6

[1] No measurements made until February 1991.

Laboratory-Determined Characteristics

At the Clark County site, rarely were large amounts of deicing chemicals applied to SR 4 (table 10). Temperatures were often above freezing throughout the winter periods, and sampling was discontinued temporarily during times when little or no deicing chemicals were applied. Cold temperatures sometimes created icy conditions, but large snowfalls were uncommon.

Summary statistics of the water-quality data collected at upgradient and downgradient wells for all 6 years sampled during 1991–99 are listed in table 11. These same statistics for each year individually are listed in the appendix in table A-7. Boxplots of chloride concentration data collected at upgradient and downgradient wells for each of the 6 years individually are shown in figure 25. Boxplots of specific conductance, dissolved calcium, dissolved sodium, and dissolved chloride for water from all levels of the upgradient well and the four downgradient sampling wells for 1991–99 combined are shown in figure 26. Patterns that emerge from those data are noted below.

Specific Conductance

At the upgradient well, CL-136, the mean specific conductance was 635 µS/cm, and the maximum was 832 µS/cm (table 11, fig. 26A). Values were slightly increasing, but generally constant, throughout the four downgradient wells (mean, 617–736 µS/cm; maximum, 885–914 µS/cm). Thus, 158 ft downgradient from the highway, the mean specific conductance at the fourth downgradient well was about the same as the upgradient or background value. Any deicing chemicals applied were not enough to cause a noticeable change in the specific conductance.

Chloride Concentration

At the upgradient well, CL-136, the mean concentration of chloride was 13 mg/L, and the maximum was 45 mg/L (table 11, fig. 26B). Mean concentrations were slightly higher at all four downgradient wells than at the upgradient well (mean, 16–32 mg/L; maximum, 54–83 mg/L). Concentrations increased along the flowpath from the first to the third downgradient well (table 11, fig. 26B). At the fourth downgradient well, CL-143, concentrations decreased to background levels (mean, 16 mg/L; maximum, 54 mg/L). Thus, 158 ft downgradient from the highway, the mean concentration was about the same as the upgradient or background concentration.

Dissolved-chloride concentrations at six sampling levels in each downgradient well at the site during a 5-month period in 1999 are represented as a series of chloride profiles in figure 27. (Each color in the profile represents an additional 15 mg/L of chloride.) This series of profiles shows how chloride moved through the aquifer after deicing chemicals were applied in January 1999. The amount and frequency of precipitation and snowmelt recharge and soil temperature can also affect chloride movement during a specific time period. In general, at this site only a small amount of deicing material was applied. Over a period of several weeks, however, during January 1999, deicing material was applied in larger quantities. Precipitation and a corresponding water-level increase in April through August contributed to the flow through the aquifer. The resulting pattern of chloride concentration in the profile plots is shown in figure 27.

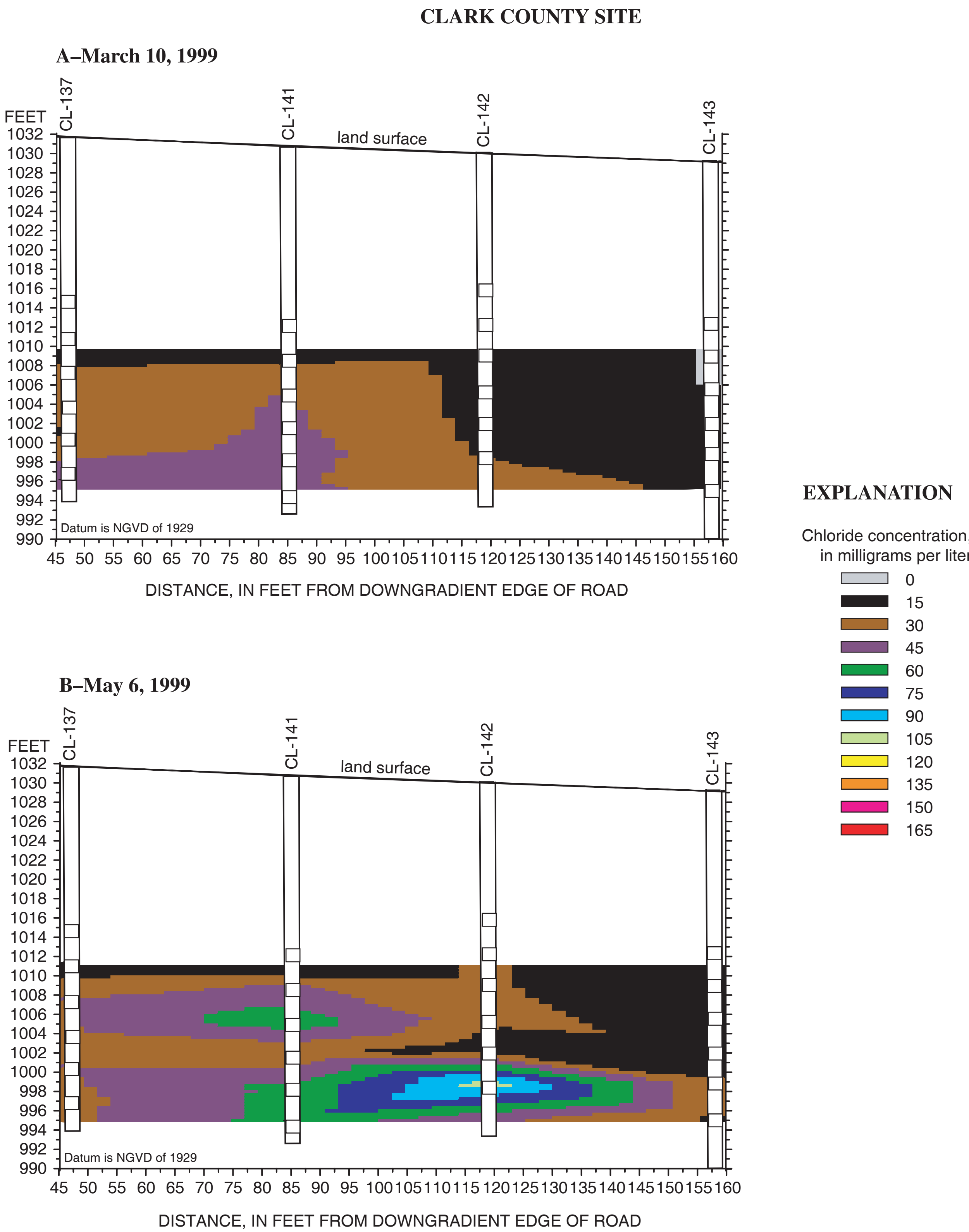


Figure 27. Profiles of chloride concentrations at the study site in Clark County, Ohio, March 10, 1999, through August 3, 1999.

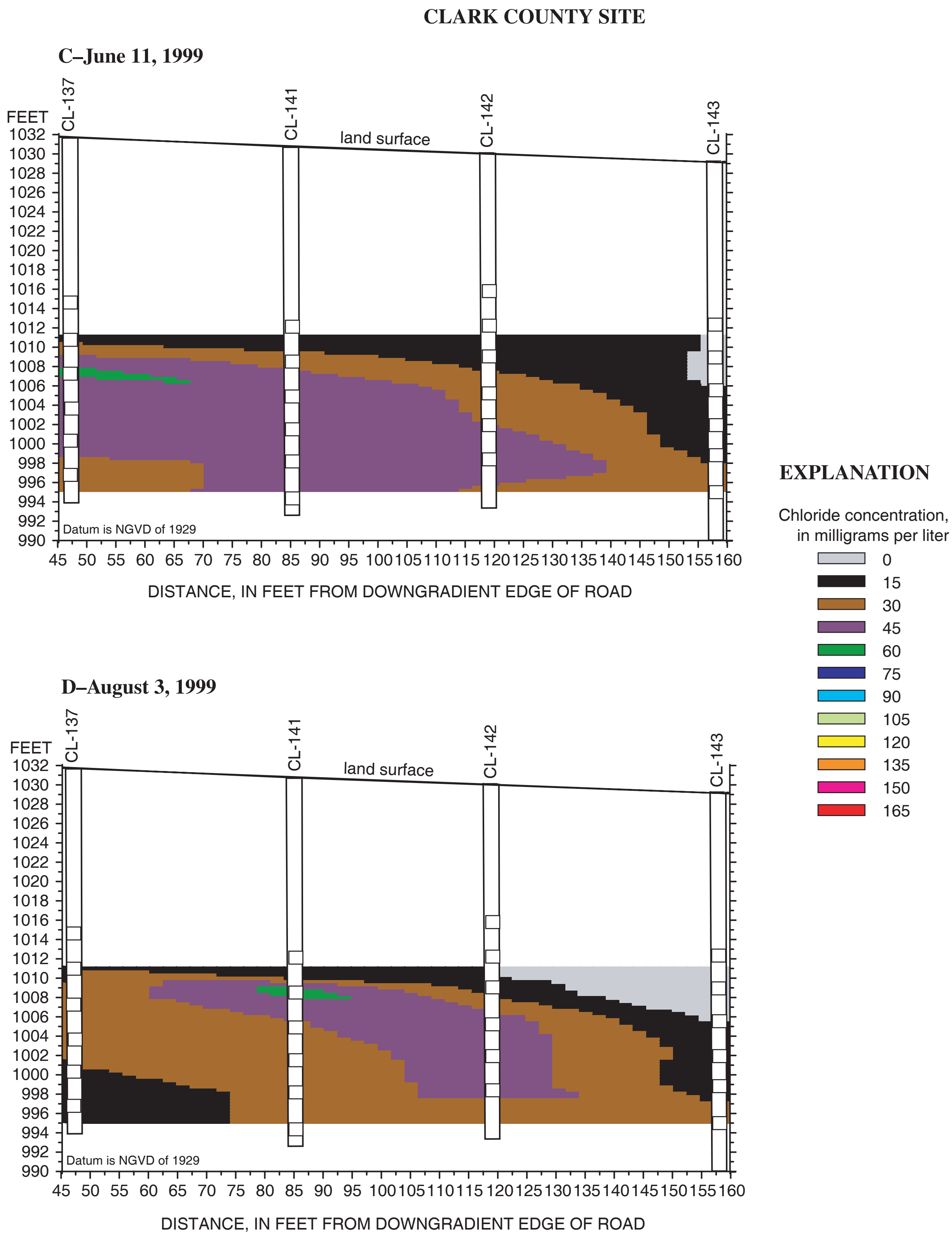


Figure 27. Profiles of chloride concentrations at the study site in Clark County, Ohio, March 10, 1999, through August 3, 1999.—Continued

The surficial material at this site is a medium to coarse sand with gravel and large cobbles that may contribute to a preferential flowpath depending on velocity, but the vertical distribution of chloride concentration can be seen with the multilevel wells even though the concentration changes are minimal. In May 1999 (fig. 27B), areas of a vertical distribution of chloride with a maximum concentration of 105 mg/L can be seen; the plume is then diluted and moved through the aquifer.

Soil samples were collected on nine occasions at this site during 1993–99 (table A-2). The range of chloride concentration of the samples collected from the ditch along the highway was 4–210 mg/L and decreased to 4–19 mg/L by 80 ft downgradient from the highway. The data are listed in the appendix in table A-2.

Sodium Concentration

At the upgradient well, CL-136, the mean concentration of sodium was 6 mg/L, and the maximum was 25 mg/L (table 11, fig. 26C). Concentrations were slightly higher at all the downgradient wells (mean, 8–18 mg/L; maximum, 25–36 mg/L). Concentrations remained fairly constant downgradient along the flowpath to the third downgradient well. Mean concentrations were highest at the third downgradient well, although mean and maximum concentrations were similar to those at the first and second downgradient wells. At the fourth downgradient well, CL-143, concentrations decreased to background levels (mean, 8 mg/L; maximum, 25 mg/L). Thus, 158 ft downgradient from the highway, the mean concentration at the fourth downgradient well was about the same as the upgradient or background concentration.

Calcium Concentration

During the study period at this site, no calcium chloride ($CaCl_2$) was applied to the highway. The mean calcium concentration in the upgradient well, CL-136, was 102 mg/L, and the maximum was 135 mg/L. There was a slight increase in the mean concentration in the first downgradient well, CL-137 (111 mg/L) (table 11, fig. 26D), which gradually decreased by the furthest downgradient well, CL-143, to a mean of 97 mg/L. Calcium present may be due to gypsum impurities in the local salt source formation.

Lucas County Site

Site Characteristics

The Lucas County site (fig. 28) is on SR 2, 1/4 mi southwest of the Interstate 80/90 (Ohio Turnpike) overpass in Monclova Township near Holland, Ohio. SR 2 is a four-lane undivided highway and has first-priority designation for ODOT deicing. This site is in the Eastern Lake Section of the Central Lowland Physiographic Province (Fenneman, 1946) and is part of an old lakebed and shoreline from postglacial Lake Whittlesey, a former enlarged stage of present-day Lake Erie, formed during the retreat of several stages of Wisconsinan glaciation (Fenneman, 1938). The site is nearly flat, and the slope of the area is 0.5 ft over 450 ft, or 0.001. The site is owned and maintained by the Toledo Express Airport. Both sides of the highway are mowed fields. Access to the downgradient side was restricted because it is within the outer boundaries of the airport runway area.

SR 2 is a wide four-lane undivided highway with shallow open-ditch drainage and no center median divider. About 200 ft east of the site, at the East Airport access road, the ditches drain into culverts that empty into a nearby stream. Total pavement width, including shoulders, is 70 ft, and the grassy berm is 2–3 ft wide. The highway is very flat and straight at this site.

The soil type on both sides of the highway is of the Granby-Ottokee-Tedrow association; upgradient is the Tedrow fine sand, and near the road, both upgradient and downgradient, is the Granby loamy fine sand (U.S. Department of Agriculture, 1980b). Beneath the soils layer, the surficial material at this site is almost entirely fine- to medium-grained sand to a depth of 31–35 ft. At this depth, a gray silty clay formation is encountered which, according to local well logs obtained from ODNR, continues to bedrock. Bedrock at this site is the Traverse Group, most likely the Tenmile Creek Dolomite (Larsen, 1994a, 1994b), and lies at about 70 ft below land surface. Both soils are poorly drained. An individual well log was constructed for each of the wells. A geologic section of the site was constructed on the basis of these logs (fig. 29).

The nine-winter (1990–99) average annual use of sodium chloride in Lucas County as a whole was 4,267 tons (table 1). The maximum for this nine-winter period was 5,332 tons in 1993–94, and the minimum for this period was 2,029 tons in 1997–98. Data collected at this site (table 12) indicate the nine-winter average annual use of sodium chloride was 8.46 ton/2-ln mi (16,928 lb/2-ln mi), which is 13 percent less than the State average of 9.7 ton/2-ln mi (19,380 lb/2-ln mi) (Ohio Department of Transportation, written commun., 1999). In addition to sodium chloride and abrasives, a small amount of liquid calcium chloride ($CaCl_2$) also was applied to the highway in about 22 percent of the cases during the study period.

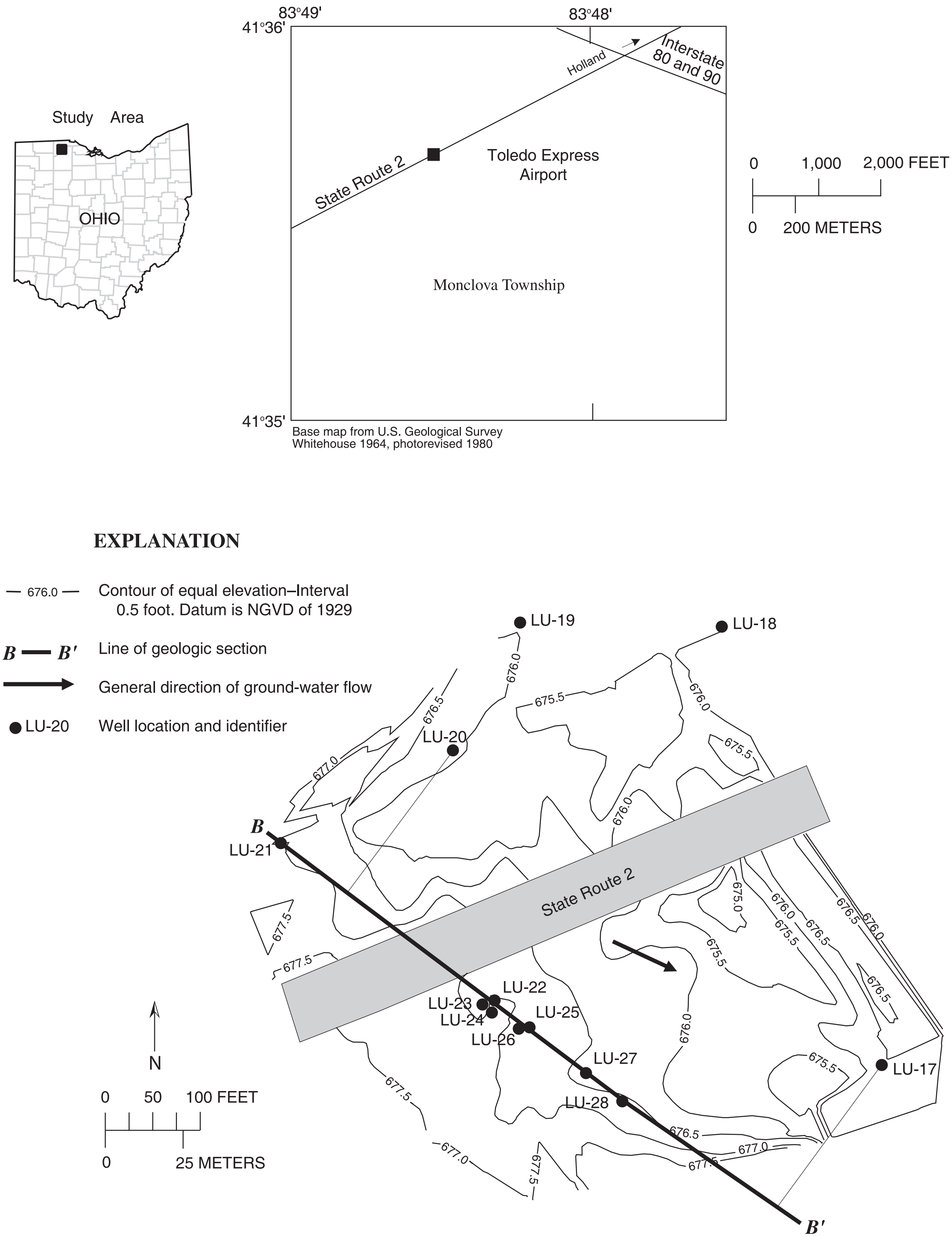
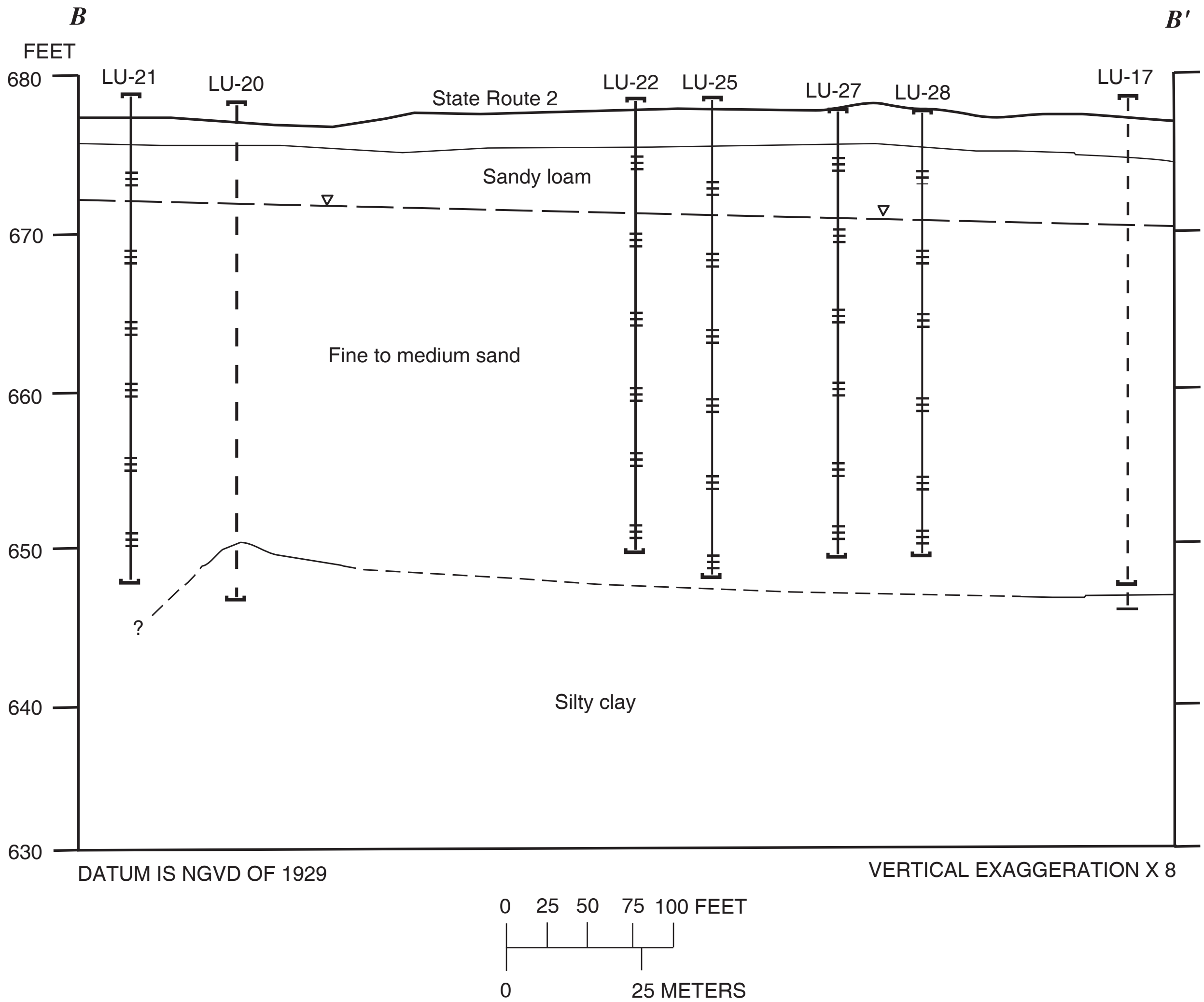


Figure 28. Topography, well locations, and ground-water flow direction, Lucas County, Ohio, study site.



EXPLANATION

LU-22 Well location and identifier–Well logs on file with the U.S. Geological Survey, Columbus, Ohio, office. Dashed well has been projected onto section line

Top of casing

Sampling interval–Wells with multiple sampling intervals are screened the full length of casing

Bottom of well

Bottom of boring–Wells in which the bottom of the boring extends below the bottom of the well were backfilled to the depth shown as the bottom of the well

Mean water level

Geologic contact–Dashed where approximately located

Figure 29. Geologic section *B-B′*, Lucas County, Ohio, study site. (Section trace shown in fig. 28.)

Table 12. Sodium chloride application amounts by month and year, Lucas County, Ohio, study site.

[Amounts measured by pounds per 2-lane mile]

	October	November	December	January	February	March	April	Yearly total
1990-91	0	0	14,100	2,600	2,850	0	0	19,550
1991-92	0	900	3,000	8,400	0	3,800	0	16,100
1992-93	0	800	400	3,800	4,800	5,200	0	15,000
1993-94	0	0	3,600	5,000	3,600	700	1,200	14,100
1994-95	0	0	1,600	5,800	1,600	600	0	9,600
1995-96	0	800	4,600	6,800	1,400	1,000	0	14,600
1996-97	0	1,800	3,200	6,200	2,000	0	0	13,200
1997-98	0	1,200	4,200	2,800	0	2,800	0	11,000
1998-99	0	0	0	28,000	4,800	6,400	0	39,200
Total	0	5,500	34,700	69,400	21,050	20,500	1,200	152,350
Average	0	611	3,856	7,711	2,339	2,278	133	16,928

Climate

Average annual precipitation for the area is 33.0 in. (table 3). Average annual temperature for the area is 9.2° C (48.5° F), with the monthly normal high of 28.6° C (83.4° F) in July and the monthly normal low of -9.5° C (14.9° F) in January (Midwestern Regional Climate Center, 2000). Annual precipitation based on data collected at the site, as well as precipitation at the nearest NOAA site, is listed by year in the table below. Average annual snowfall is 38.8 in. for nearby reporting areas. The annual snowfall during the study period averaged 31.3 in. (Midwestern Regional Climate Center, 2000).

Lucas County site		
Water year	Onsite precipitation (inches)	Nearest NOAA site[1] precipitation (inches)
1991	[2]15.76	[2]18.06
1992	33.56	45.31
1993	[3]32.34	34.20
1994	[3]17.43	27.98
1995	[3]16.35	28.34
1996	[3]8.47	29.77
1997	[3]30.12	40.06
1998	[3]25.95	32.96
1999	24.56	28.08

[1] Refer to table 2 for site name.

[2] No measurements made until February 1991.

[3] Incomplete data.

Hydrogeology

The ground-water level ranged from 3.2 to 8.1 ft below land surface during the study period at this site (table 3). The direction of flow varied from about 45° to 65° and averaged about 60° to the alignment of the highway, as determined by the triangulation method using available wells; average water-table gradient is about 0.003. At this site, the ground-water level responds to precipitation within 1 day, a result of the porous aquifer materials at the surface and the shallow water table. Additional data regarding water-table gradient and flow direction can be found in the appendix in table A-3.

Results of single-well aquifer tests (slug tests) on the aquifer indicate that the hydraulic conductivity is 6 ft/d. Assuming an average gradient of 0.003 and an effective porosity of 43 percent, the ground-water velocity was computed to be 0.04 ft/d.

Ground-water velocity and bulk hydraulic conductivity also were computed by use of water-quality data. Peaks of dissolved-chloride concentration were noted at sites where enough deicing chemicals were applied to result in obvious peaks over at least a 4-year period. Using the procedure described in the "Methods of Investigation" section of this report, the median of the average ground-water velocity and the median bulk hydraulic conductivity were computed. At the Lucas County site, the computation was done 44 times, resulting in a median of the average ground-water velocities of 0.295 ft/d (s= 0.066) and a median bulk hydraulic conductivity of 31.52 ft/d (s= 7.01).

Effects of Highway Deicing Chemicals on Water Quality

Field-monitored characteristics (rainfall, specific conductance, and ground-water levels recorded from dedicated instrumentation at wells near the first downgradient sampling well) and the amount of sodium chloride applied to the highway are shown in figure 30. The amounts of sodium chloride applied to the highway adjacent to each site, as recorded by each ODOT outpost driver, are listed in table 12. Plots of these characteristics can be used to help compare the events that resulted in increased specific conductance with ambient site conditions and deicer applications. Movement of chloride and other deicing-related constituents from the highway, with time, is indicated by boxplots of laboratory-determined data (figs. 31 and 32).

Field-Monitored Characteristics

Specific Conductance

Specific conductance of ground water near the highway at this site was elevated at times but rarely reached the relatively high levels measured at the other northern Ohio sites (Ashtabula and Portage County sites) (fig. 30); however, Lucas County is not in the snowbelt area east of Lake Erie as are the other two sites. As is evident from the table below, specific conductance recorded continuously in well LU-23 near the first downgradient water-quality sampling well at this site ranged from a maximum of 1,820 μS/cm in 1999 to a minimum of 107 μS/cm in 1991, a range of 1,713 μS/cm. For comparison, the mean specific conductance of the upgradient well for the study period was 342 μS/cm (table 13).

Water year	Lucas County site Specific conductance, maximum (μS/cm)	Specific conductance, minimum (μS/cm)
1991	[1]1,790	[1]107
1992	1,000	303
1993	936	418
1994	1,280	516
1995	1,010	439
1996	1,240	430
1997	1,320	239
1998	1,640	217
1999	1,820	193

[1] No measurements made until February 1991.

Air and Soil Temperature

During the study period, air temperature at this site ranged from 38.2° C in 1995 to a minimum of -28.1° C in 1994.

Water year	Lucas County site Air temperature, maximum (° C)	Air temperature, minimum (° C)
1991	[1]34.5	[1]0.0
1992	33.6	-19.8
1993	35.5	-19.7
1994	37.7	-28.1
1995	38.2	-18.6
1996	32.5	-21.2
1997	34.6	-14.2
1998	36.5	-12.4
1999	35.4	-22.1

[1] No measurements made until February 1991.

During the study period, soil temperature ranged from a maximum of 32.0° C in 1999 to a minimum of -4.7° C in 1994.

Water year	Lucas County site Soil temperature, maximum (° C)	Soil temperature, minimum (° C)
1991	[1]30.0	[1]0.5
1992	26.7	0.4
1993	28.9	0.0
1994	31.3	-4.7
1995	29.2	-4.3
1996	26.2	-2.0
1997	27.1	-0.1
1998	28.2	1.2
1999	32.0	-0.4

[1] No measurements made until February 1991.

Laboratory-Determined Characteristics

The Lucas County site received steady applications of deicing chemicals, although they usually were not applied in large quantities (table 12). Temperatures were often below freezing, creating icy road conditions, but average annual snowfall was 20–30 in. less than the sites in the snowbelt area. Summary statistics of the water-quality data collected at upgradient and downgradient wells for all 9 years sampled during 1991–99 are listed in table 13. These same statistics for each year individually are listed in the appendix in table A-8. Boxplots of chloride concentration data collected at upgradient and downgradient wells for each of the 9 years individually are shown in figure 31.

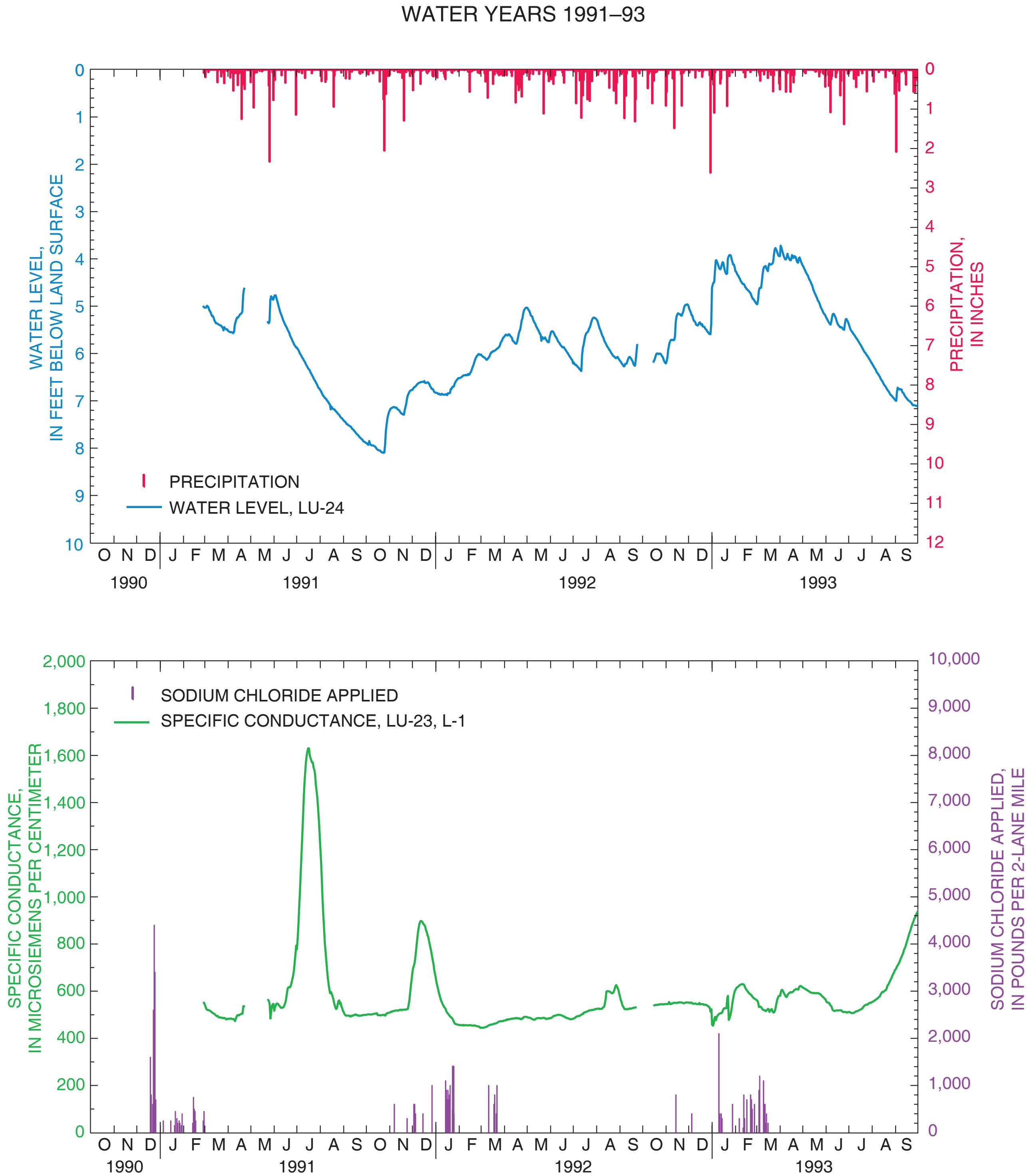
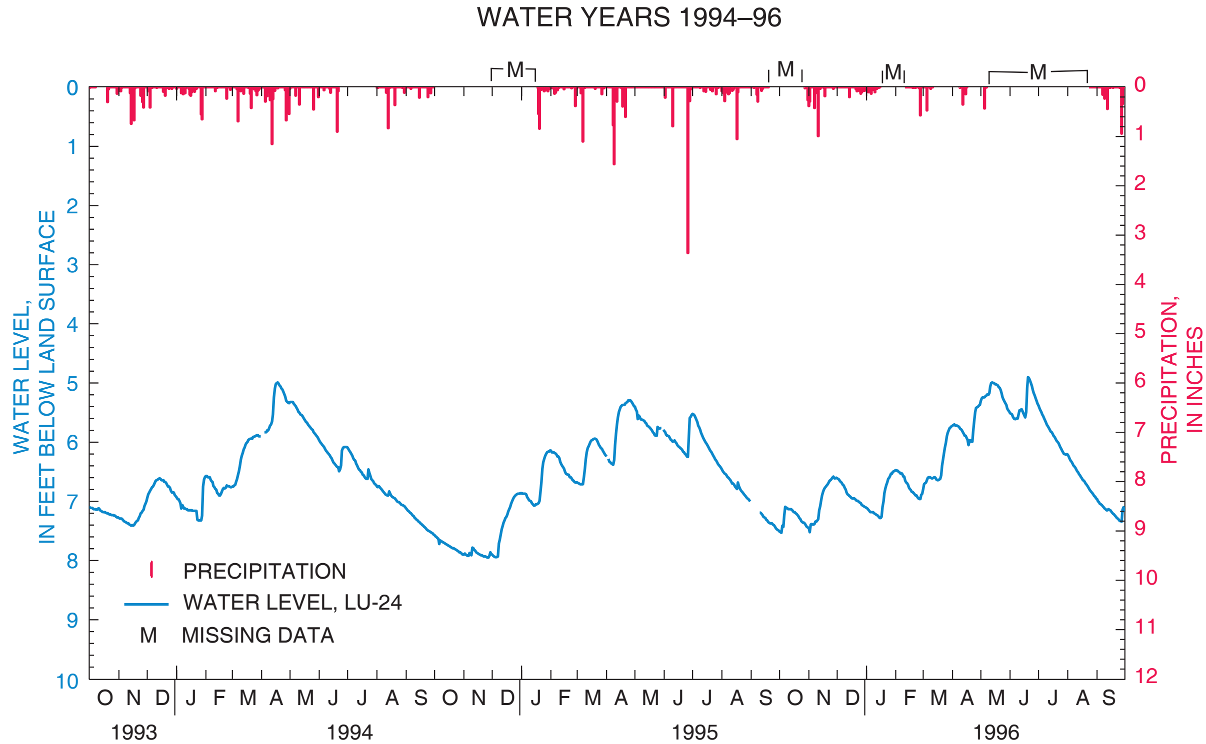


Figure 30. Ground-water levels, precipitation, specific conductance, and sodium chloride application, Lucas County, Ohio, study site, water years 1991-99.



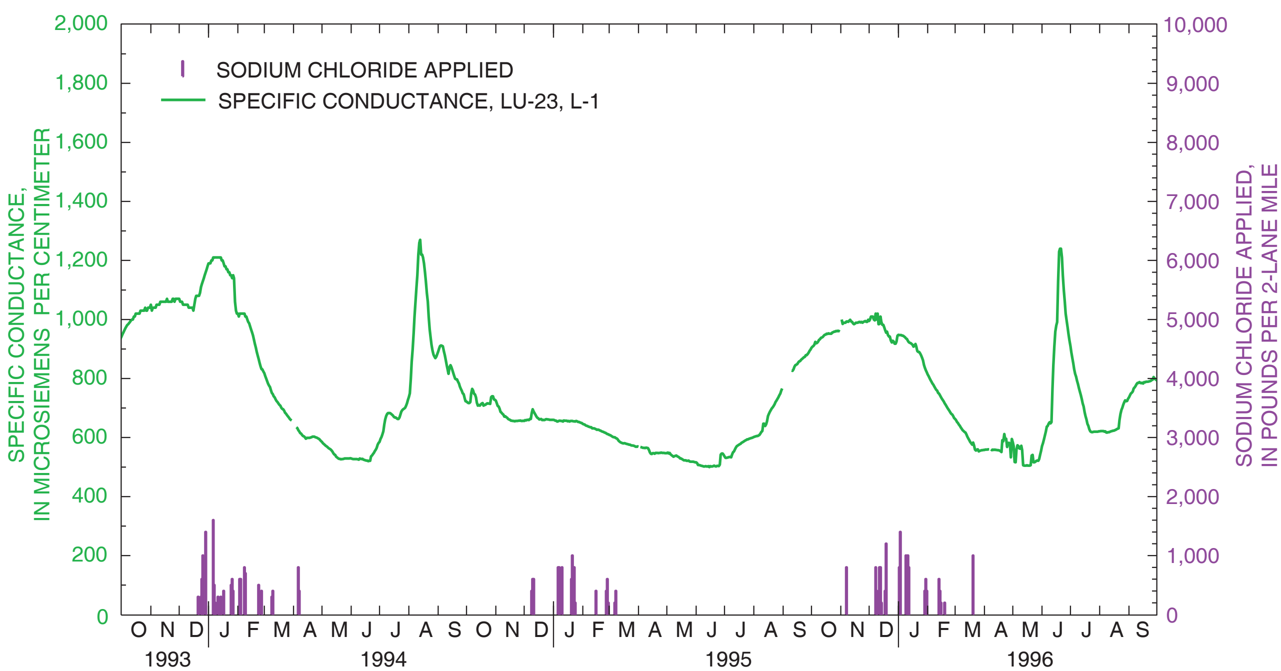


Figure 30. Ground-water levels, precipitation, specific conductance, and sodium chloride application, Lucas County, Ohio, study site, water years 1991-99.—Continued

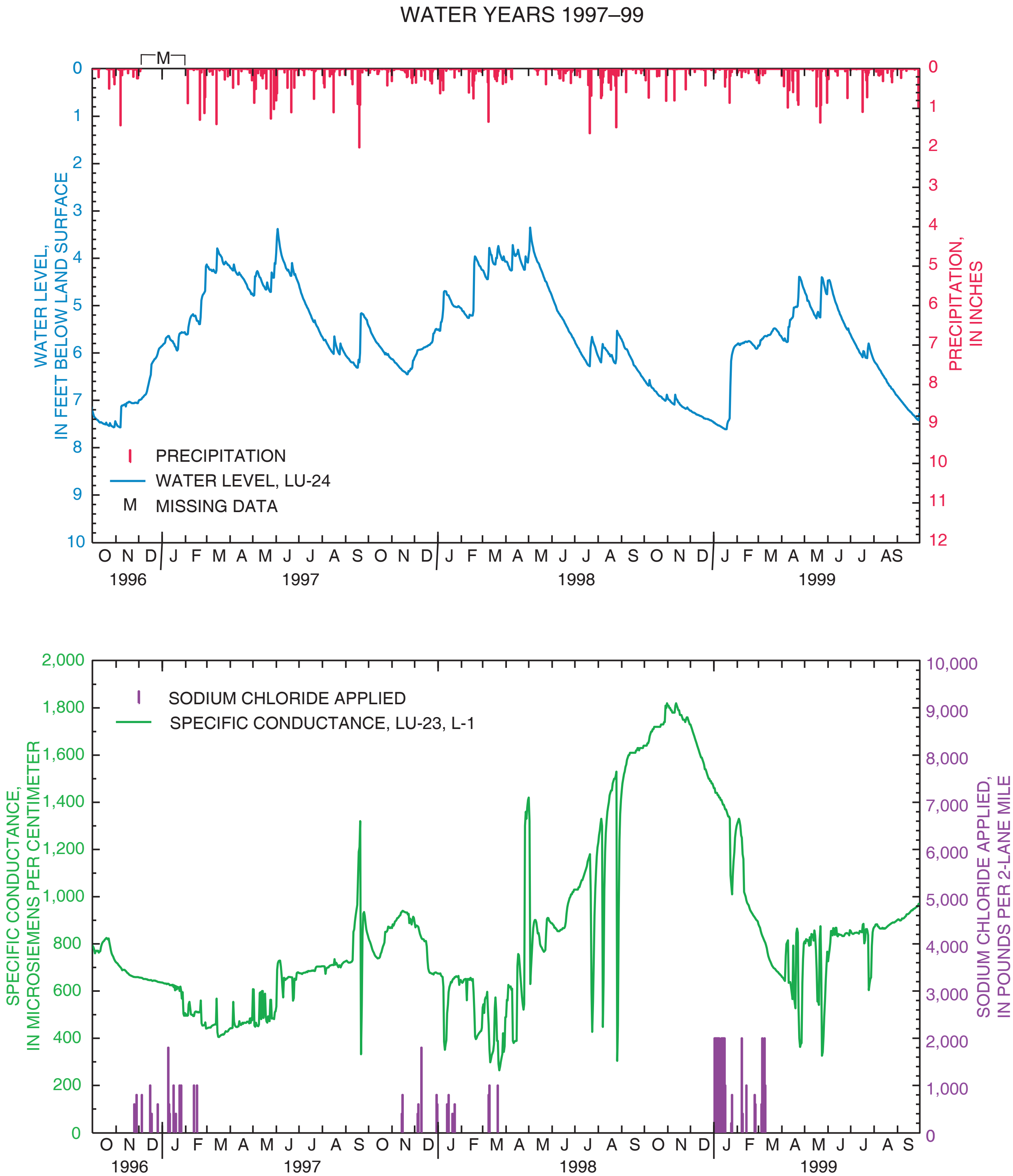


Figure 30. Ground-water levels, precipitation, specific conductance, and sodium chloride application, Lucas County, Ohio, study site, water years 1991-99.—Continued

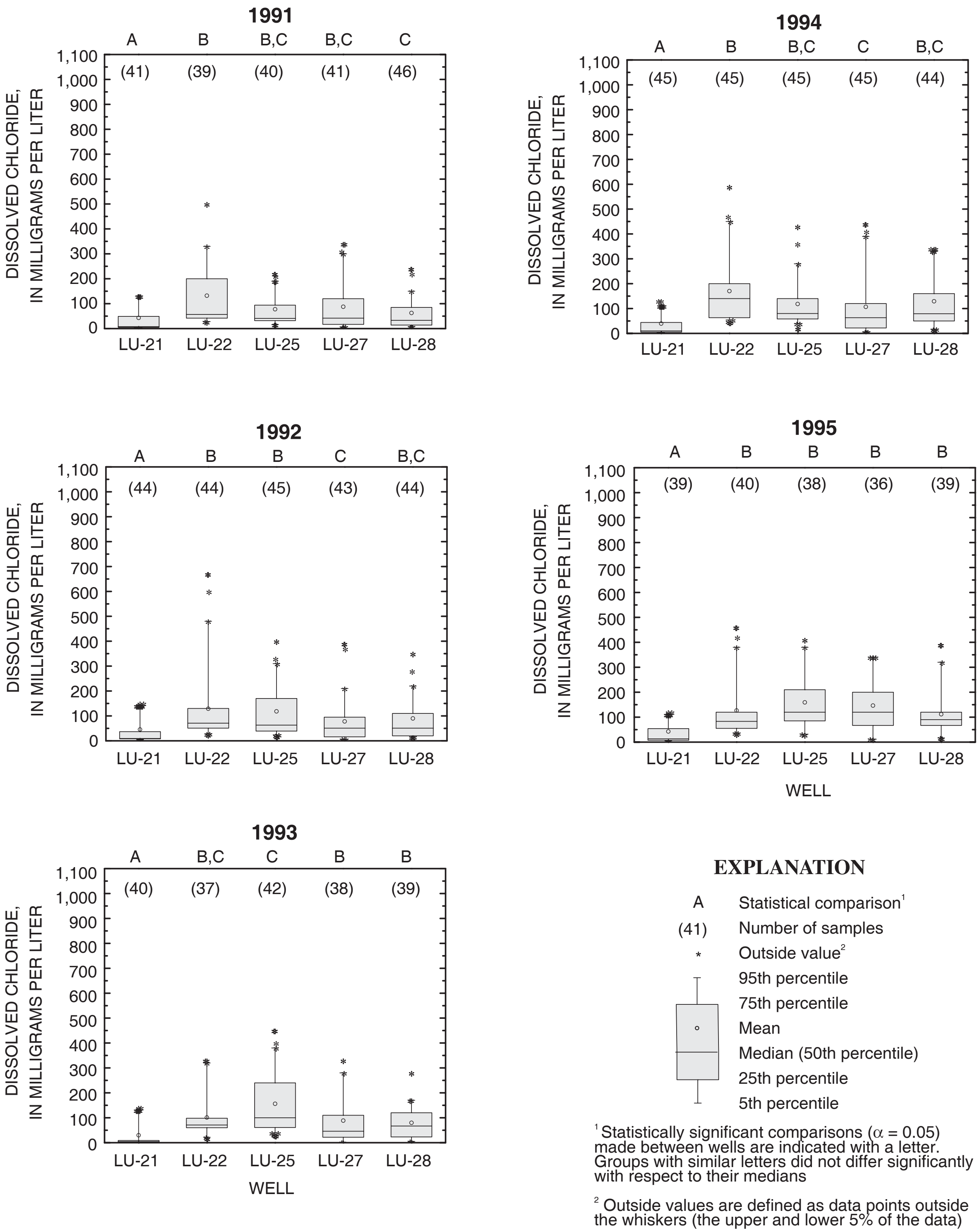


Figure 31. Distribution of concentrations of dissolved chloride in ground-water samples, Lucas County, Ohio, study site, January 1991-September 1999. (Plots are shown in downgradient order from left to right. Far left plot is upgradient from highway; others are downgradient.)

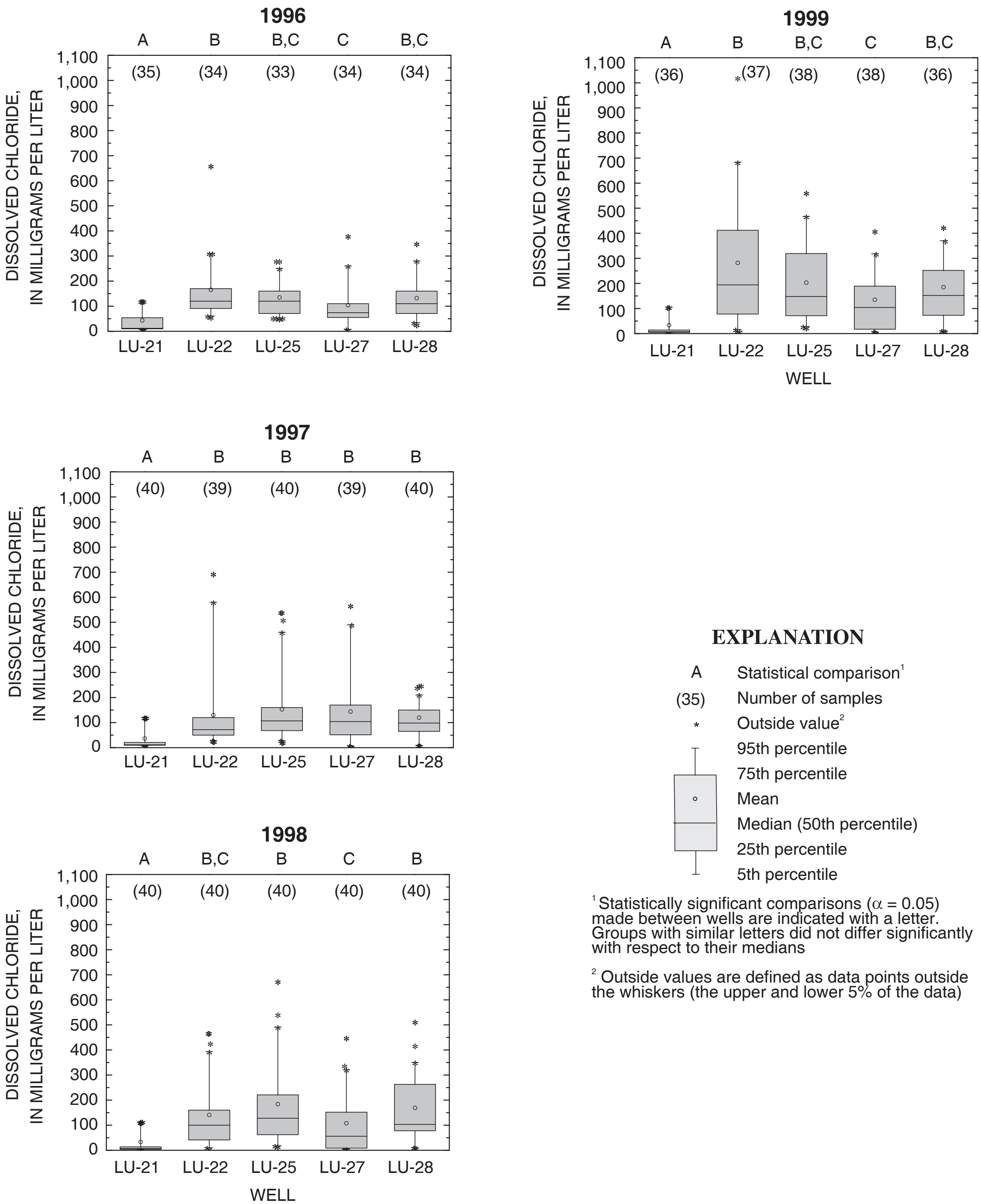


Figure 31. Distribution of concentrations of dissolved chloride in ground-water samples, Lucas County, Ohio, study site, January 1991-September 1999. (Plots are shown in downgradient order from left to right. Far left plot is upgradient from highway; others are downgradient.)—Continued

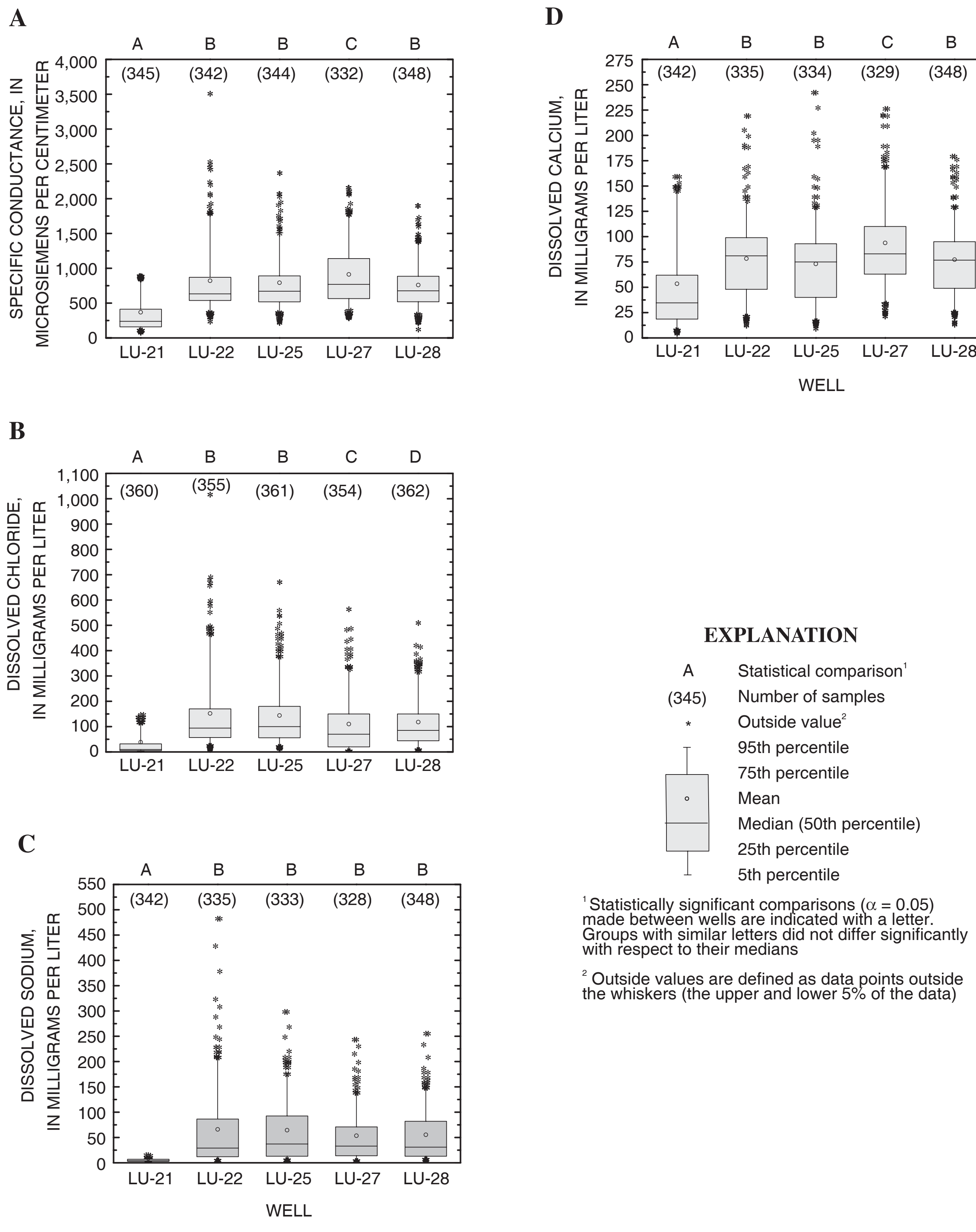


Figure 32. Distribution of (*A*) specific conductance and concentrations of dissolved (*B*) chloride, (*C*) sodium, and (*D*) calcium in ground-water samples, Lucas County, Ohio, study site, January 1991-September 1999. (Plots are shown in downgradient order from left to right. Far left plot is upgradient from the highway; others are downgradient.)

Table 13. Water-quality data for multilevel wells, Lucas County, Ohio, study site, water years 1991-99.

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific Conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
LU-21	Upgradient	Maximum	903	160	17	150
		Minimum	87	5	1	0
		Mean	342	52	5	31
		Median	239	35	4	10
		N	345	342	342	360
LU-22	1st downgradient	Maximum	3,520	220	484	1,020
		Minimum	247	13	5	6
		Mean	794	76	62	145
		Median	634	81	29	94
		N	342	335	335	355
LU-25	2nd downgradient	Maximum	2,380	243	300	674
		Minimum	229	10	5	16
		Mean	766	71	61	137
		Median	672	75	37	100
		N	344	334	333	361
LU-27	3rd downgradient	Maximum	2,170	227	245	567
		Minimum	295	22	3	1
		Mean	886	92	50	103
		Median	770	83	34	70
		N	332	329	328	354
LU-28	4th downgradient	Maximum	1,910	180	257	513
		Minimum	134	14	6	4
		Mean	733	76	52	110
		Median	676	77	32	85
		N	348	348	348	362

Boxplots of specific conductance, dissolved calcium, dissolved sodium, and dissolved chloride for water from all levels of the upgradient well and the four downgradient sampling wells for 1991–99 combined are shown in figure 32. Patterns that emerge from those data are noted below.

Specific Conductance

At the upgradient well, LU-21, the mean specific conductance was 342 µS/cm, and the maximum was 903 µS/cm (table 13, fig. 32A). Values were generally highest at the first downgradient well, LU-22, (mean, 794 µS/cm; maximum, 3,520 µS/cm). Mean values were generally the same for all downgradient wells; however, higher outliers were found at well LU-22. At the third downgradient well, LU-27, the mean specific conductance was 886 µS/cm, and the maximum was 2,170 µS/cm. At the fourth downgradient well, the mean specific conductance was 733 µS/cm, and the maximum was 1,910 µS/cm. Thus, 228 ft downgradient from the highway, the mean specific conductance at the fourth downgradient well was about twice the upgradient or background value, although the mean value of the first, second, and third wells had not decreased significantly. This pattern may be due to the extremely low ground-water velocity (0.04 ft/day) at this site.

Chloride Concentration

At the upgradient well, LU-21, the mean concentration of chloride was 31 mg/L, and the maximum was 150 mg/L (table 13, fig. 32B). The concentration at the lowest level in the upgradient well (level 1) was uncharacteristically high during specific times each year; none of the other levels showed this pattern. Maximum concentrations shown for LU-21 also reflect this pattern. Therefore, the median concentrations may be more representative of the upgradient conditions. Concentrations from the first downgradient well, LU-22 (mean, 145 mg/L; maximum, 1,020 mg/L), and the second downgradient well, LU-25 (mean, 137 mg/L; maximum 674 mg/L), were generally similar, although values at LU-22 were more extreme. At the third downgradient well, LU-27, the mean concentration dropped to 103 mg/L, and the maximum was 567 mg/L. At the fourth downgradient well, the mean concentration was similar to that at the third downgradient well (mean, 110 mg/L; maximum 513 mg/L). Thus, 228 ft downgradient from the highway, the median concentration at the fourth downgradient well was about 3.5 times the upgradient or background (median) concentration. Concentrations may approach background farther down the flowpath, but no wells were located in that area. Dissolved-chloride concentrations at six sampling levels in each downgradient well at the site during a 4-month period in 1999 are represented as a series of chloride profiles in figure 33. (Each color in the profile represents an additional 75 mg/L of chloride.) This series of profiles shows how chloride moved through the aquifer after deicing chemicals were applied from May through September 1999. The amount and frequency of precipitation and snowmelt recharge and the soil temperature can also affect this movement during a specific time period. During winter 1998–99, deicing-chemical application was very infrequent until January, when deicing was frequent throughout the entire month. Deicing chemicals continued to be applied sporadically from February through early March 1999. These applications were followed by spring and summer precipitation and an accompanying rise in water level. This pattern is shown in the profile plots on figure 33. The tail end of a previous chloride plume can be seen around LU-28, the fourth downgradient well in figure 33A. The vertical distribution of areas of increased chloride concentration can be seen in the first two downgradient wells in figure 33B. Data shown in figure 33C from August 1999, indicate an extreme vertical distribution of chloride concentration, likely a result of the repeatedly high volume of deicing chemicals applied in January 1999. A plume of chloride in the 825 mg/L maximum range can be seen at the first downgradient well, LU-22; the plume dilutes and moves through the system during the next month.

Soil samples were collected on nine occasions at this site during 1993–99 (table A-2 in the appendix). The chloride concentration of the samples collected from the ditch along the highway was 5–54 mg/L and decreased to 2–13 mg/L by 80 ft downgradient from the highway. The data are shown in the appendix in table A-2.

Sodium Concentration

At the upgradient well, LU-21, the mean concentration of sodium was 5 mg/L, and the maximum was 17 mg/L (table 13, fig. 32C). Mean concentration at the fourth downgradient well was about 10 times higher downgradient from the highway, although the concentrations were fairly constant throughout the four downgradient wells (mean, 50–62 mg/L; maximum, 245–484 mg/L).

Calcium Concentration

In addition to sodium chloride and abrasives, varying amounts of either solid or liquid calcium chloride ($CaCl_2$) were applied either to the highway or to the deicing-chemical loads directly, in about 22 percent of the applications, during the study period. The mean concentration at the upgradient well, LU-21, was 52 mg/L, and the maximum was 160 mg/L. The mean concentration of samples from the first, second, and third downgradient wells was 71–92 mg/L and the maximum was 220–243 mg/L. These concentrations decreased gradually to a mean of 76 mg/L and a maximum of 180 mg/L at the fourth downgradient well (table 13, fig. 32D).

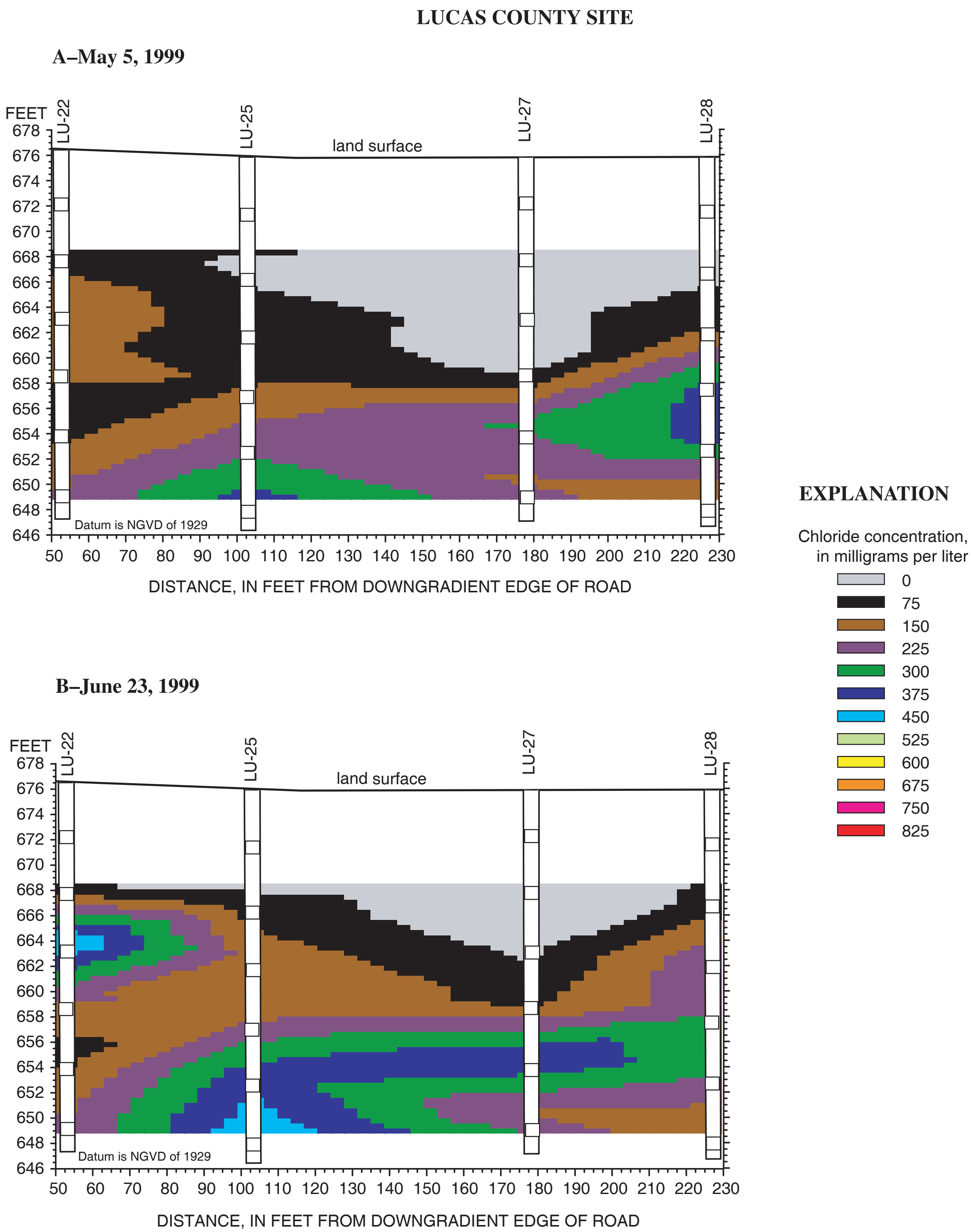


Figure 33. Profiles of chloride concentrations at the study site in Lucas County, Ohio, May 5, 1999, through September 2, 1999.

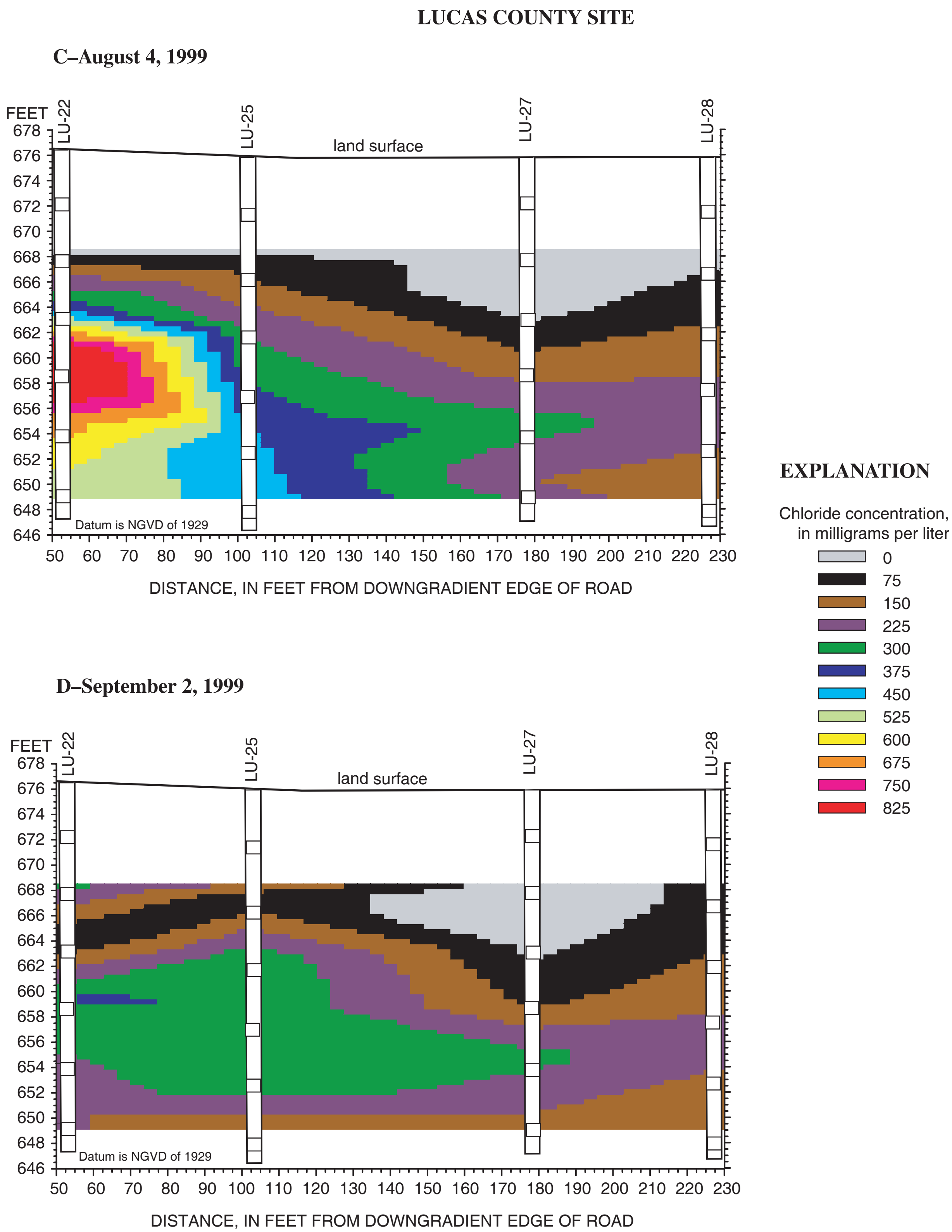


Figure 33. Profiles of chloride concentrations at the study site in Lucas County, Ohio, May 5, 1999, through September 2, 1999.—Continued

Pickaway County Site

Site Characteristics

The Pickaway County site (fig. 34) is on SR 104, 1/4 mile north of the SR 22 junction in Wayne Township near Circleville, Ohio. SR 104 has second-priority designation for ODOT deicing. This site is on an outwash terrace in the Till Plains Section of the Central Lowland Physiographic Province (Fenneman, 1946). The slope of the site area is minimal, 0.4 ft over 420 ft, or 0.001. There is a small intermittent stream about 200 ft to the south and east of the site. About 1,000 ft from the highway on the downgradient side, the land drops somewhat sharply to the next terrace level toward the Scioto River, several miles away. The ditches along the highway are shallow, and the material of the soils and aquifer are porous, allowing for easy infiltration of runoff. The downgradient side of the highway is occasionally used for farmland and pasture. The upgradient side is a mowed lawn and home surrounded by cultivated farmland.

SR 104 is a two-lane, undivided highway that runs north to south. Drainage is by shallow, open ditches. Total pavement width, including shoulders, is 27 ft; the gravel berm is 3–4 ft wide. The highway is straight at this site, but it slopes down slightly to the south where it crosses the intermittent stream.

The soil type is the Eldean-Genesee-Warsaw association; far downgradient is the Eldean loam, and upgradient and downgradient near the road is the Warsaw loam (U.S. Department of Agriculture, 1980c). Both are well drained soils. Beneath the soils layer, the surficial material at this site is brown to gray, fine to coarse sand and gravel to a depth of 30–36 ft. Underlying this sand and gravel is a layer of gray, silty clay of varied thickness. From well logs and maps obtained from ODNR, it is apparent that more sand and gravel underlies this clay to a depth of approximately 100 ft, where the Ohio Black Shale is present (Shrake, 1993a, 1993b). An individual well log was constructed for each of the wells. A geologic section of the site was constructed on the basis of these logs (fig. 35).

The nine-winter (1990–99) average annual use of sodium chloride in Pickaway County as a whole was 1,507 tons (table 1). The maximum for this nine-winter period was 2,758 tons in 1998–99, and the minimum for this period was 698 tons in 1996–97. Data collected at this site (table 14) indicate the nine-winter average annual use of sodium chloride was 4.11 ton/2-ln mi (8,228 lb/2-ln mi), which is 58 percent less than the State average of 9.7 ton/2-ln mi (19,380 lb/2-ln mi) (Ohio Department of Transportation, written commun., 1999). In addition to sodium chloride and abrasives, a small amount of liquid calcium chloride ($CaCl_2$) also was applied to the highway in about 15 percent of the treatments during the study period.

Climate

Average annual precipitation for the area is 38.6 in. (table 3). Average annual temperature for the area is 10.9° C (51.7° F), with the monthly normal high of 29.4° C (85.0° F) in July and the monthly normal low of -7.8° C (17.9° F) in January (Midwestern Regional Climate Center, 2000). Annual precipitation based on data collected at the site, as well as precipitation at the nearest NOAA site, is listed by year in the table below. Average annual snowfall is 16.4 in. for nearby reporting areas. The annual snowfall during the study period averaged 13.8 in. (Midwestern Regional Climate Center, 2000).

Pickaway County site		
Water year	Onsite precipitation (inches)	Nearest NOAA site[1] precipitation (inches)
1991	[2]20.39	[2]24.35
1992	[3]26.48	40.28
1993	33.33	33.71
1994	38.76	[3]43.68
1995	33.11	34.13
1996	41.22	[3]47.33
1997	[3]33.32	[3]40.24
1998	[3]34.58	39.40
1999	24.06	[3]27.30

[1] Refer to table 2 for site name.

[2] No measurements made until February 1991.

[3] Incomplete data.

Hydrogeology

The ground-water level ranged from 6.5 to 13 ft below land surface during the study period at this site (table 3). During the study period, the direction of flow varied from about 45° to 81° to the alignment of the highway, as determined by the triangulation method using available wells; average water-table gradient is about 0.003. At this site, the ground-water level responds to precipitation within 1 day, a result of the porous aquifer materials at the surface. Additional data regarding water-table gradient and flow direction can be found in the appendix in table A-3.

Results of single-well aquifer tests (slug tests) on the aquifer indicate that the hydraulic conductivity is 18 ft/d. Assuming an average gradient of 0.003 and an effective porosity of 40 percent, the ground-water velocity was computed to be 0.14 ft/d.

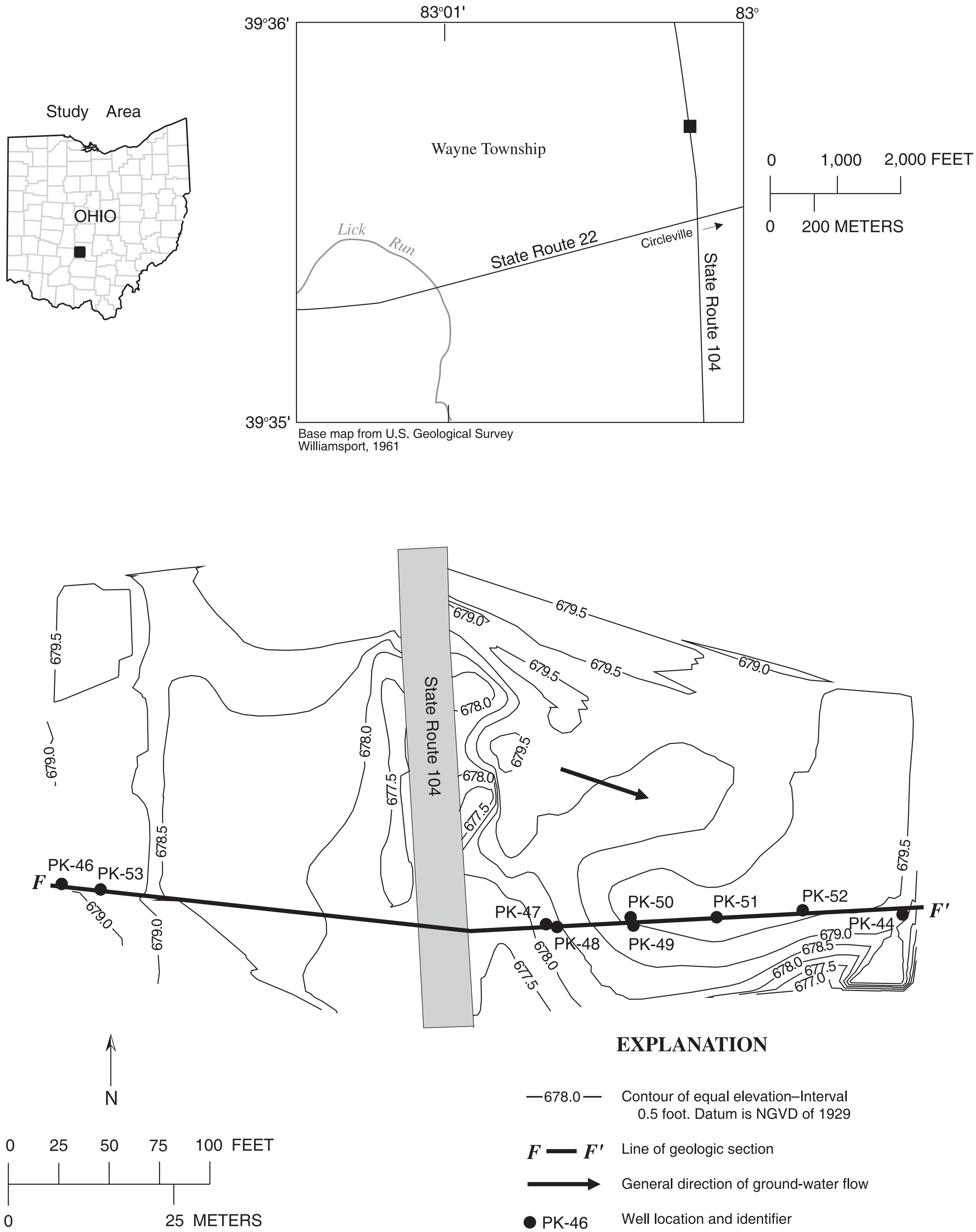
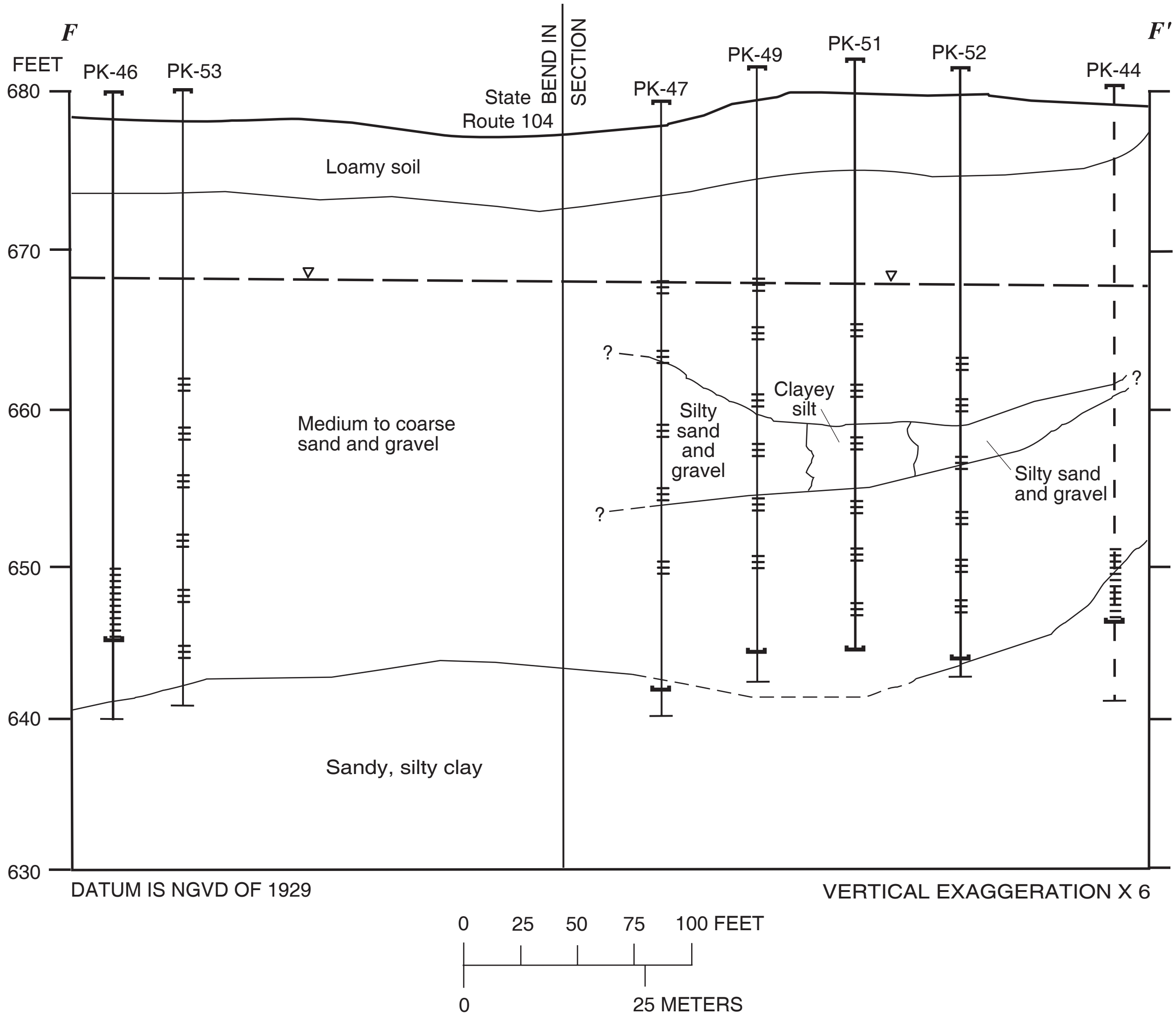


Figure 34. Topography, well locations, and ground-water flow direction, Pickaway County, Ohio, study site.



EXPLANATION

PK-48 Well location and identifier–Well logs on file with the U.S. Geological Survey, Columbus, Ohio, office. Dashed well has been projected onto section line

Top of casing

Sampling interval–Wells with multiple sampling intervals are screened the full length of casing

Bottom of well

Bottom of boring–Wells in which the bottom of the boring extends below the bottom of the well were backfilled to the depth shown as the bottom of the well

Mean water level

Geologic contact–Dashed where approximately located

Figure 35. Geologic section *F-F′*, Pickaway County, Ohio, study site. (Section trace shown in fig. 34.)

Table 14. Sodium chloride application amounts by month and year, Pickaway County, Ohio, study site.

[Amounts measured by pounds per 2-lane mile]

	October	November	December	January	February	March	April	Yearly totals
1990-91	0	0	1,000	650	100	1,100	0	2,850
1991-92	0	0	0	1,300	500	0	0	1,800
1992-93	0	0	0	0	9,250	1,250	0	10,500
1993-94	0	0	1,200	7,800	1,500	0	0	10,500
1994-95	0	0	0	6,000	2,200	1,200	0	9,400
1995-96	0	0	3,600	6,400	1,200	2,400	0	13,600
1996-97	0	700	300	1,700	1,000	0	0	3,700
1997-98	0	800	4,000	300	0	0	0	5,100
1998-99	0	0	1,200	10,800	2,600	2,000	0	16,600
Total	0	1,500	11,300	34,950	18,350	7,950	0	74,050
Average	0	167	1,256	3,883	2,039	883	0	8,228

Effects of Highway Deicing Chemicals on Water Quality

Field-monitored characteristics (rainfall, specific conductance, and ground-water levels recorded from dedicated instrumentation at a well near the first downgradient sampling well) and the amount of sodium chloride applied to the highway are shown in figure 36. The amounts of sodium chloride applied to the highway adjacent to the site, as recorded by each ODOT outpost driver, are listed in table 14. Plots of these characteristics can be used to help compare the events that resulted in increased specific conductance with ambient site conditions and deicer applications. Movement of chloride and other deicing-related constituents from the highway, with time, are indicated by boxplots of laboratory-determined data (figs. 37 and 38).

Field-Monitored Characteristics

Specific Conductance

Specific conductance of ground water at this site varied somewhat during the study period (fig. 36). As is evident from the table in the right-hand column, specific conductance recorded continuously in well PK-48 near the first downgradient water-quality sampling well at this site ranged from a maximum of 933 μS/cm in 1994 to a minimum of 565 μS/cm in 1998 (a range of 368 μS/cm). For comparison, the mean specific conductance of the upgradient well for the study period was 543 μS/cm (table 15).

Pickaway County site		
Water year	Specific conductance, maximum (μS/cm)	Specific conductance, minimum (μS/cm)
1991	[1]717	[1]586
1992	699	585
1993	799	593
1994	933	621
1995	747	610
1996	919	604
1997	792	589
1998	715	565
1999	629	591

[1] No measurements made until February 1991.

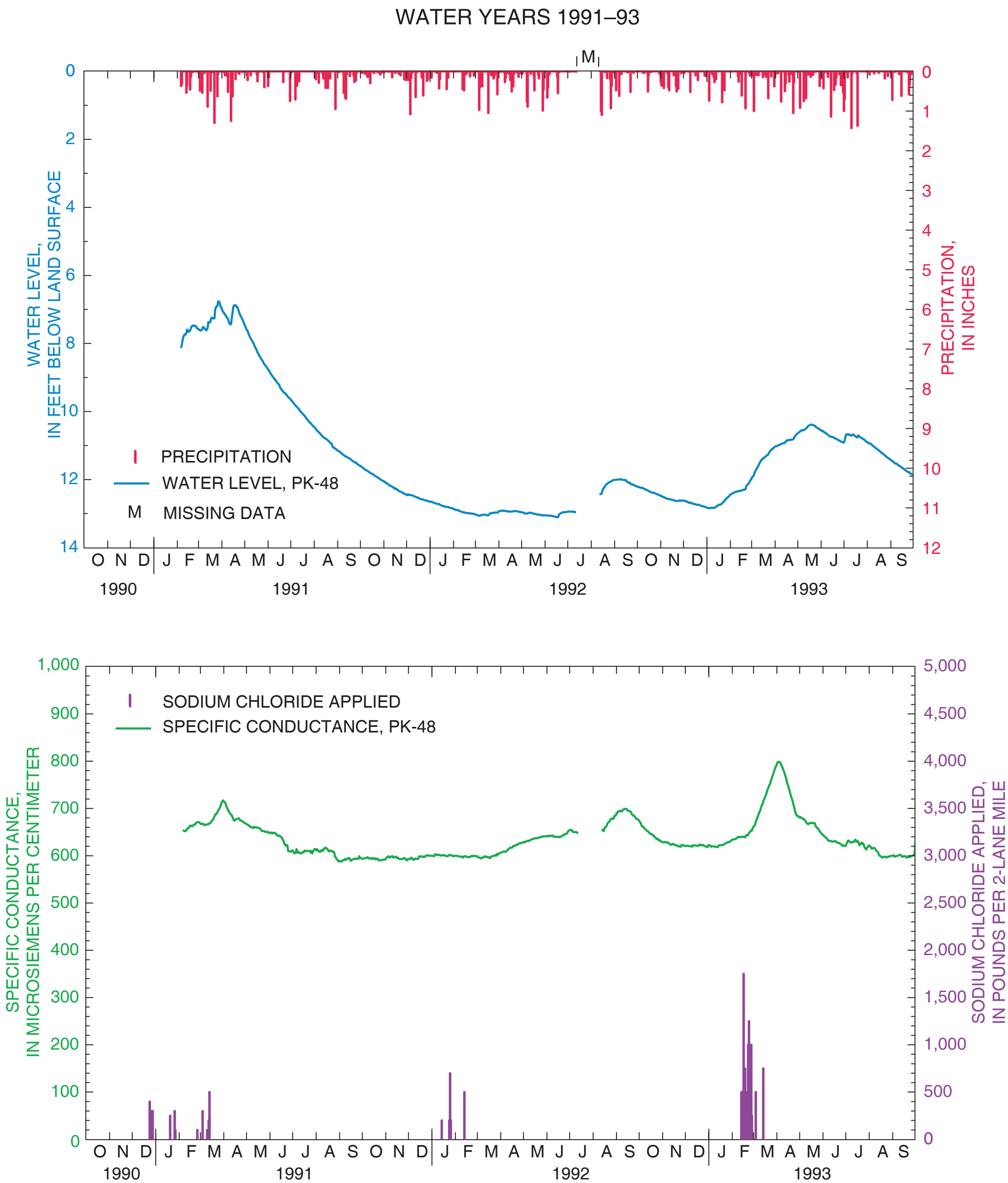


Figure 36. Ground-water levels, precipitation, specific conductance, and sodium chloride application, Pickaway County, Ohio, study site, water years 1991-99.

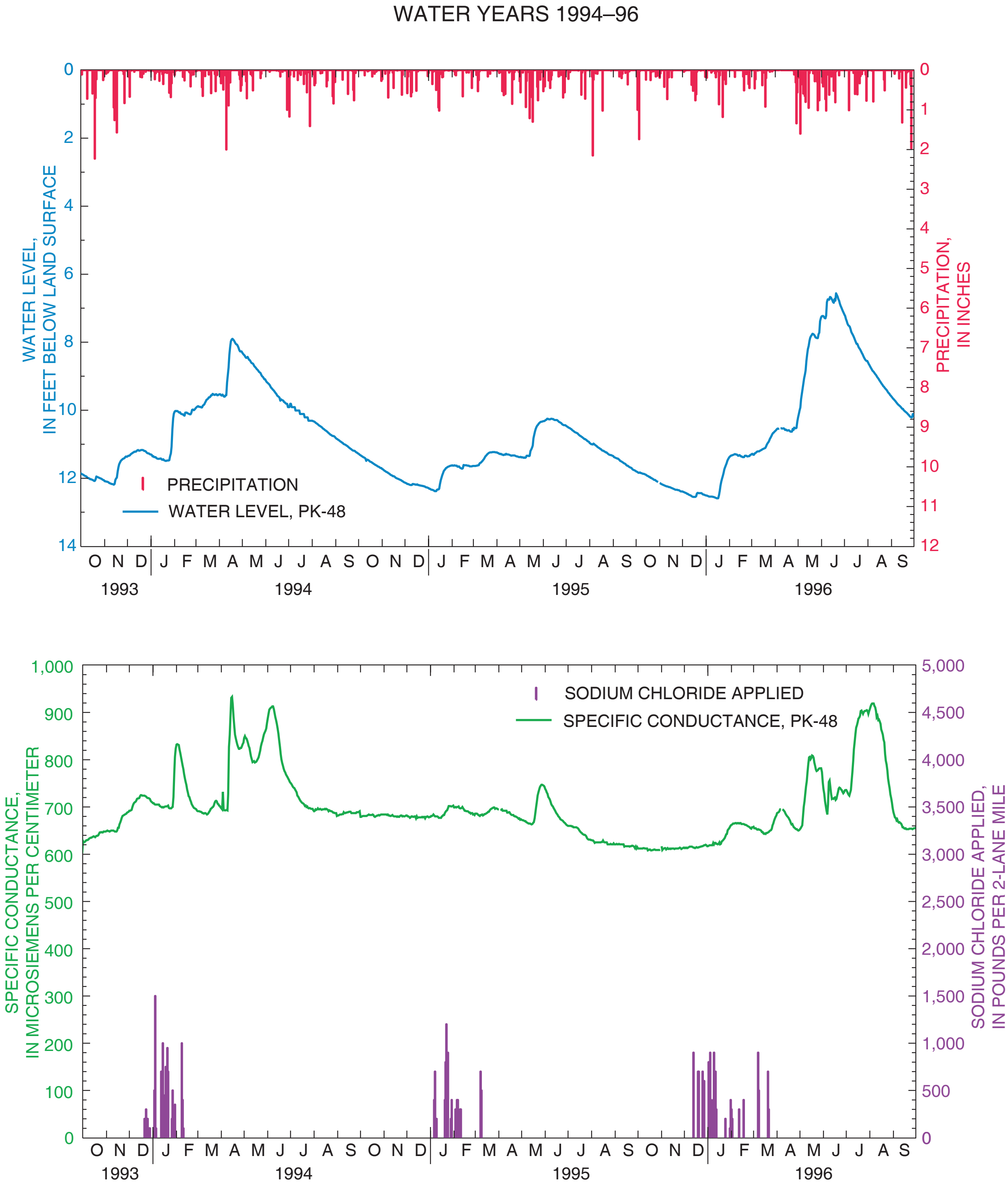


Figure 36. Ground-water levels, precipitation, specific conductance, and sodium chloride application, Pickaway County, Ohio, study site, water years 1991-99.—Continued

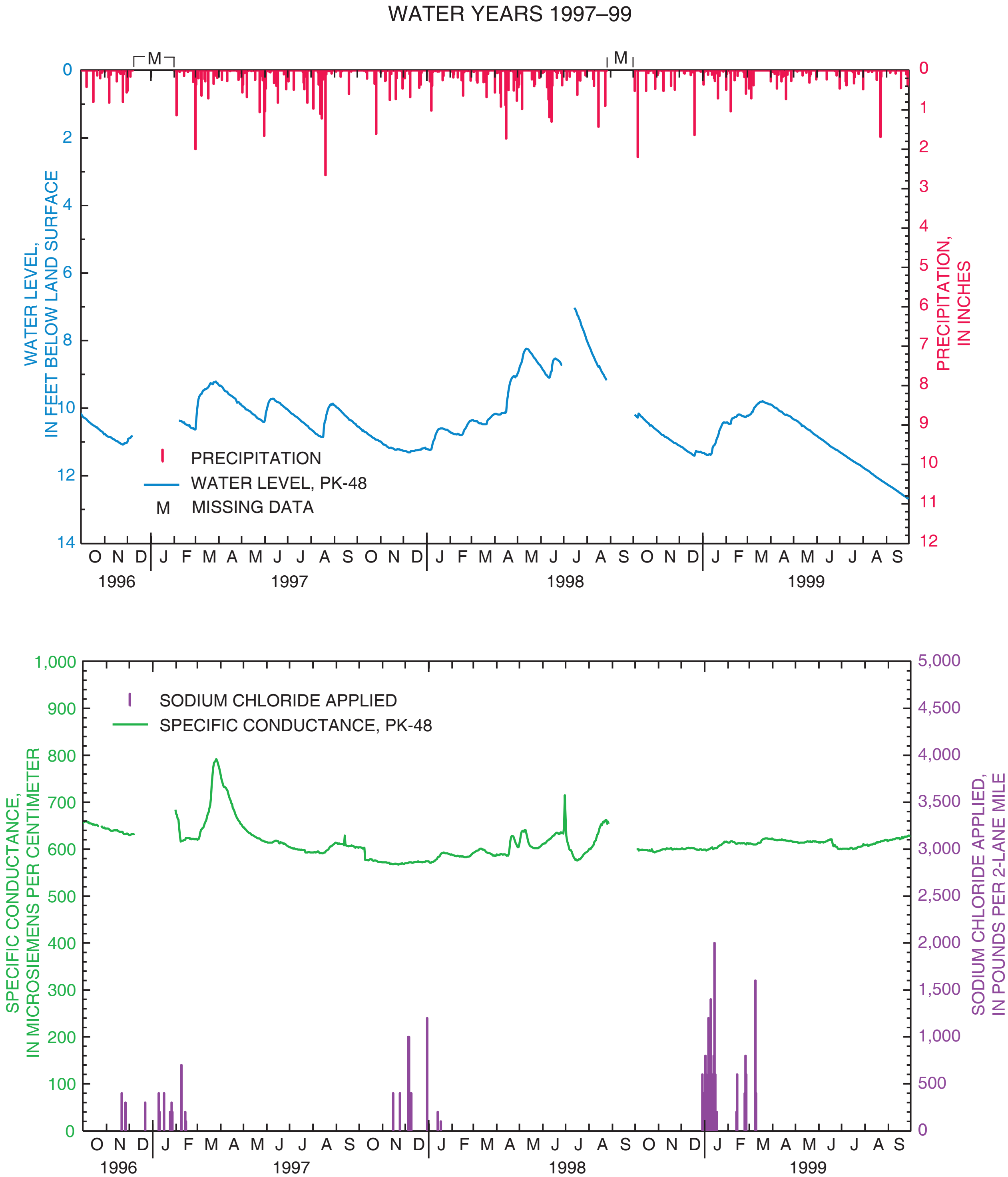


Figure 36. Ground-water levels, precipitation, specific conductance, and sodium chloride application, Pickaway County, Ohio, study site, water years 1991-99.—Continued

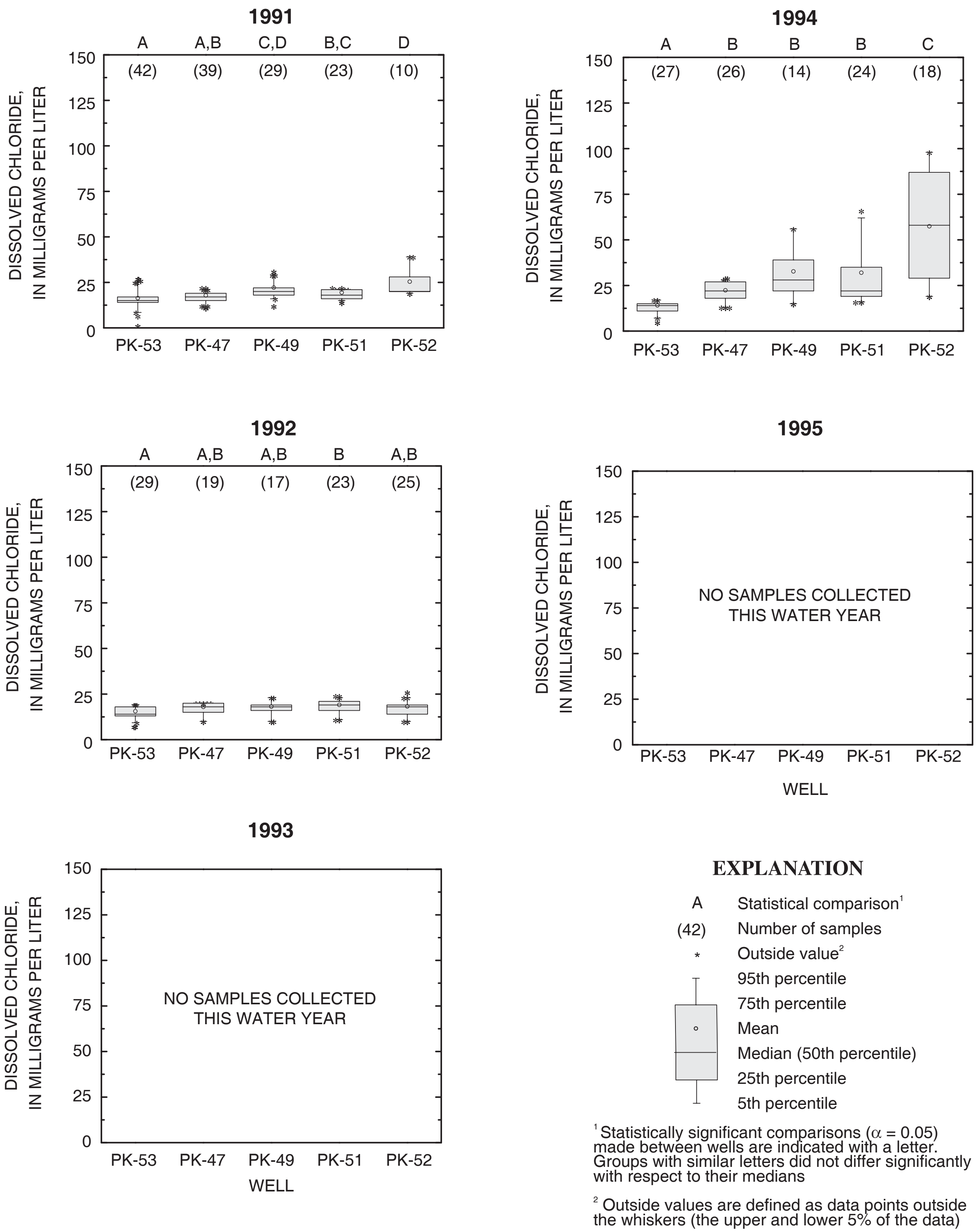


Figure 37. Distribution of concentrations of dissolved chloride in ground-water samples, Pickaway County, Ohio, study site, January 1991-September 1999. (Plots are shown in downgradient order from left to right. Far left plot is upgradient from highway; others are downgradient.)

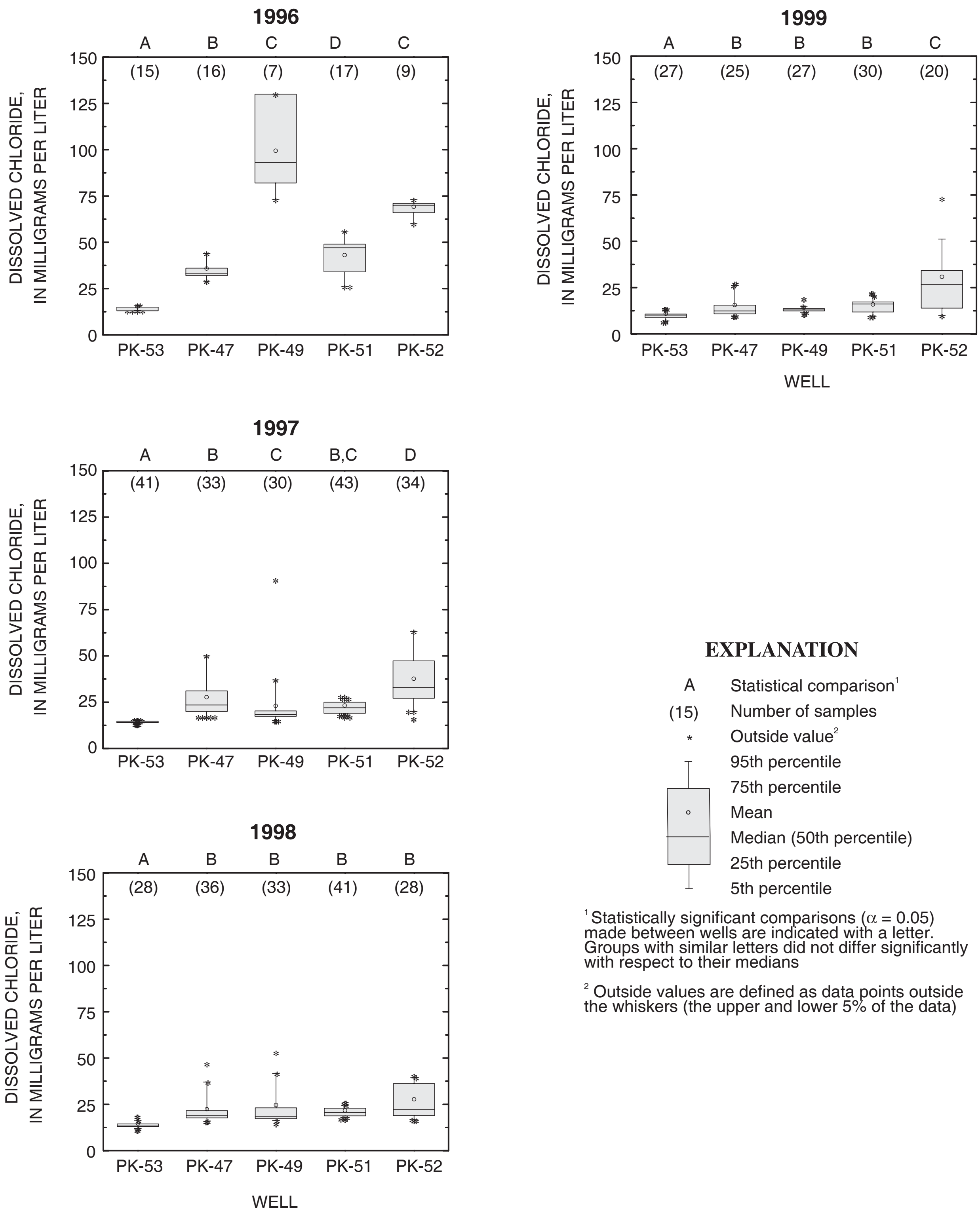


Figure 37. Distribution of concentrations of dissolved chloride in ground-water samples, Pickaway County, Ohio, study site, January 1991-September 1999. (Plots are shown in downgradient order from left to right. Far left plot is upgradient from highway; others are downgradient.)—Continued

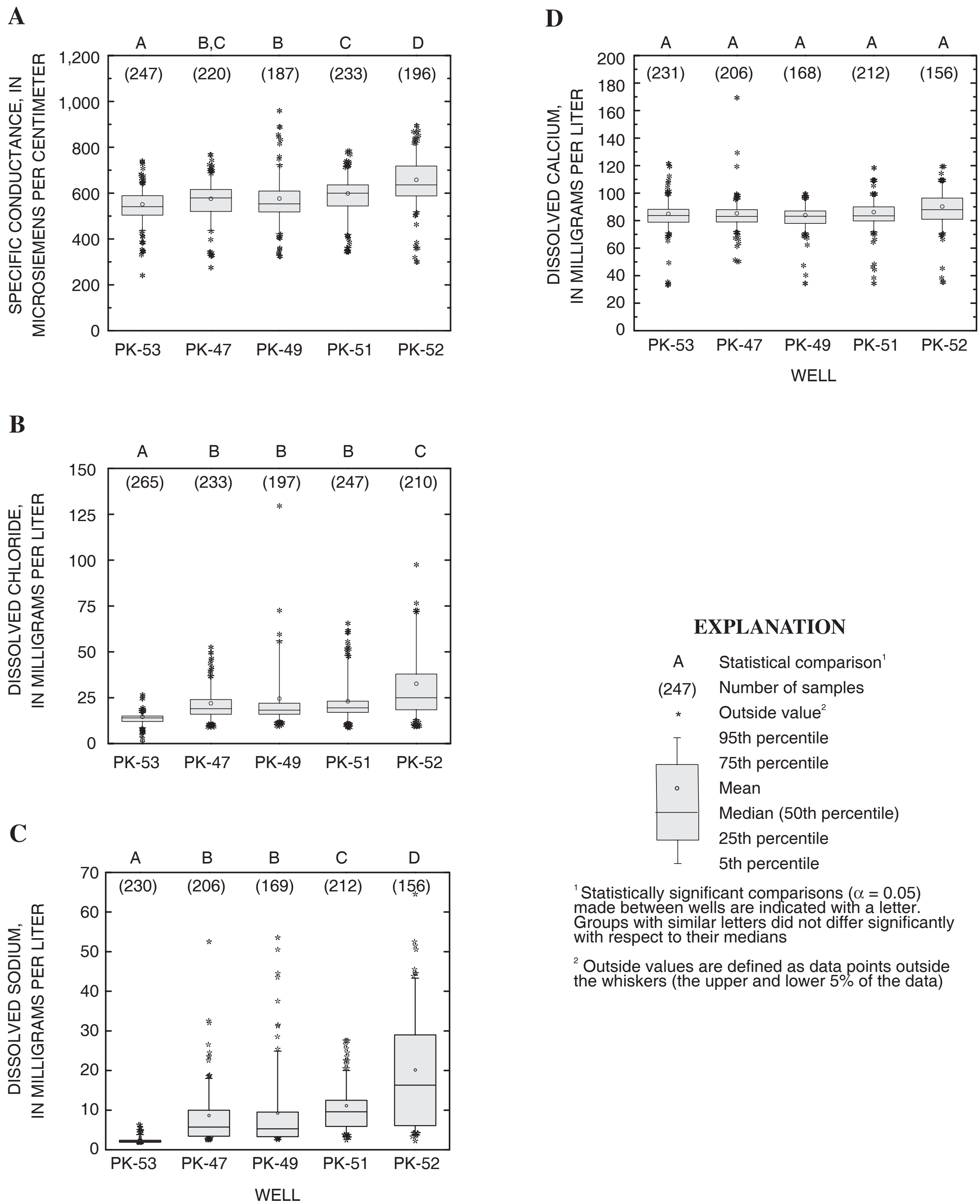


Figure 38. Distribution of (*A*) specific conductance and concentrations of dissolved (*B*) chloride, (*C*) sodium, and (*D*) calcium in ground-water samples, Pickaway County, Ohio, study site, January 1991-September 1999. (Plots are shown in downgradient order from left to right. Far left plot is upgradient from the highway; others are downgradient.)

Table 15. Water-quality data for multilevel wells, Pickaway County, Ohio, study site, water years 1991-99.

[μS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (μS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
PK-53	Upgradient	Maximum	743	122	6	27
		Minimum	245	34	1	1
		Mean	543	84	2	14
		Median	541	84	2	14
		N	247	231	230	265
PK-47	1st downgradient	Maximum	771	170	52	53
		Minimum	279	51	2	9
		Mean	568	84	8	21
		Median	579	83	6	19
		N	220	206	206	233
PK-49	2nd downgradient	Maximum	963	100	53	130
		Minimum	328	35	2	10
		Mean	568	83	8	23
		Median	553	83	5	18
		N	187	168	169	197
PK-51	3rd downgradient	Maximum	787	119	27	66
		Minimum	348	35	2	9
		Mean	590	85	10	22
		Median	600	84	10	20
		N	233	212	212	247
PK-52	4th downgradient	Maximum	898	120	64	98
		Minimum	304	36	2	10
		Mean	650	89	19	32
		Median	636	88	17	25
		N	196	156	156	210

Air and Soil Temperature

During the study period, air temperature at this site ranged from 38.3° C in 1999 to a minimum of -34.1° C in 1994.

For the study period, soil temperature ranged from a maximum of 32.5° C in 1991 to a minimum of 2.2° C in 1994.

Pickaway County site		
Water Year	Air temperature, maximum (° C)	Air temperature, minimum (° C)
1991	[1]37.0	[1]0.0
1992	33.0	-19.8
1993	37.0	-18.9
1994	35.9	-34.1
1995	37.5	-22.4
1996	33.5	-21.5
1997	34.6	-10.2
1998	34.5	-11.4
1999	38.3	-21.2

[1] No measurements made until February 1991.

Pickaway County site		
Water year	Soil temperature, maximum (° C)	Soil temperature, minimum (° C)
1991	[1]32.5	[1]1.0
1992	27.0	8.9
1993	24.6	0.3
1994	25.3	-2.2
1995	26.2	-1.5
1996	24.7	-1.4
1997	24.9	-0.3
1998	24.7	2.0
1999	28.3	-1.7

[1] No measurements made until February 1991.

Laboratory-Determined Characteristics

At the Pickaway County site, large amounts of deicing chemicals were rarely applied to the highway (table 14). Temperatures were often above freezing throughout the winters, and, in some cases, sampling was discontinued temporarily when little or no deicing chemicals were applied. No samples at all were collected in water years 1993 and 1995. Cold temperatures sometimes created icy conditions, but large snowfalls were uncommon. Summary statistics of the water-quality data collected at upgradient and downgradient wells for all 7 available years of data combined are listed in table 15. These same statistics for each year individually are listed in the appendix in table A-9. Boxplots of chloride concentration data collected at upgradient and downgradient wells for each of the 7 years individually are shown in figure 37. Boxplots of specific conductance, dissolved calcium, dissolved sodium, and dissolved chloride for water from all levels of the upgradient well and the four downgradient sampling wells for 1991–99 combined are shown in figure 38. Patterns that emerge from those data are noted below.

Specific Conductance

At the upgradient well, PK-53, the mean specific conductance was 543 µS/cm, and the maximum was 743 µS/cm (table 15, fig. 38A). Values were generally constant throughout the four downgradient wells (mean, 568–650 µS/cm; maximum 771–963 µS/cm). Thus, 168 ft downgradient from the highway, the mean specific conductance at the fourth downgradient well was about the same as the upgradient or background concentration. A pattern of increases and decreases is not seen at this site because of low constituent concentrations and a low deicing-chemical input into the aquifer.

Chloride Concentration

At the upgradient well, PK-53, the mean concentration of chloride was 14 mg/L, and the maximum was 27 mg/L. Concentrations were slightly higher at the downgradient wells (mean, 21–32 mg/L; maximum, 53–130 mg/L) (table 15, fig. 38B). Concentrations remained fairly constant downgradient along the flowpath through the fourth downgradient well. Thus, 168 ft downgradient from the highway, the mean concentration at the fourth downgradient well was about 2.3 times the upgradient or background concentration. The pattern observed at most of the other sites was not observed here because of low chloride concentrations resulting from a low deicing-chemical input into the aquifer in most years.

Dissolved-chloride concentrations at six sampling levels in each downgradient well at the site during a 5-month period in 1996 are represented as a series of chloride profiles in figure 39. (Each color in the profile represents an additional 15 mg/L of chloride.) This series of profiles shows how chloride moved through the aquifer in several episodes after deicing chemicals were applied during the winter 1995–96 at the site. The amount and frequency of precipitation and snowmelt recharge and the soil temperature can also affect this movement during a specific time period. During winter 1995–96, deicing material application was most frequent in December and January, although application occurred sporadically through March. This pattern is shown in figure 39 in the profile plots. A plume of chloride in the 120 mg/L maximum range can be seen in the aquifer during July 1996 (fig. 39B). Although not highly concentrated, this plume may be more visible than most because of several large and frequent storms during April through August, which facilitated chemical movement into the aquifer more quickly and steadily than other years. By December 1996, the chloride concentration had returned to background (fig. 39E).

Soil samples were collected on nine occasions at this site during 1993–99 (table A-2 in the appendix). The chloride concentration of the samples collected from the ditch along the highway ranged from 6 to 92 mg/L and decreased to 5–56 mg/L by 80 ft downgradient from the highway. The data are shown in the appendix in table A-2.

Sodium Concentration

At the upgradient well, PK-53, the mean concentration of sodium was 2 mg/L, and the maximum was 6 mg/L (table 15, fig. 38C). Concentrations were slightly higher at the downgradient wells (mean, 8–19 mg/L; maximum, 27–64 mg/L); however, concentrations at all wells were lowest among all of the study sites. Concentrations remained fairly constant downgradient along the flowpath through the fourth downgradient well. Thus, 168 ft downgradient from the highway, the mean concentration at the fourth downgradient well was about 9 times the upgradient or background concentration; however, because concentrations in all wells were low, this increase is negligible in terms of water-quality considerations. A pattern of changing sodium concentrations in the downgradient wells is not evident, because of low concentrations and a low deicing-chemical input into the aquifer.

Calcium Concentration

In addition to sodium chloride and abrasives, liquid calcium chloride ($CaCl_2$) was applied to the highway only once during the study period. This is reflected in the uniformity of the mean calcium concentration from the upgradient well, PK-53 (84 mg/L), through the aquifer to the fourth downgradient well, PK-52 (89 mg/L) (table 15, fig. 38D).

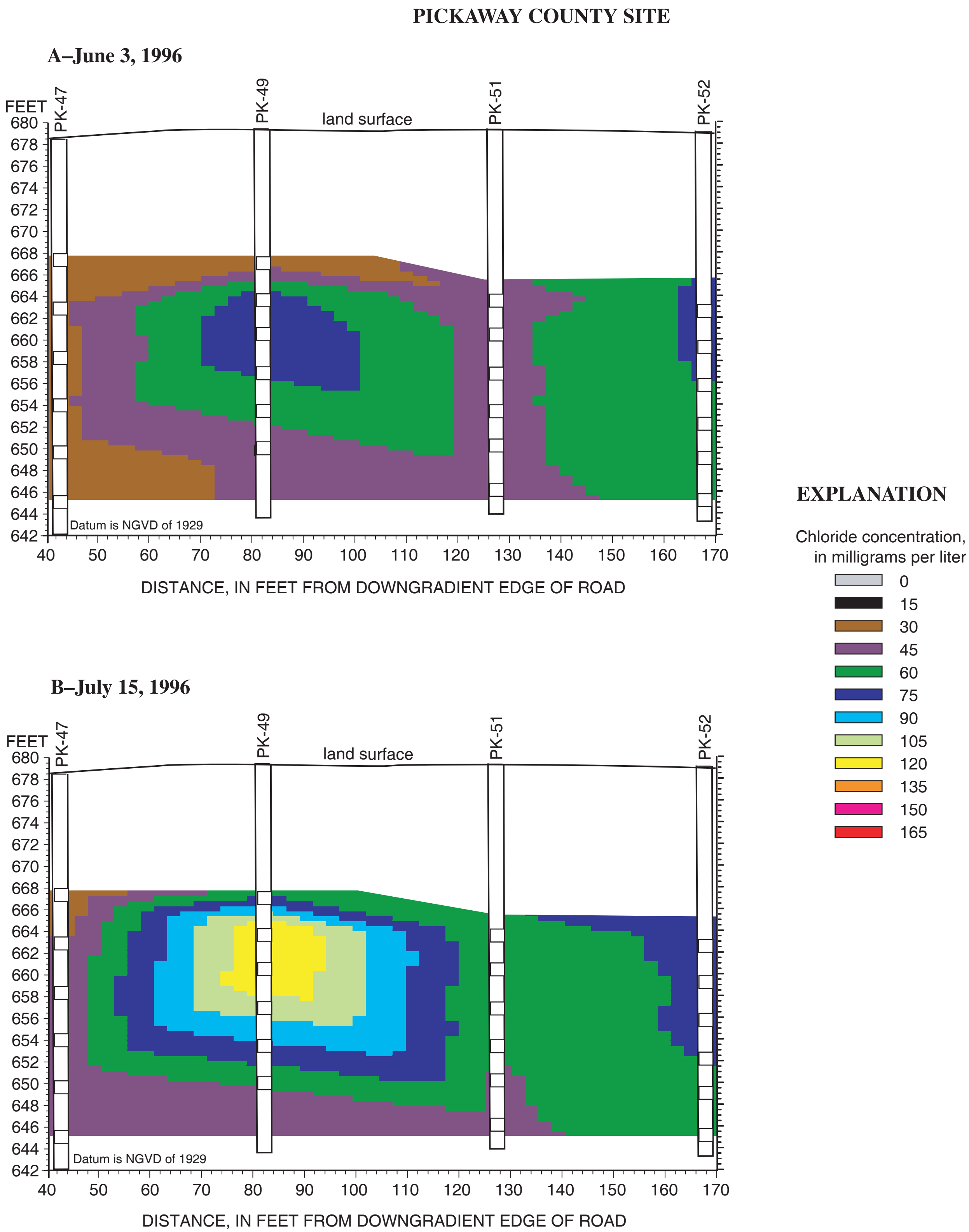


Figure 39. Profiles of chloride concentrations at the study site in Pickaway County, Ohio, June 3, 1996, through December 9, 1996.

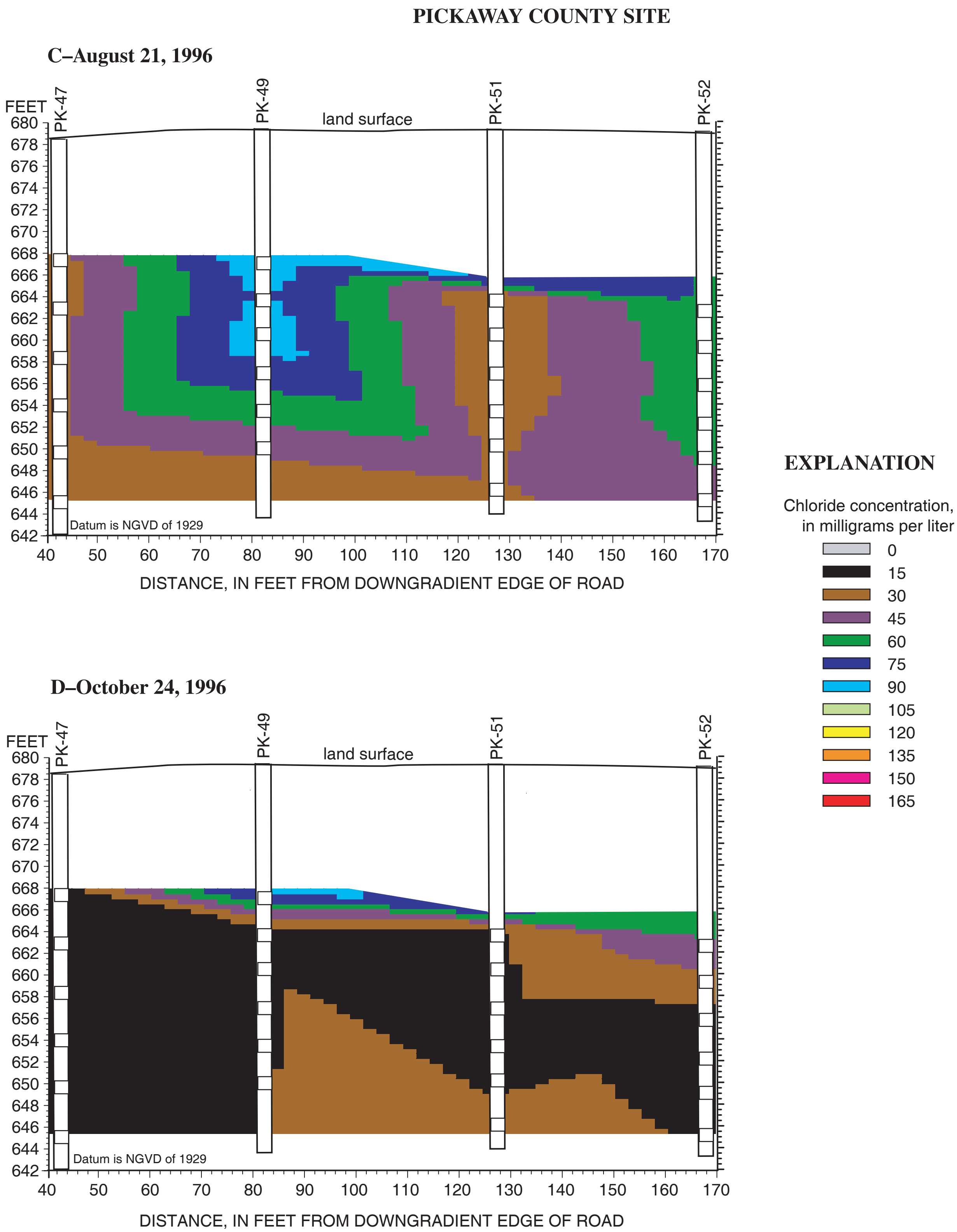


Figure 39. Profiles of chloride concentrations at the study site in Pickaway County, Ohio, June 3, 1996, through December 9, 1996.—Continued

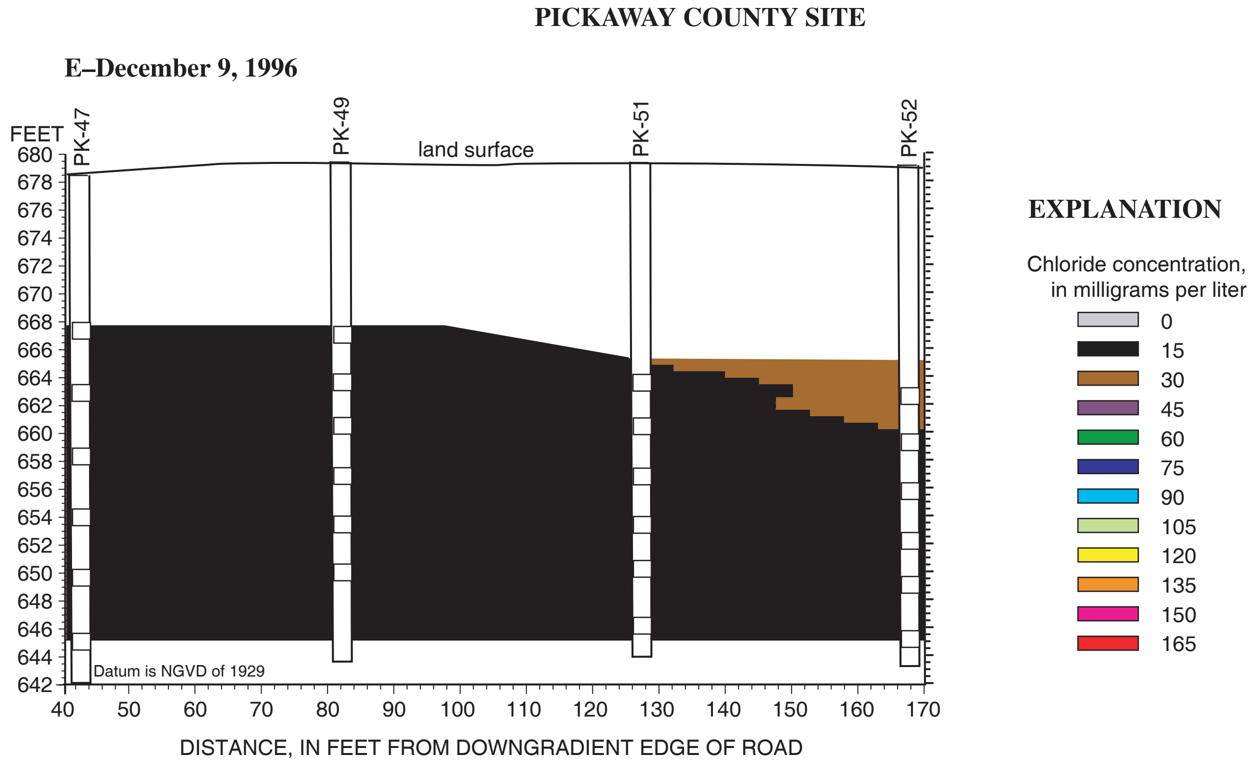


Figure 39. Profiles of chloride concentrations at the study site in Pickaway County, Ohio, June 3, 1996, through December 9, 1996.—Continued

Portage County Site

Site Characteristics

The Portage County site (fig. 40) is on SR 14, 2.75 mi northwest of the SR 44 junction in Ravenna Township near Ravenna, Ohio. SR 14 has first-priority designation for ODOT deicing. This site is in the Southern New York Section of the Appalachian Plateaus Physiographic Province (Fenneman, 1946) and is on a kame terrace formed above the Cuyahoga River Valley between the Killbuck and Grand River lobes of the Wisconsin glacier. The terrain is flat, with only a slight slope from the road in the downgradient direction. On the downgradient side, the land surface dips into a small drainage ditch, then rises about 5 ft and levels off to a flat field, which slopes very gently downward toward a stream about 500 ft from the road. On the upgradient side, a small drainage ditch levels off to the woodland at approximately the same elevation as the road surface. The slope of the area is about 4.7 ft over 130 ft, or 0.036. The downgradient side of the highway is an unused, previously mowed field with seedling trees. Just northwest of the site is a rural home surrounded by a mowed lawn. The upgradient side is all in pine woodland with an open area to the southeast planted in crops.

SR 14 is a two-lane, undivided highway that runs northwest to southeast. Drainage is by shallow open ditches. Total pavement width, including shoulders, is 30 ft; the gravel berm is 3–4 ft wide. The highway is fairly flat and straight at this site, but drops slightly in elevation 1,000 ft to the northwest.

The soils are of the Chili-Oshtemo-Wooster association; far downgradient is the poorly drained Jimtown loam, upgradient and downgradient near the road is the well-drained Chili silt loam, and along the road to the southeast is the poorly drained Damascus loam (U.S. Department of Agriculture, 1978). Beneath the soil layer, the surficial material at the site is a brown, medium to very coarse sand and gravel. A thick, gray, clayey silt underlies these materials at about 15 ft below land surface. Bedrock, most likely the Pennsylvanian Sharon Sandstone of the Pottsville Formation (Swinford and Larsen, 1996; Slucher and Larsen, 1996), is present at about 40 ft below land surface, according to local well logs obtained from ODNR. An individual well log was constructed for each of the wells. A geologic section of the site was constructed on the basis of these logs (fig. 41).

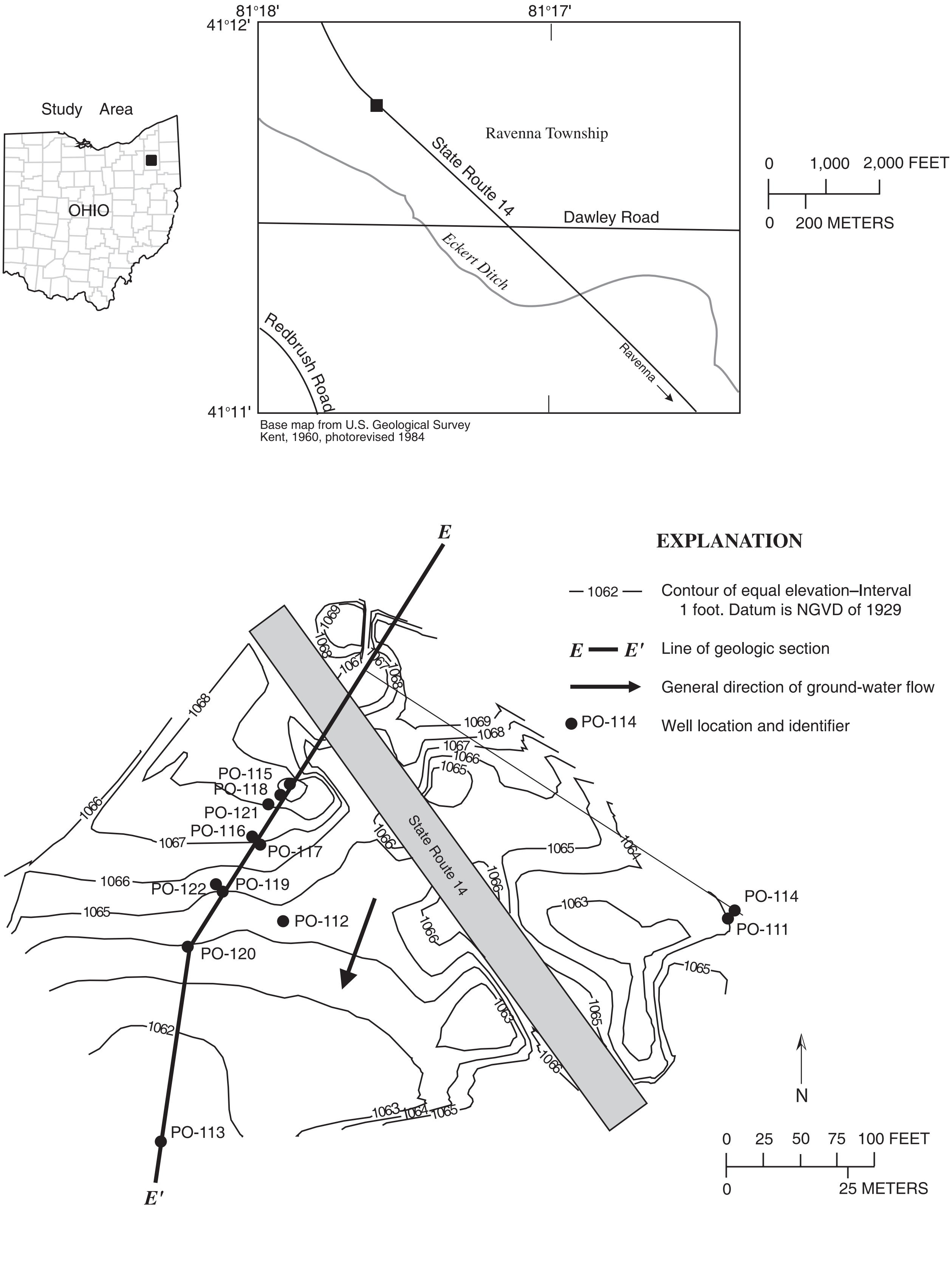
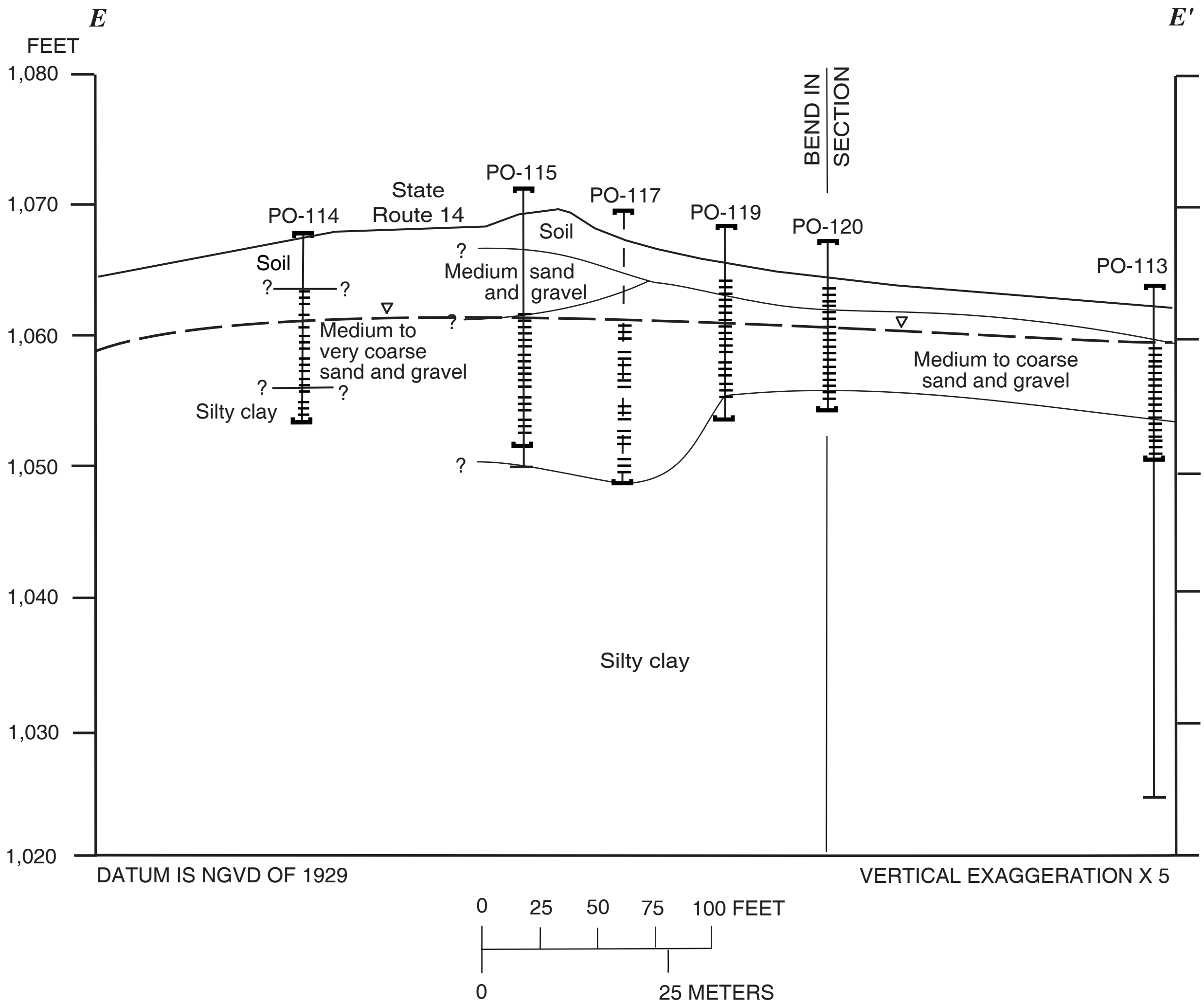
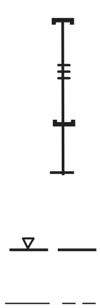


Figure 40. Topography, well locations, and ground-water flow direction, Portage County, Ohio, study site.



EXPLANATION



PO-114 Well location and identifier–Well logs on file with the U.S. Geological Survey, Columbus, Ohio, office

Top of casing

Sampling interval–Wells with multiple sampling intervals are screened the full length of casing

Bottom of well

Bottom of boring–Wells in which the bottom of the boring extends below the bottom of the well were backfilled to the depth shown as the bottom of the well

Mean water level

Geologic contact–Dashed where approximately located

Figure 41. Geologic section *E-E'*, Portage County, Ohio, study site. (Section trace shown in fig. 40.)

Table 16. Sodium chloride application amounts by month and year, Portage County, Ohio, study site.

[Amounts measured by pounds per 2-lane mile]

	October	November	December	January	February	March	April	Yearly totals
1990-91	0	0	2,400	9,400	4,285	400	0	16,485
1991-92	0	1,000	1,570	7,814	3,000	5,400	400	19,184
1992-93	0	600	2,400	3,800	9,800	6,200	0	22,800
1993-94	2,600	850	4,700	9,800	9,900	8,550	0	36,400
1994-95	0	0	1,100	9,400	10,512	2,000	0	23,012
1995-96	0	3,325	9,510	8,800	4,950	6,067	400	33,052
1996-97	0	2,800	3,400	16,740	10,000	0	0	32,940
1997-98	0	1,800	4,889	5,775	986	10,210	0	23,660
1998-99	0	0	11,850	23,325	6,200	9,100	0	50,475
Total	2,600	10,375	41,819	94,854	59,633	47,927	800	258,008
Average	289	1,153	4,647	10,539	6,626	5,325	89	28,667

The nine-winter (1990–99) average annual use of sodium chloride in Portage County, as a whole, was 9,251 tons (table 1). The maximum for this nine-winter period was 16,096 tons in 1998–99, and the minimum for this period was an estimated 6,000 tons in 1992–93. Data collected at this site (table 16) indicate the nine-winter average annual use of sodium chloride was 14.33 ton/2-ln mi (28,667 lb/2-ln mi), which is 48 percent greater than the State average of 9.7 ton/2-ln mi (19,380 lb/2-ln mi) (Ohio Department of Transportation, written commun., 1999). In addition to sodium chloride and abrasives, a small amount of liquid calcium chloride ($CaCl_2$) also was applied to the highway in about 15 percent of the applications during the study period.

Climate

Average annual precipitation for the area is 41.5 in. (table 3). Average annual temperature for the area is 9.1° C (48.4° F), with the monthly normal high of 27.3° C (81.1° F) in July and the monthly normal low of -9.2° C (15.4° F) in January (Midwestern Regional Climate Center, 2000). Annual precipitation based on data collected at the site, as well as precipitation at the nearest NOAA site, is listed by year in the table below. Average annual snowfall is 62.9 in. for nearby reporting areas; however, the average annual snowfall during the study period was 39.5 in. (Midwestern Regional Climate Center, 2000).

Portage County site		
Water year	Onsite precipitation (inches)	Nearest NOAA site[1] precipitation (inches)
1991	[2] 19.46	[2]21.45
1992	[3]20.69	41.02
1993	36.37	38.90
1994	[3]40.82	42.61
1995	27.31	36.22
1996	[3]12.18	45.79
1997	[4]-	41.91
1998	[4]-	[3]36.49
1999	[4]-	37.44

[1] Refer to table 2 for site name.

[2] No measurements made until February 1991.

[3] Incomplete data.

[4] No data.

Hydrogeology

The ground-water level ranged from 4.4–9.5 ft below land surface during the study period at this site (table 3). During the study period, the direction of flow varied from about 48° to 87° to the alignment of the highway, as determined by the triangulation method using available wells; average water-table gradient is about 0.006. At this site, the ground-water level responds to precipitation within 1 day, a result of the porous aquifer materials at the surface and the shallow water table. Additional data regarding water-table gradient and flow direction can be found in the appendix in table A-3.

Results of single-well aquifer tests (slug tests) on the aquifer indicate that the hydraulic conductivity is 20 ft/d.

Assuming an average gradient of 0.006 and an effective porosity of 38 percent, the ground-water velocity was computed to be 0.32 ft/d.

Effects of Highway Deicing Chemicals on Water Quality

Field-monitored characteristics (rainfall, specific conductance, and ground-water levels recorded from dedicated instrumentation at a well near the first downgradient sampling well) and the amount of sodium chloride applied to the highway are shown in figure 42. The amount of sodium chloride applied to the highway adjacent to each site, as recorded by each ODOT outpost driver, is listed on table 16. Plots of these characteristics can be used to help compare the events that resulted in increased specific conductance with ambient site conditions and deicer applications. Movement of chloride and other deicing-related constituents from the highway, with time, are indicated by boxplots of laboratory-determined data (figs. 43 and 44).

Field-Monitored Characteristics

Specific Conductance

Specific conductance of ground water varied considerably during the study period (fig. 42). As is evident from the table below, specific conductance recorded continuously in well PO-116 or PO-121 near the first downgradient water-quality sampling well at this site ranged from a maximum value of 2,930 µS/cm in 1999, to a minimum of 119 µS/cm in 1994. For comparison, the mean specific conductance at the upgradient well for the study period was 461 µS/cm (table 17).

Portage County site		
Water year	Specific conductance, maximum (µS/cm)	Specific conductance, minimum (µS/cm)
1991	[1]2,080	[1]329
1992	2,540	136
1993	2,000	125
1994	2,020	119
1995	1,520	[2]1,060
1996	1,330	410
1997	1,500	341
1998	1,570	296
1999	2,930	266

[1] No measurements made until February 1991.

[2] Incomplete data.

Air and Soil Temperature

During the study period, air temperature at this site ranged from 36.0° C in 1991 and 1999 to a minimum of -32.2° C in 1994.

Portage County site		
Water Year	Air temperature, maximum (° C)	Air temperature, minimum (° C)
1991	[1]36.0	[1]-15.5
1992	31.9	-19.1
1993	35.9	-24.9
1994	34.6	-32.2
1995	35.7	-19.7
1996	33.7	-25.5
1997	33.8	-25.1
1998	34.3	-17.3
1999	36.0	-19.4

[1] No measurements made until February 1991.

During the study period, soil temperature ranged from 28.5° C in 1992 to -0.4° C in 1994.

Portage County site		
Water Year	Soil temperature, maximum (° C)	Soil temperature, minimum (° C)
1992	[1]28.5	[1]12.9
1993	26.2	0.4
1994	27.1	-0.4
1995	28.4	0.1
1996	24.3	0.4
1997	22.1	0.3
1998	22.3	0.5
1999	23.5	-0.1

[1] No measurements made until July 1992.

Laboratory-Determined Characteristics

The amount of deicing chemicals applied to the highway at the Portage County site was fairly steady during the winter months (table 16). Cold temperatures often created icy conditions, and substantial snowfalls were common. Summary statistics of the water-quality data collected at upgradient and downgradient wells for all 9 years sampled during 1991–99 are listed in table 17. These same statistics for each year individually are listed in the appendix in table A-10.

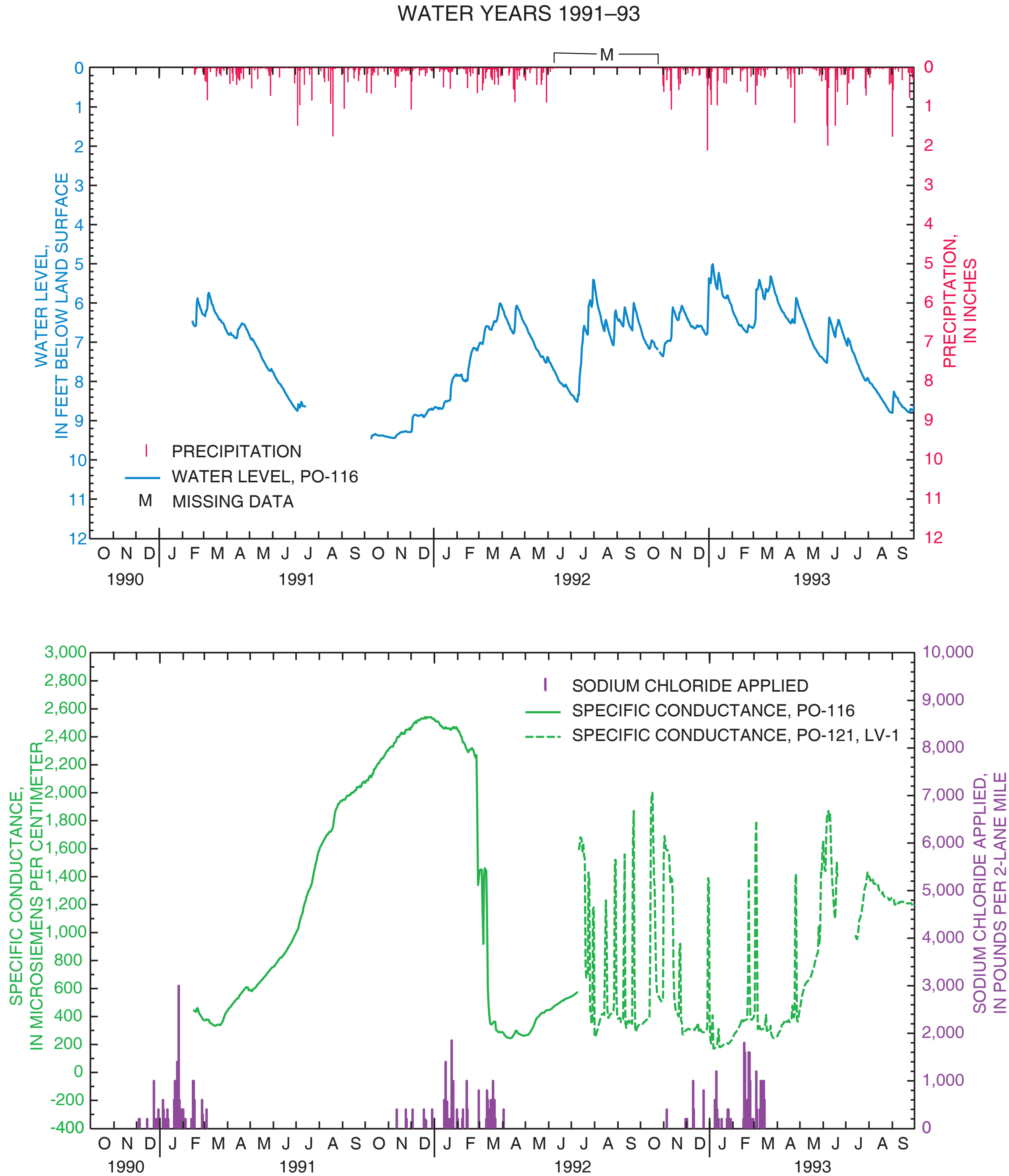
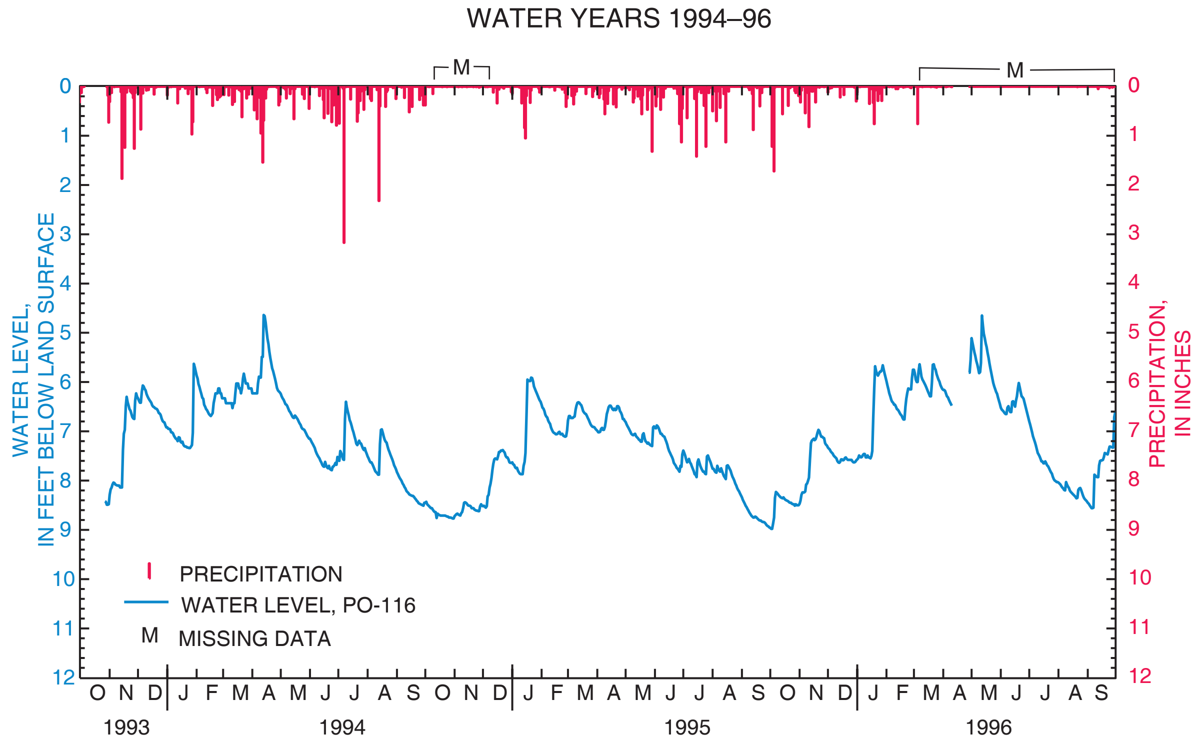


Figure 42. Ground-water levels, precipitation, specific conductance, and sodium chloride application, Portage County, Ohio, study site, water years 1991-99.



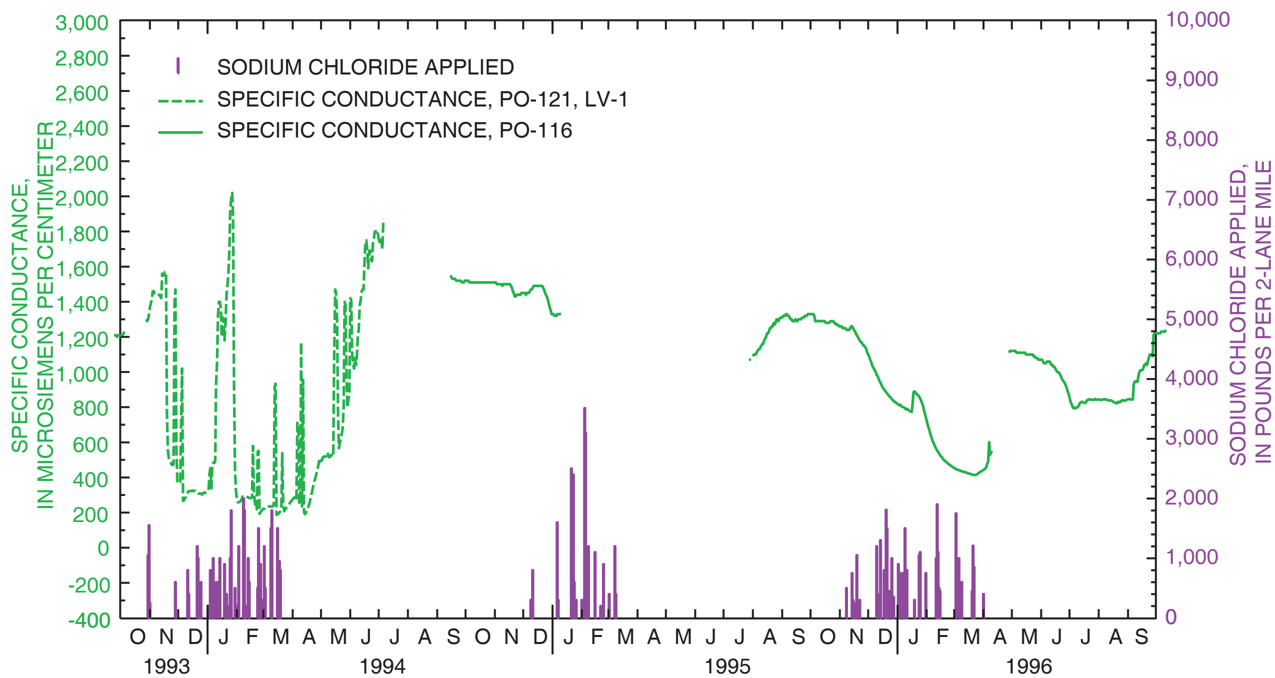


Figure 42. Ground-water levels, precipitation, specific conductance, and sodium chloride application, Portage County, Ohio, study site, water years 1991-99.—Continued

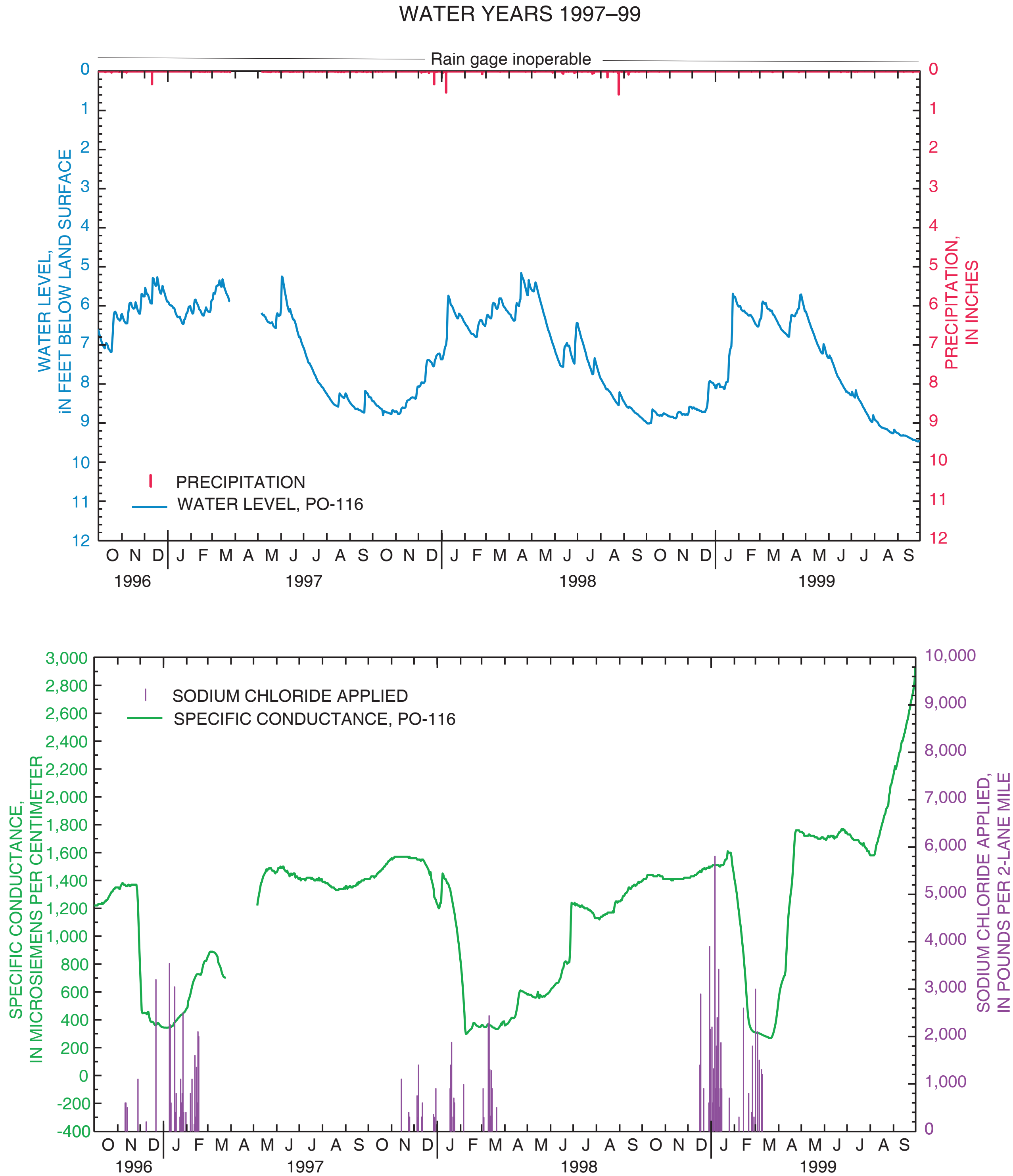


Figure 42. Ground-water levels, precipitation, specific conductance, and sodium chloride application, Portage County, Ohio, study site, water years 1991-99.—Continued

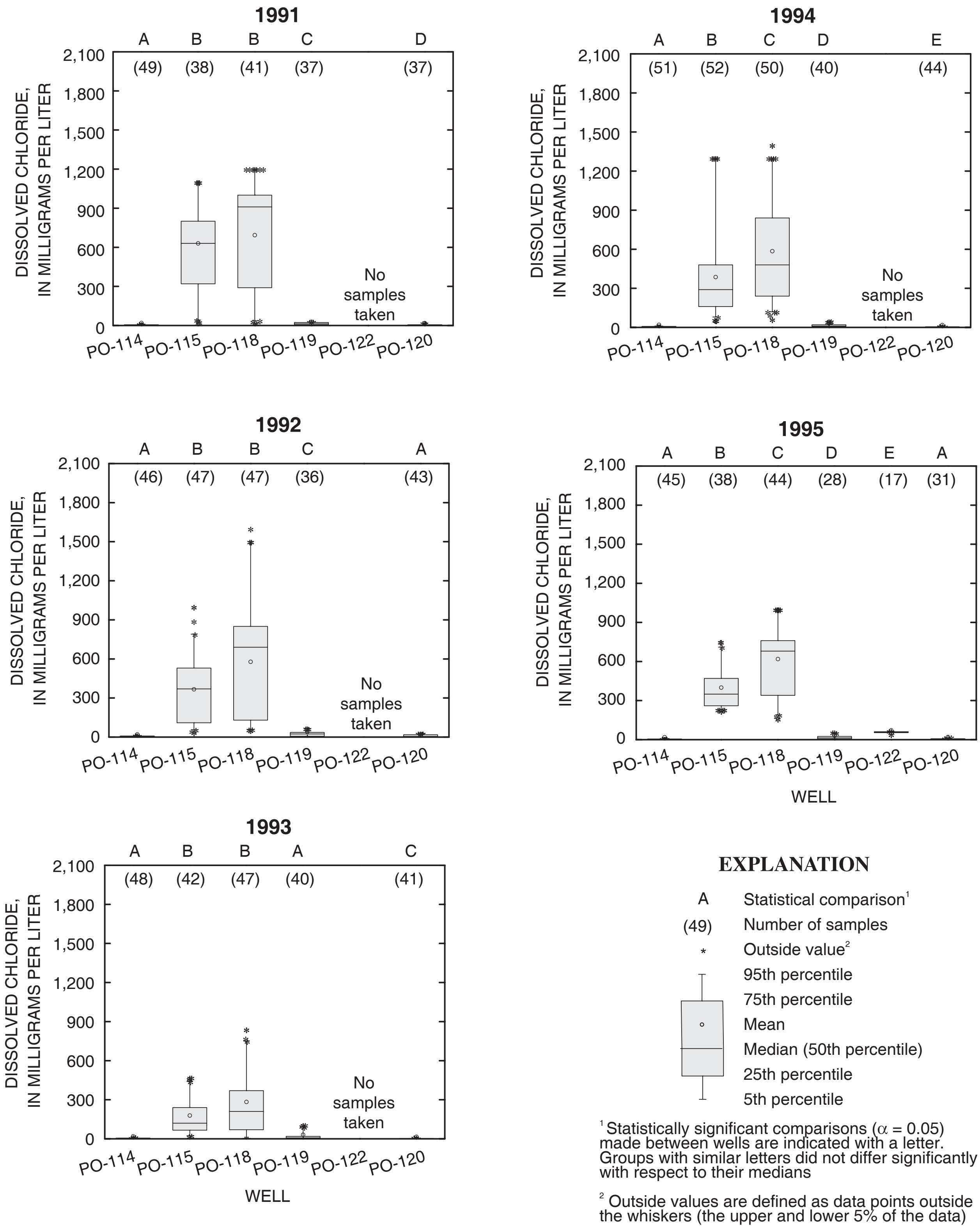


Figure 43. Distribution of concentrations of dissolved chloride in ground-water samples, Portage County, Ohio, study site, January 1991-September 1999. (Plots are shown in downgradient order from left to right. Far left plot is upgradient from highway; others are downgradient.)

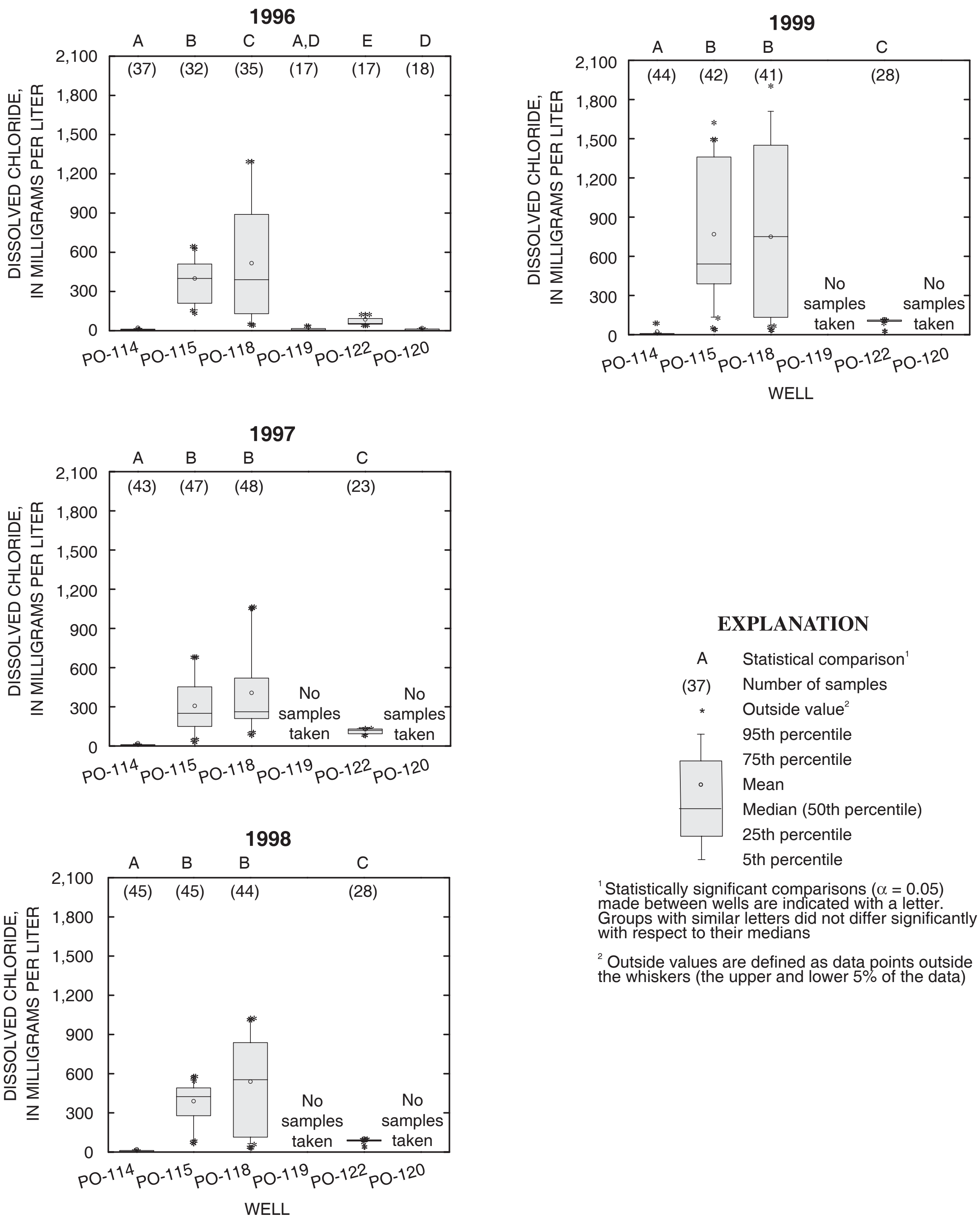


Figure 43. Distribution of concentrations of dissolved chloride in ground-water samples, Portage County, Ohio, study site, January 1991-September 1999. (Plots are shown in downgradient order from left to right. Far left plot is upgradient from highway; others are downgradient.)—Continued

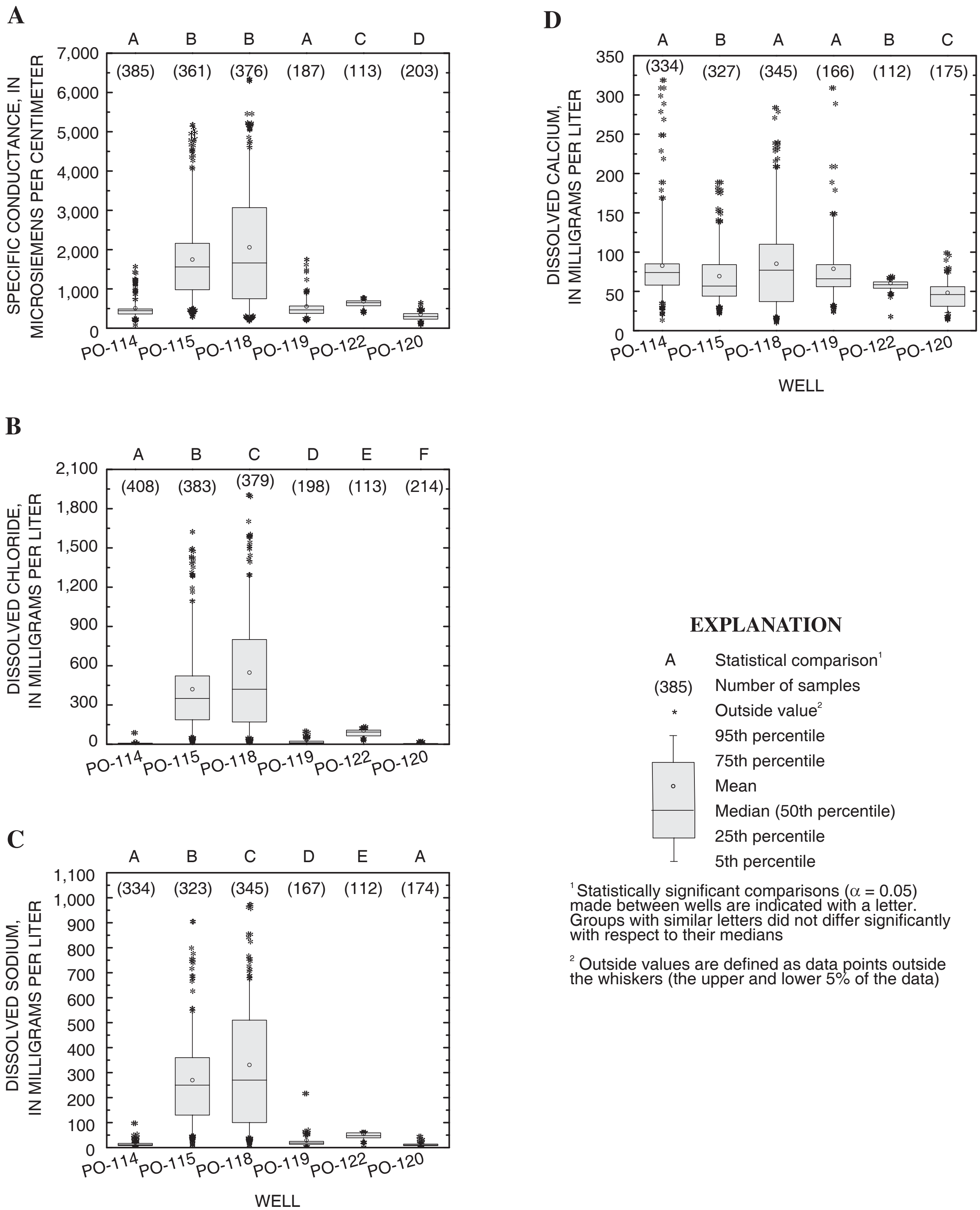


Figure 44. Distribution of (*A*) specific conductance and concentrations of dissolved (*B*) chloride, (*C*) sodium, and (*D*) calcium in ground-water samples, Portage County, Ohio, study site, January 1991-September 1999. (Plots are shown in downgradient order from left to right. Far left plot is upgradient from the highway; others are downgradient.)

Table 17. Water-quality data for multilevel wells, Portage County, Ohio, study site, water years 1991-99.

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
PO-114	Upgradient	Maximum	1,590	320	101	94
		Minimum	104	0	1	0
		Mean	461	80	14	7
		Median	446	74	11	6
		N	385	334	334	408
PO-115	1st downgradient	Maximum	5,200	190	908	1,630
		Minimum	310	23	13	1
		Mean	1,702	67	263	406
		Median	1,560	57	250	350
		N	361	327	323	383
PO-118	2nd downgradient	Maximum	6,360	285	976	1,910
		Minimum	212	11	11	2
		Mean	2,011	83	324	534
		Median	1,660	77	270	420
		N	376	345	345	397
PO-119	3rd downgradient	Maximum	1,770	310	220	106
		Minimum	218	25	6	1
		Mean	508	76	22	18
		Median	466	66	18	11
		N	187	166	167	198
PO-122	3rd downgradient	Maximum	794	70	64	140
	alternate well	Minimum	408	19	5	33
		Mean	637	58	47	90
		Median	649	59	49	93
		N	113	112	112	113
PO-120	4th downgradient	Maximum	671	100	48	27
		Minimum	107	15	2	0
		Mean	306	46	11	5
		Median	296	46	10	4
		N	203	175	174	214

Boxplots of chloride concentration data collected at upgradient and downgradient wells for each of the 9 years individually are shown in figure 43. Boxplots of specific conductance, dissolved calcium, dissolved sodium, and dissolved chloride for water from all levels of the upgradient well and the four downgradient sampling wells for 1991–99 combined are shown in figure 44. Patterns that emerge from those data that require further discussion are noted below.

Specific Conductance

At the upgradient well, PO-114, the mean specific conductance was 461 µS/cm, and the maximum was 1,590 µS/cm (table 17, fig. 44A). Values increased considerably at the first two downgradient wells. At the first downgradient well, the mean specific conductance was 1,702 µS/cm, and the maximum was 5,200 µS/cm. At the second downgradient well, the mean value was 2,011 µS/cm, and the maximum was 6,360 µS/cm. Values remained elevated downgradient along the flowpath through the second downgradient well. At the third downgradient well, PO-119, and the fourth downgradient well, PO-120, specific conductance was much lower (mean, 508–306 µS/cm maximum, 1,770–671 µS/cm) than at the first and second downgradient wells. At the fourth downgradient well, mean and maximum values were lower than those found at the upgradient well. At the alternate third downgradient well, PO-122, the mean specific conductance was 637 µS/cm and the maximum was 794 µS/cm (Dec. 1994–Sept. 1999). This result also may be due to the configuration of the clay units present. Although the specific conductance at the upgradient and third and fourth downgradient wells was relatively high among the sites sampled, and the chloride concentration is among the lowest, another ion besides chloride may be contributing to the high specific conductance at this site.

Chloride Concentration

At the upgradient well, PO-114, the mean concentration of chloride was 7 mg/L and the maximum was 94 mg/L (table 17, fig. 44B). Concentrations were much higher than background, however, at the first two downgradient wells. At the first downgradient well, the mean concentration was 406 mg/L and the maximum was 1,630 mg/L. At the second downgradient well, the mean concentration was 534 mg/L and the maximum was 1,910 mg/L. At the third downgradient well, PO-119, and the fourth downgradient well, PO-120, concentrations were near background (mean, 5–18 mg/L; maximum, 27–106 mg/L). These wells are completed just above a clay confining unit but are slightly shallower than the first two downgradient wells. At the alternate third downgradient well, PO-122, the mean concentration was 90 mg/L and the maximum was 140 mg/L (Dec. 1994–Sept. 1999). The fate of the ground water with elevated chloride found in the first and second downgradient wells is unknown at this time beyond a distance of about 100 ft downgradient from the highway; however it is suspected that density flow may drive the water with higher chloride concentration downward into the less permeable silt and clay layer. Dissolved-chloride concentrations at each of six sampling levels in each well at the site are shown in figure 45. In figures 45I and 45J an additional well, PO-122, is shown. This well was installed in December 1994 in an attempt to drill deeper into the aquifer to determine the flowpath of the ground water with elevated chloride concentrations. Because it was installed later than the original multilevel wells, however, a multilevel tube sampler was installed. A truck-mounted auger vehicle would have been needed to install an additional multilevel dialysis sampler. The newly established tree saplings in the area would also have been destroyed with the installation. Samples from well PO-122 did not reveal answers to the question of where the ground water with elevated chloride levels was flowing because the lower three levels of the tube sampler were frequently clogged with silt. Analysis of the deicing chemical movement through the aquifer at this site was based on the available data.

A vertical distribution of chloride concentrations is evident during most times of the year in the first downgradient well, and, to a slightly lesser extent, in the second downgradient well. For example, in PO-115 in June 1994, chloride concentration in levels 1 and 2 reached 1,300 mg/L but was only 650 mg/L in level 6, although samples from levels 1, 2, and 3 were often in a similar, elevated range. Preferential flowpaths can be monitored in this way, especially at sites with mixed aquifer materials. Dissolved-chloride concentrations during a 13-month period in 1994–95 at six sampling levels in each downgradient well are represented as a series of chloride profiles in figure 45. (Each color in the profile represents an additional 150 mg/L of chloride.) It is easy to see at this site that water with elevated chloride concentraton is most highly concentrated in the bottom levels of the well, even at the first downgradient well. Deicing chemicals were applied at the Portage County site frequently and in moderately high levels from January through March 1994. Frequent spring rainfall helped keep the ground-water level up during the spring months, which helped move the chemicals into the aquifer. Although the aquifer is shallow at this site (average 10–18 ft depth), the ground-water velocity, at 0.47 ft/d, helped move the chemicals through the aquifer in a very visible plume (fig. 45) during summer and fall 1994. The series of chloride profiles in figure 45 shows an example of ground water with a chloride concentration in the less than (<) 100 mg/L range in February 1994 (fig. 45) increasing to a maximum of 1,300 mg/L by June 1994 (fig. 45) and returning to a concentration of <200 mg/L by March 1995 (fig. 45).

Soil samples were collected on nine occasions at this site from 1993–99 (table A-2 in the appendix). Chloride concentrations of samples collected in the ditch along the highway were 6–154 mg/L and decreased to 10–27 mg/L by 80 ft downgradient from the highway. The data are shown in the appendix in table A-2.

Sodium Concentration

At the upgradient well, PO-114, the mean concentration of sodium was 14 mg/L, and the maximum was 101 mg/L (table 17, fig. 44C). Concentrations were substantially higher at the first two downgradient wells. At the first downgradient well, the mean concentration was 263 mg/L, and the maximum was 908 mg/L. At the second downgradient well, the mean concentration was 324 mg/L, and the maximum was of 976 mg/L. Concentrations rose slightly downgradient along the flowpath through the second downgradient well. At the third downgradient well, PO-119, and the fourth downgradient well, PO-120, concentrations were much lower (mean, 22 and 11 mg/L; maximum, 220 and 48 mg/L) than those found at the first and second downgradient wells. At the alternate third downgradient well, PO-122, the mean concentration was 47 mg/L, and the maximum was 64 mg/L (Dec. 1994–Sept. 1999). As noted in the chloride discussion above, the ground water carrying the dissolved deicing chemicals appears to be diverted between the second and third downgradient well.

Calcium Concentration

In addition to sodium chloride and abrasives, liquid calcium chloride ($CaCl_2$) was applied to the highway in about 22 percent of the applications, during the study period. The mean concentration at the upgradient well, PO-114, was 80 mg/L, which decreased downgradient to a mean of 46 mg/L at the fourth downgradient well, PO-120 (table 17, fig. 44D). Maximum concentrations at the upgradient and first three downgradient wells ranged from 190 to 320 mg/L, but declined considerably to 70–100 mg/L by the furthest downgradient wells (PO-120, PO-122).

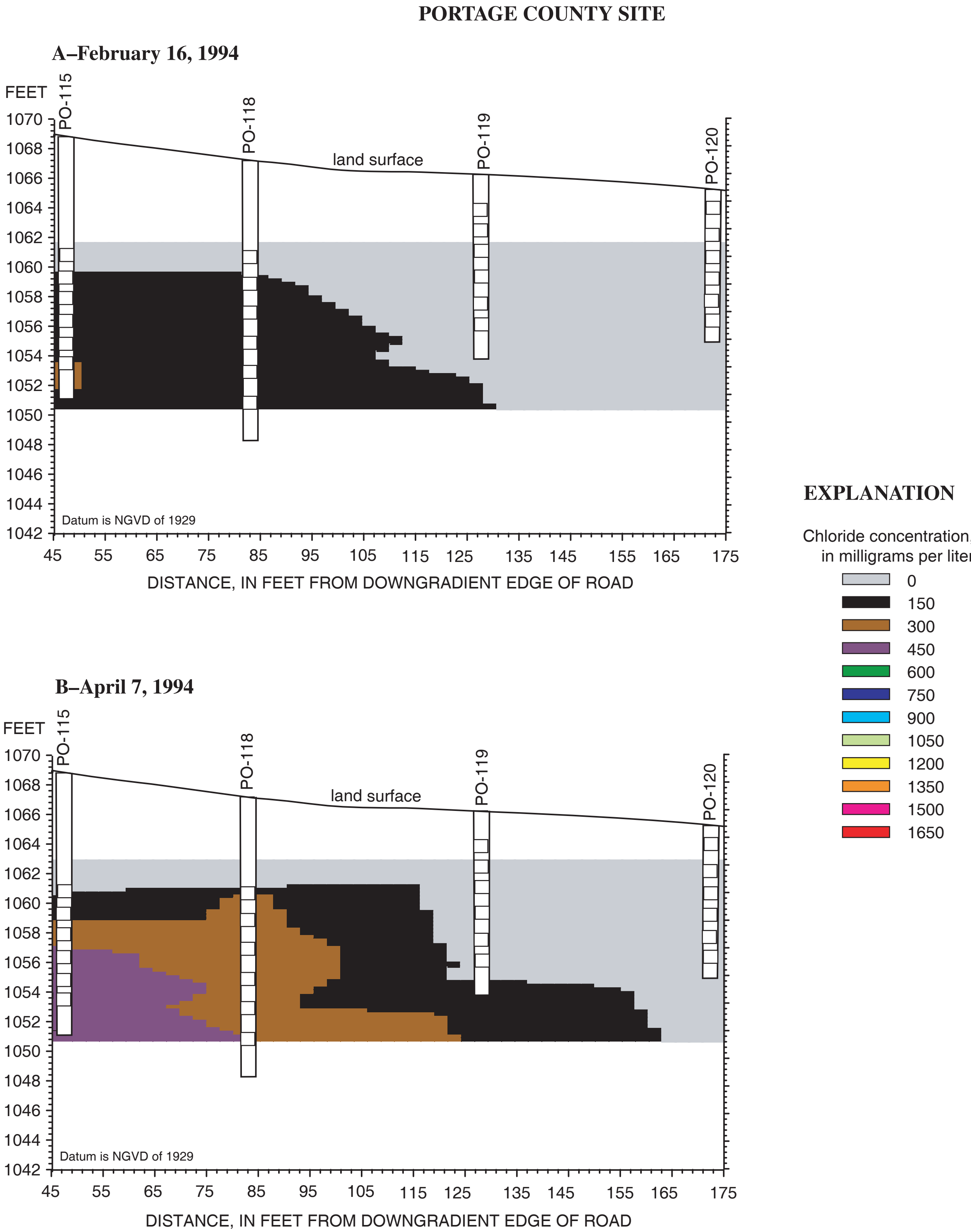


Figure 45. Profiles of chloride concentrations at the study site in Portage County, Ohio, February 16, 1994, through March 2, 1995.

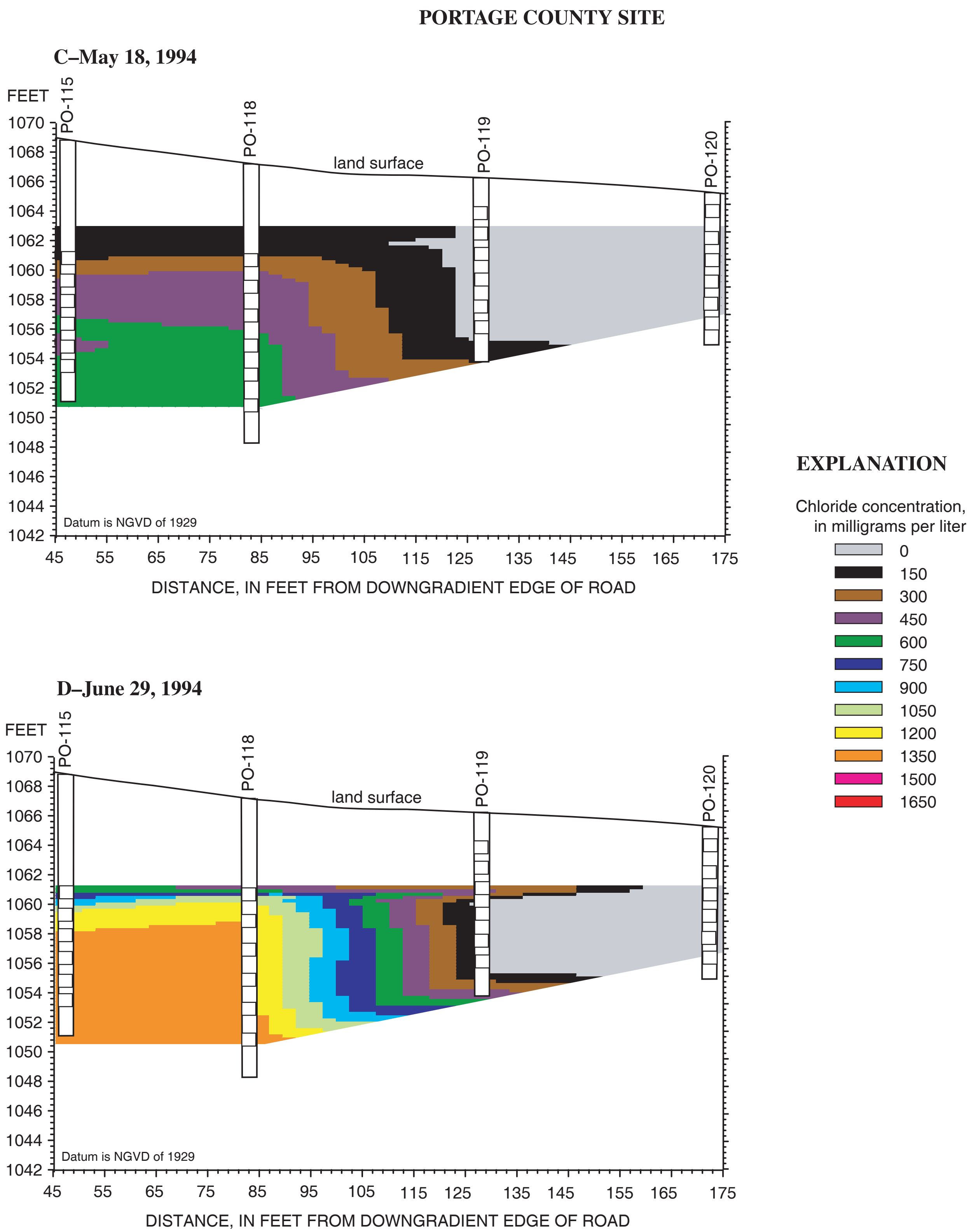


Figure 45. Profiles of chloride concentrations at the study site in Portage County, Ohio, February 16, 1994, through March 2, 1995.—Continued

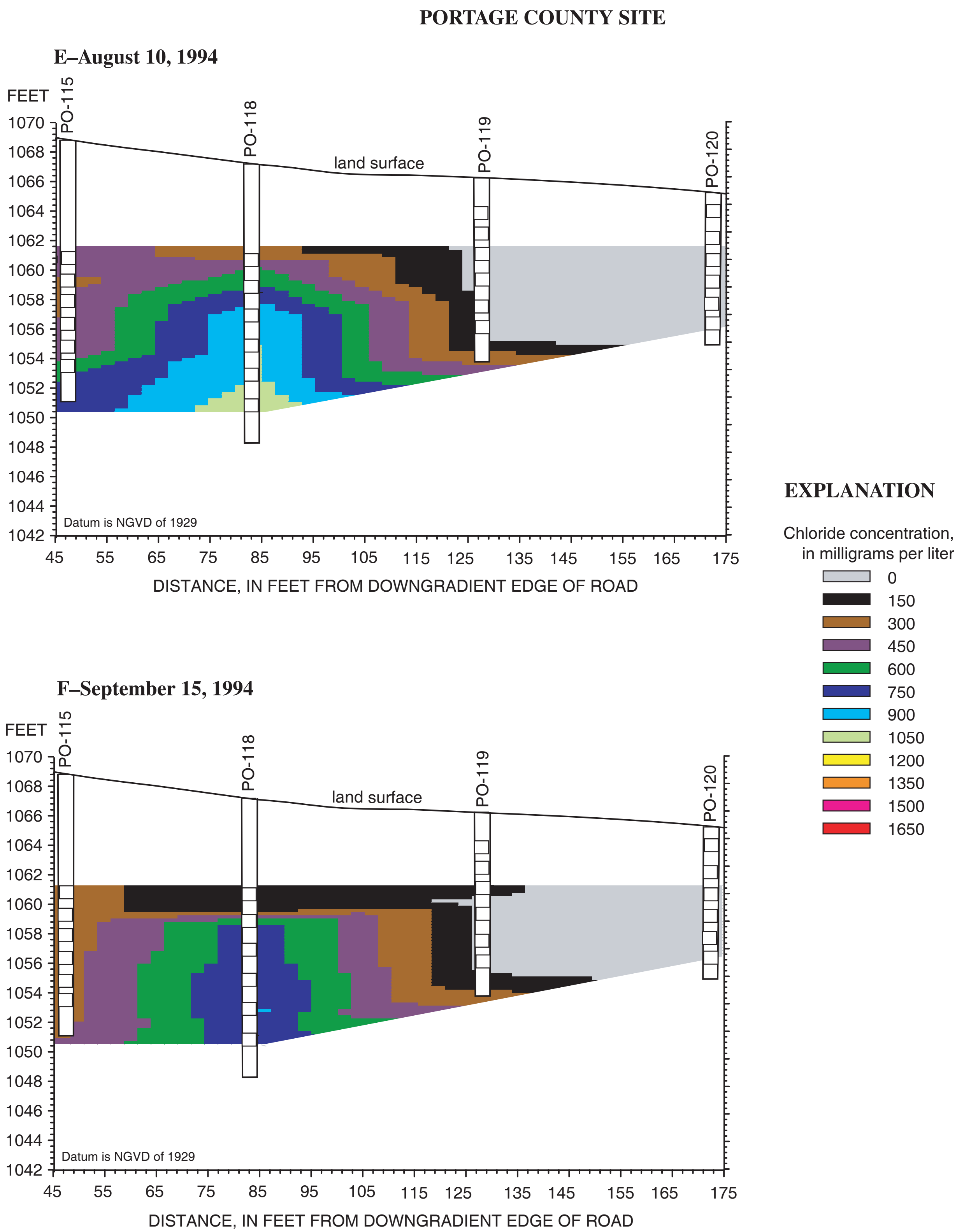


Figure 45. Profiles of chloride concentrations at the study site in Portage County, Ohio, February 16, 1994, through March 2, 1995.—Continued

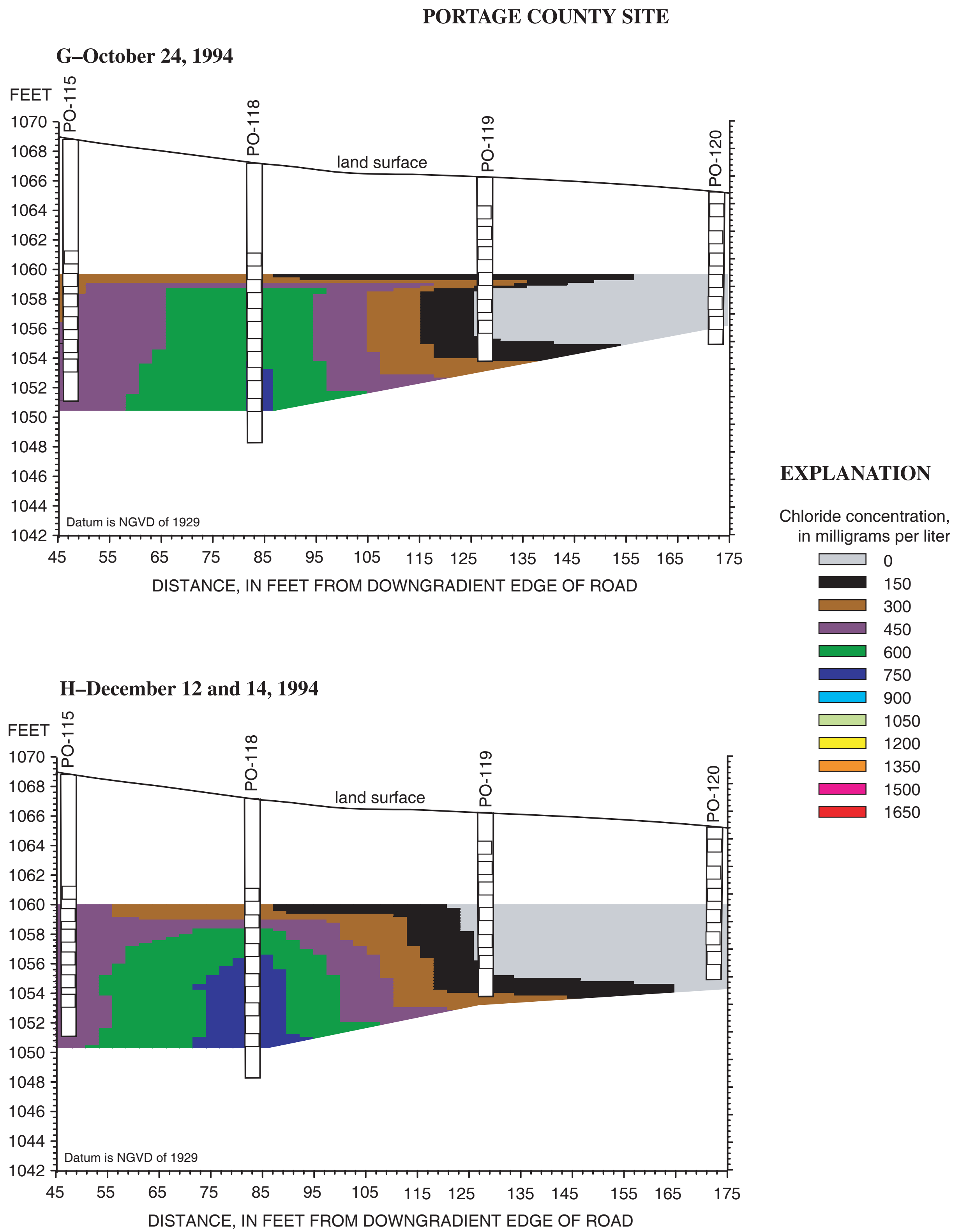


Figure 45. Profiles of chloride concentrations at the study site in Portage County, Ohio, February 16, 1994, through March 2, 1995.—Continued

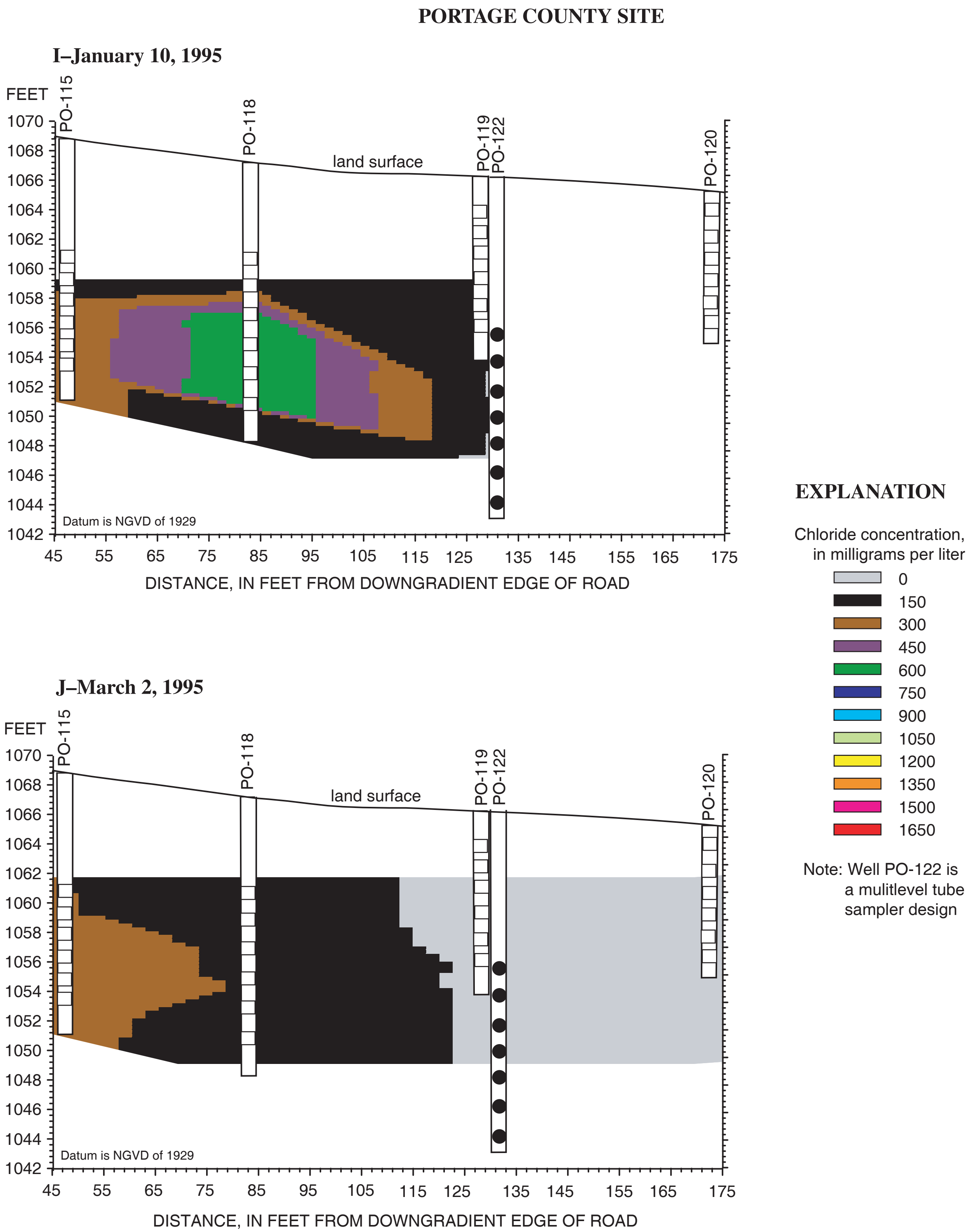


Figure 45. Profiles of chloride concentrations at the study site in Portage County, Ohio, February 16, 1994, through March 2, 1995.—Continued

Richland County Site

Site Characteristics

The Richland County site (fig. 46) is on SR 97, 1/2 mile northwest of the Interstate 71 junction in Washington Township, 2.5 mi southeast of Lexington, Ohio, and 3 mi northwest of Bellville, Ohio. SR 97 has second-priority designation for ODOT deicing. This site is in the Southern New York Section of the Appalachian Plateaus Physiographic Province (Fenneman, 1946) and is on a kame and outwash terrace formed along the sides of the Clear Fork of the Mohican River, a glacial-outwash stream. The site is on a steeply sloping hillside with a cut-out area on the upgradient side of the highway and a more gently sloping hillside on the downgradient side, toward the river. The slope of the area is 24 ft over 300 ft, or 0.08. Runoff tends toward the drainage ditches on either side of the road and slowly infiltrates the aquifer through a 10- to 15-ft unsaturated zone. The downgradient side of the highway is an unused field, which is mowed at least once per year. The upgradient side is a fairly steep, unused grassy hillside with a cut-out area, where sand and gravel were previously extracted. The upgradient well is in this cut-out area.

SR 97 is a two-lane, undivided highway that runs northwest to southeast. Drainage is by shallow, open ditches. Total pavement width, including shoulders, is 22 ft, and the gravel berm is 3–4 ft wide. The highway is straight and flat at the site, bending to the west 1,000 ft to the northwest of the site.

The soils are of the Shoals-Chili-Wheeling association (U.S. Department of Agriculture, 1975). The Chili loam predominates downgradient, and the Wooster silt loam predominates upgradient; both are well-drained soils. Beneath the soils layer, the surficial material at the site ranges from silty fine sand to very coarse sand and gravel. A gray till, which is about 2–5 ft thick, underlies these materials at about 22–30 ft below land surface. Bedrock is the Blackhand Sandstone of the Cuyahoga formation (Totten, 1973), a coarse- to medium-grained sandstone. Well logs obtained from ODNR indicate that the bedrock range in depth from 15 ft below land surface near the valley walls to more than 30 ft below land surface toward the river. An individual well log was constructed for each of the wells. A geologic section of the site was constructed on the basis of these logs (fig. 47).

The nine-winter (1990–99) average annual use of sodium chloride in Richland County as a whole was 5,829 tons (table 1). The maximum for this nine-winter period was 8,852 tons in 1998–99, and the minimum for this period was 4,252 tons in 1994–95. Data collected at this site (table 18) indicate the nine-winter average annual use of sodium chloride was 6.20 ton/2-ln mi (12,402 lb/2-ln mi), which is 36 percent less than the State average of 9.7 ton/2-ln mi (19,380 lb/2-ln mi) (Ohio Department of Transportation, written commun., 1999). In addition to sodium chloride and abrasives, a small amount of liquid calcium chloride ($CaCl_2$) also was applied to the highway in about 28 percent of the applications, during the study period.

Climate

Average annual precipitation for the area is 39.7 in (table 3). Average annual temperature for the area is 9.8° C (49.6° F), with the monthly normal high of 27.8° C (82.1° F) in July and the monthly normal low of -8.4° C (16.8° F) in January (Midwestern Regional Climate Center, 2000). Annual precipitation based on data collected at the site, as well as precipitation at the nearest NOAA site, is listed by year in the table below. Average annual snowfall is 42.6 in. for nearby reporting areas. During the study period, annual snowfall averaged 41.9 in. (Midwestern Regional Climate Center, 2000).

Richland County site		
Water year	Onsite precipitation (inches)	Nearest NOAA site[1] precipitation (inches)
1991	[2]18.77	[2]20.62
1992	36.79	[3]31.24
1993	[3]38.83	[3]33.62
1994	[3]29.07	[3]29.37
1995	[3]41.71	[3]32.21
1996	[3]29.12	44.07
1997	[3]27.43	41.83
1998	[3]38.80	33.75
1999	35.81	[3]27.60

[1] Refer to table 2 for site name.

[2] No measurements made until February 1991.

[3] Incomplete data.

Hydrogeology

The ground-water level ranged from about 11 to 18 ft below land surface, during the study period at this site (table 3). The direction of flow varied from about 59° to 62° to the alignment of the highway, as determined by the triangulation method using available wells; average water-table gradient was about 0.052. At this site, the ground-water level responds to precipitation within 1 day, a result of the porous aquifer materials at the surface and the shallow water table. Additional data regarding water-table gradient and flow direction can be found in the appendix in table A-3.

Results of single-well aquifer tests (slug tests) on the aquifer indicate that the hydraulic conductivity is 5 ft/d. Assuming an average gradient of 0.052 and an effective porosity of 40 percent, the ground-water velocity was computed to be 0.65 ft/d.

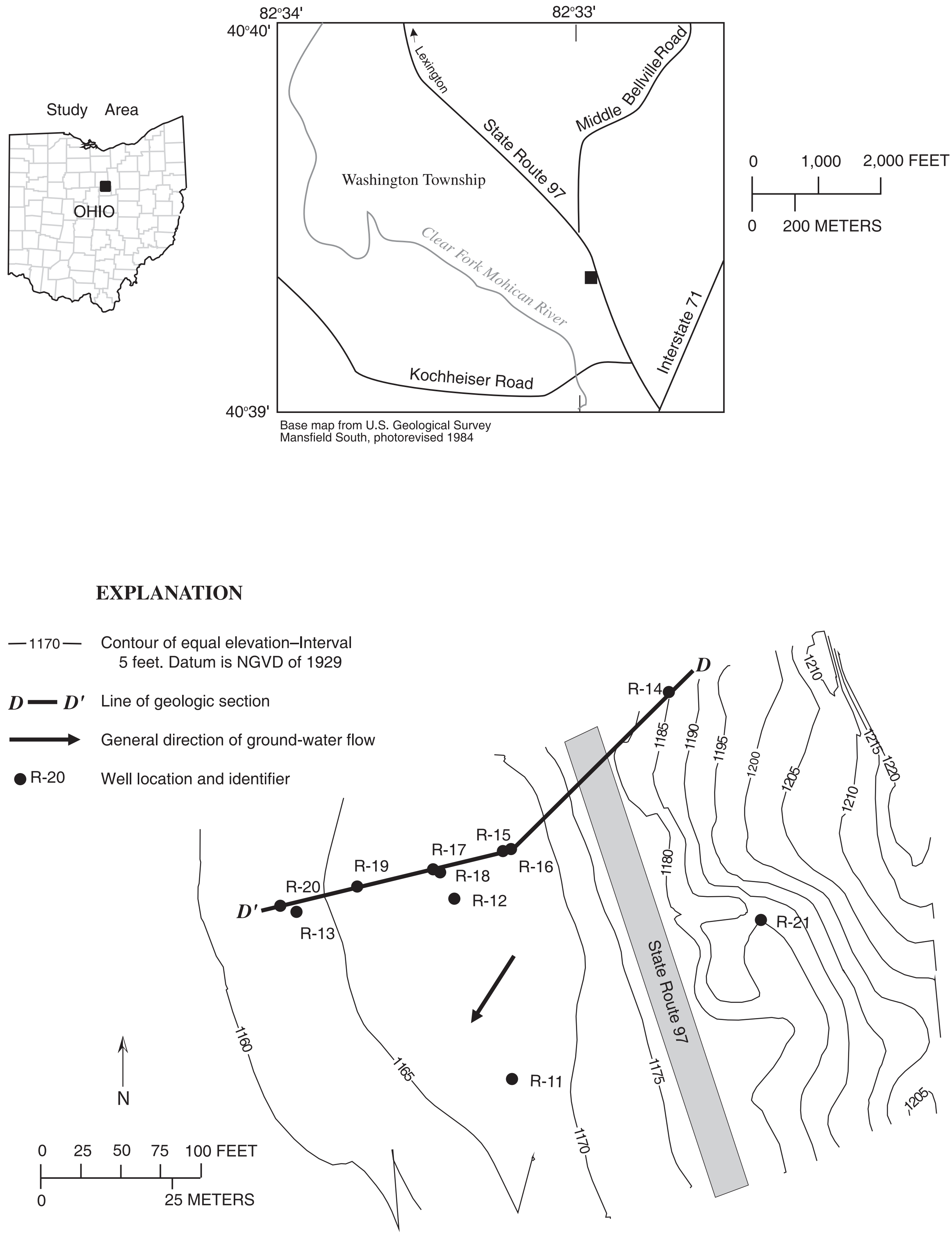
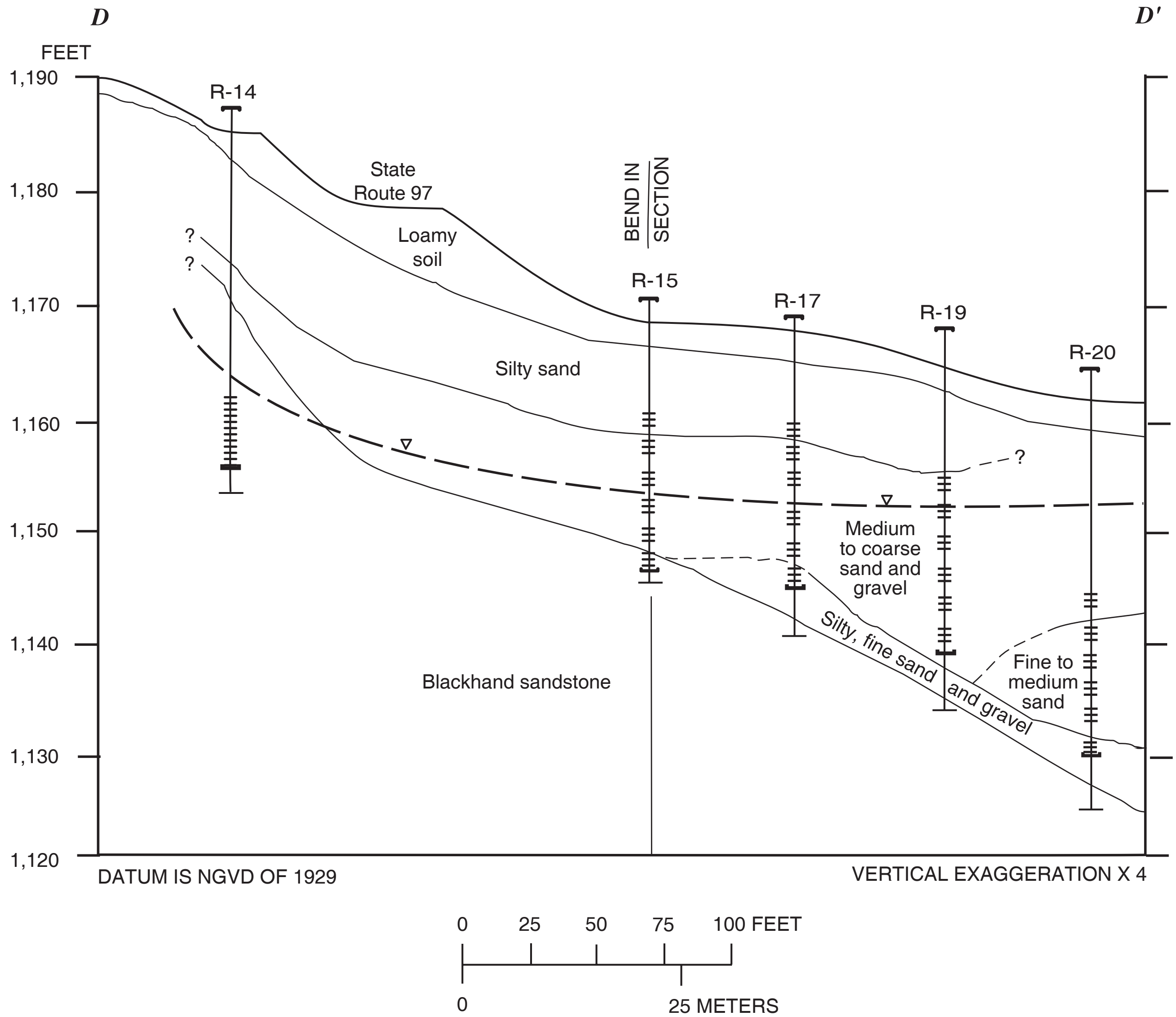


Figure 46. Topography, well location, and ground-water flow direction, Richland County, Ohio, study site.



EXPLANATION

R-14 Well location and identifier–Well logs on file with the U.S. Geological Survey, Columbus, Ohio, office

Top of casing

Sampling interval–Wells with multiple sampling intervals are screened the full length of casing

Bottom of well

Bottom of boring–Wells in which the bottom of the boring extends below the bottom of the well were backfilled to the depth shown as the bottom of the well

Mean water level

Geologic contact–Dashed where approximately located

Figure 47. Geologic section *D-D′*, Richland County, Ohio, study site. (Section trace shown in fig. 46.)

Table 18. Sodium chloride application amounts by month and year, Richland County, Ohio, study site.

[Amounts measured by pounds per 2-lane mile]

	October	November	December	January	February	March	April	Yearly total
1990-91	0	0	0	7,250	5,500	1,750	0	14,500
1991-92	0	250	3,000	4,750	1,000	1,750	0	10,750
1992-93	0	100	2,000	3,500	10,250	4,750	0	20,600
1993-94	0	0	3,000	3,250	1,500	0	0	7,750
1994-95	0	0	0	4,775	1,500	250	0	6,525
1995-96	0	250	5,000	9,000	3,750	1,250	250	19,500
1996-97	0	2,250	3,250	2,750	2,750	0	0	11,000
1997-98	0	1,000	3,750	1,250	0	500	0	6,500
1998-99	0	0	2,000	6,000	2,500	4,000	0	14,500
Total	0	3,850	22,000	42,525	28,750	14,250	250	111,625
Average	0	428	2,444	4,725	3,194	1,583	28	12,402

Ground-water velocity and bulk hydraulic conductivity also were computed by use of water-quality data. Peaks of dissolved-chloride concentration were noted at sites where enough deicing chemicals were applied to result in obvious peaks over at least a 4-year period. Using the procedure described in the "Methods of Investigation" section of this report, median of the average ground-water velocity and median bulk hydraulic conductivity were computed. At the Richland County site, the computation was done 15 times, resulting in a median of the average ground-water velocities of 0.60 ft/d (s= 0.896) and a median bulk hydraulic conductivity of 4.58 ft/d (s= 6.90).

Effects of Highway Deicing Chemicals on Water Quality

Field-monitored characteristics (rainfall, specific conductance, and ground-water levels recorded from dedicated instrumentation at a well near the first downgradient sampling well) and the amount of sodium chloride applied to the highway are shown in figure 48. The amounts of sodium chloride applied to the highway adjacent to each site, as recorded by each ODOT outpost driver, are listed in table 18. Plots of these characteristics can be used to help compare the events that resulted in increased specific conductance with ambient site conditions and deicer applications. Movement of chloride and other deicing-related constituents from the highway with time is indicated by boxplots of laboratory-determined data (figs. 49 and 50).

Field-Monitored Characteristics

Specific Conductance

As is evident from the table below, specific conductance recorded continuously in well R-16 near the first downgradient water-quality sampling well at this site ranged from a maximum of 774 µS/cm in 1995 to a minimum of 157 µS/cm in 1991 (fig. 48). For comparison, the upgradient well averaged 258 µS/cm (table 19).

Richland County site		
Water year	Specific conductance, maximum (µS/cm)	Specific conductance, minimum (µS/cm)
1991	[1]436	[1]157
1992	634	306
1993	645	219
1994	540	221
1995	774	206
1996	603	265
1997	457	189
1998	427	239
1999	602	312

[1] No measurements made until February 1991.

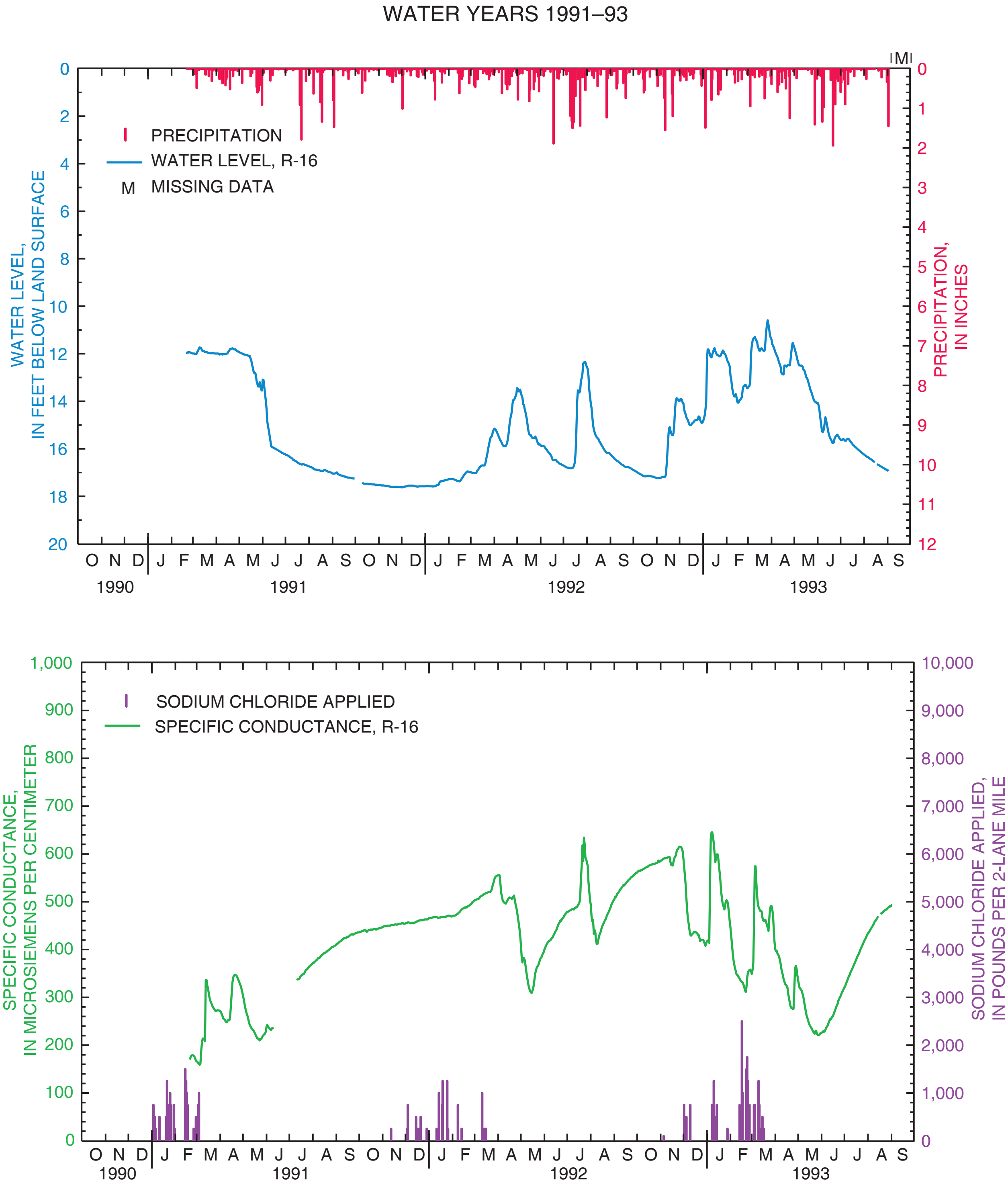


Figure 48. Ground-water levels, precipitation, specific conductance, and sodium chloride application, Richland County, Ohio, study site, water years 1991-99.

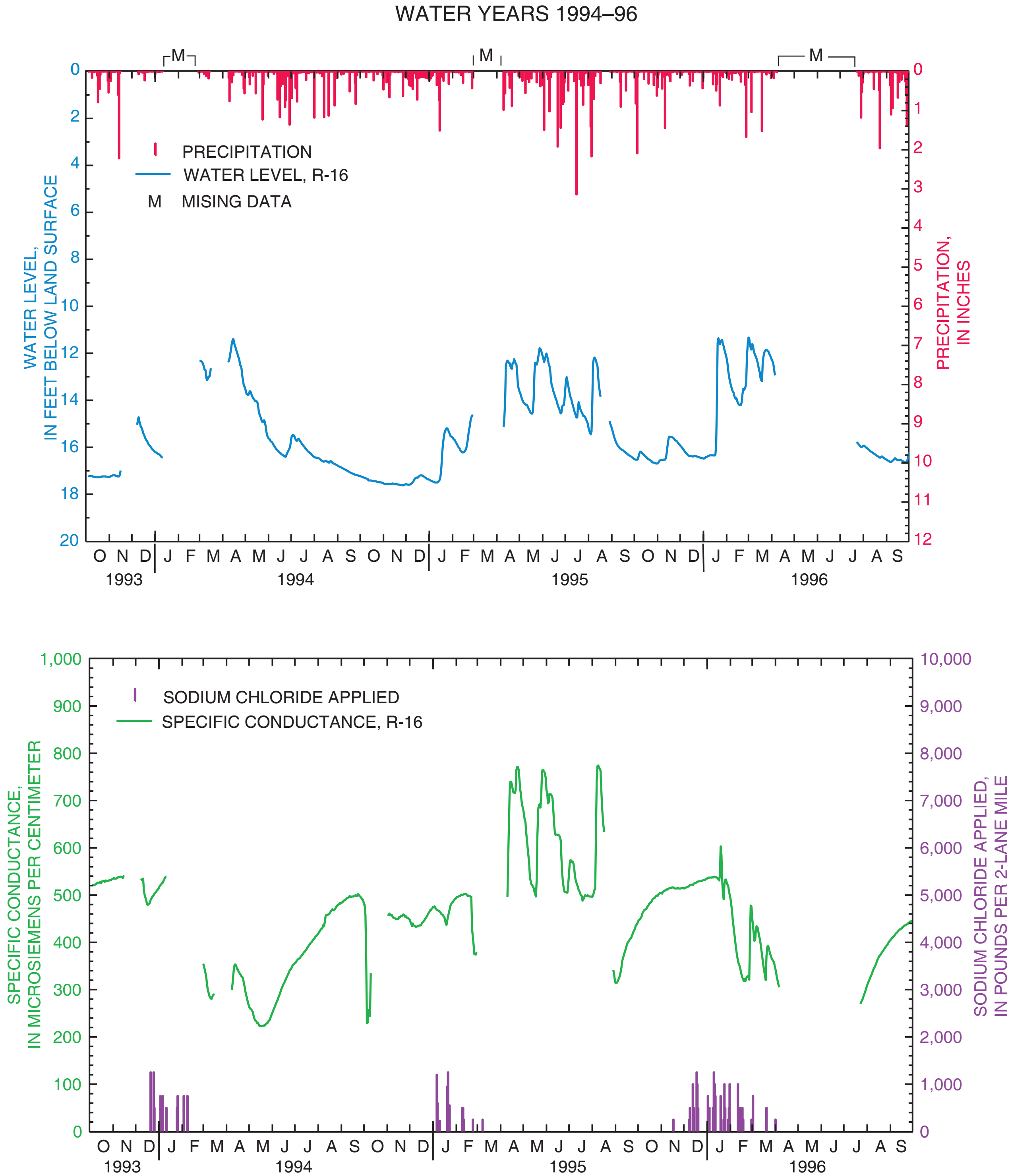
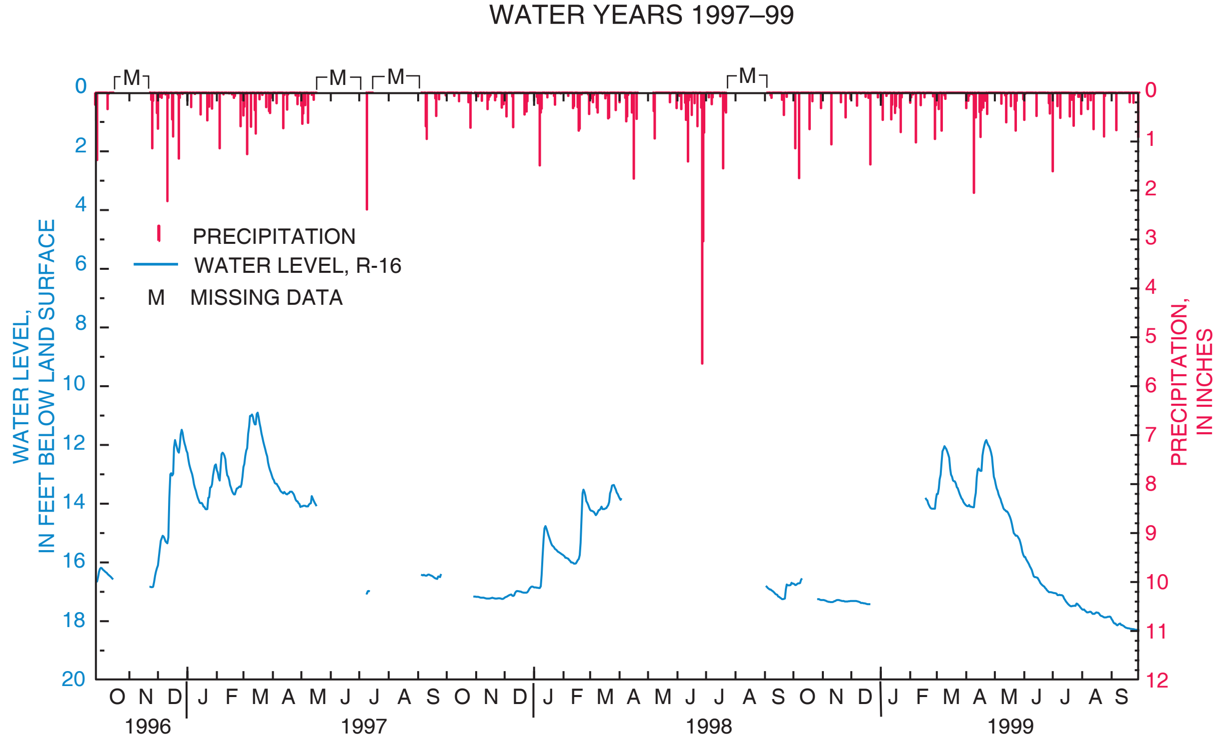


Figure 48. Ground-water levels, precipitation, specific conductance, and sodium chloride application, Richland County, Ohio, study site, water years 1991-99.—Continued



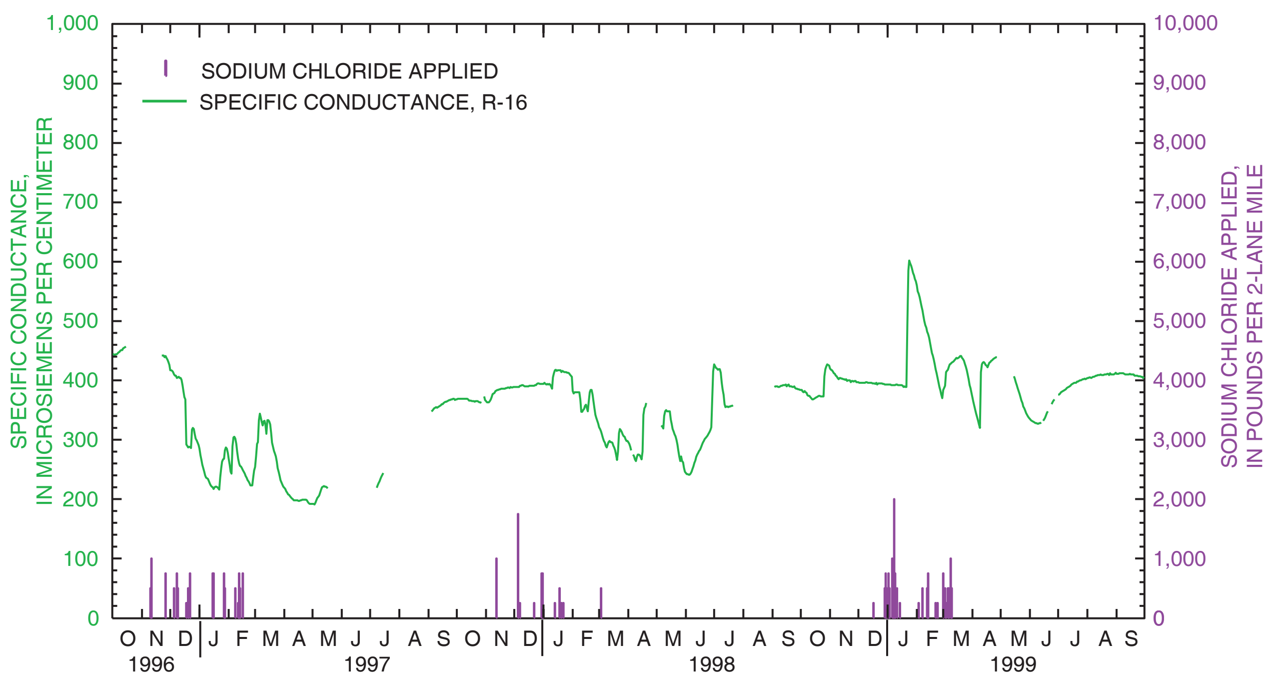


Figure 48. Ground-water levels, precipitation, specific conductance, and sodium chloride application, Richland County, Ohio, study site, water years 1991-99.—Continued

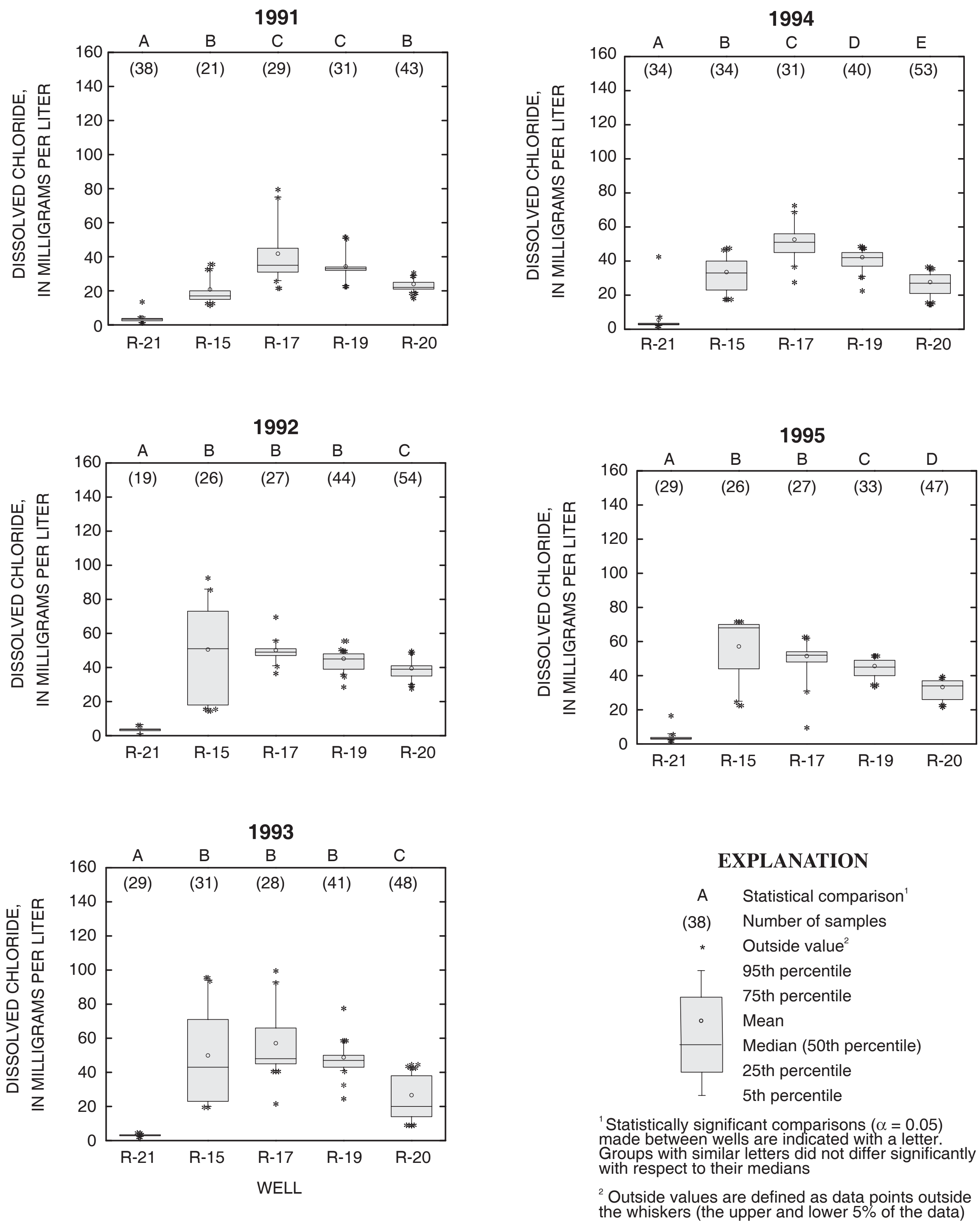


Figure 49. Distribution of concentrations of dissolved chloride in ground-water samples, Richland County, Ohio, study site, January 1991-September 1999. (Plots are shown in downgradient order from left to right. Far left plot is upgradient from highway; others are downgradient.)

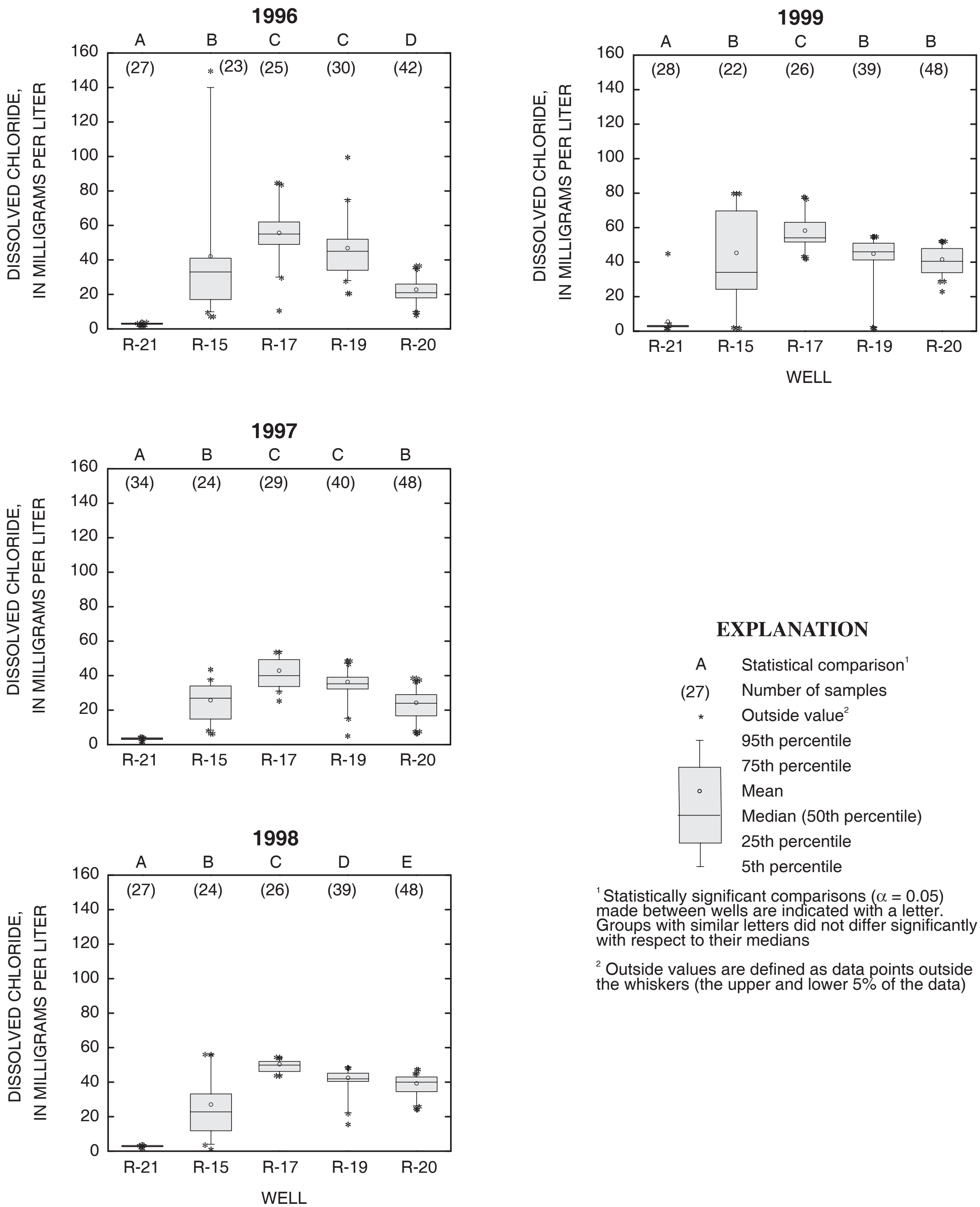


Figure 49. Distribution of concentrations of dissolved chloride in ground-water samples, Richland County, Ohio, study site, January 1991-September 1999. (Plots are shown in downgradient order from left to right. Far left plot is upgradient from highway; others are downgradient.)—Continued

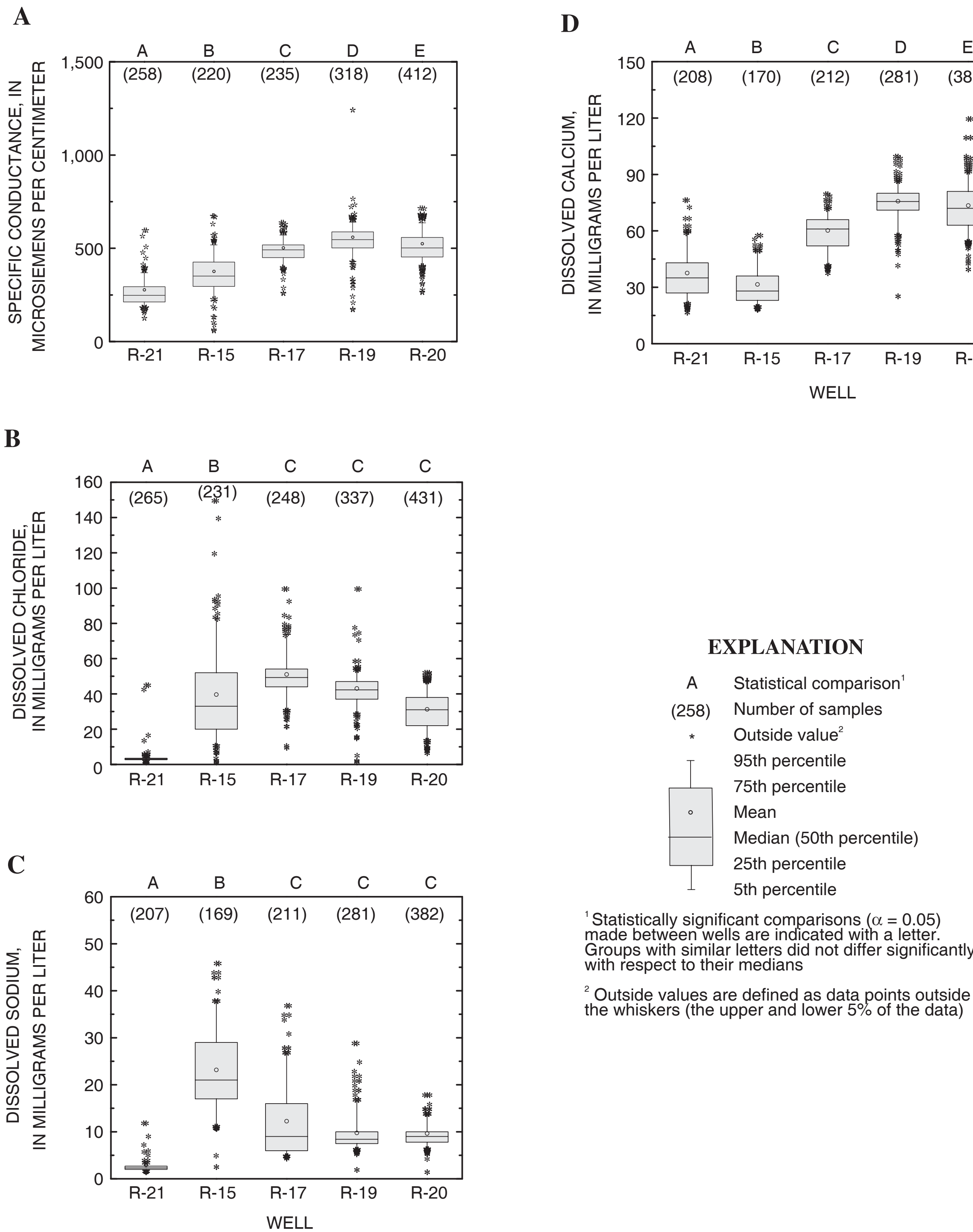


Figure 50. Distribution of (*A*) specific conductance and concentrations of dissolved (*B*) chloride, (*C*) sodium, and (*D*) calcium in ground-water samples, Richland County, Ohio, study site, January 1991-September 1999. (Plots are shown in downgradient order from left to right. Far left plot is upgradient from the highway; others are downgradient.)

Table 19. Water-quality data for multilevel wells, Richland County, Ohio, study site, water years 1991-99.

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
R-21	Upgradient	Maximum	585	77	12	45
		Minimum	113	17	2	1
		Mean	258	36	2	4
		Median	248	36	2	3
		N	258	208	207	265
R-15	1st downgradient	Maximum	661	58	46	150
		Minimum	46	18	3	1
		Mean	357	30	23	38
		Median	352	28	21	33
		N	220	170	169	231
R-17	2nd downgradient	Maximum	626	80	37	100
		Minimum	246	38	4	10
		Mean	498	59	12	50
		Median	492	61	9	49
		N	234	212	211	248
R-19	3rd downgradient	Maximum	1,230	100	29	100
		Minimum	159	26	2	2
		Mean	540	75	9	42
		Median	546	76	8	42
		N	318	281	281	337
R-20	4th downgradient	Maximum	703	120	18	52
		Minimum	251	40	2	7
		Mean	506	72	9	30
		Median	502	72	9	31
		N	412	381	382	431

Air and Soil Temperature

Air temperature ranged from a maximum of 36.0° C in 1991 to a minimum of -26.1° C in 1992.

During the study period, soil temperature ranged from a maximum of 29.3° C in 1993 and 1994 to a minimum of -1.6° C in 1996.

Richland County site		
Water year	Air temperature, maximum (° C)	Air temperature, minimum (° C)
1991	[1]36.0	[1]-9.5
1992	30.4	-26.1
1993	33.0	-24.6
1994	34.0	-23.1
1995	34.4	-23.0
1996	31.5	-23.6
1997	30.7	-23.4
1998	32.4	-17.4
1999	34.5	-25.0

[1] No measurements made until February 1991.

Richland County site		
Water year	Soil temperature, maximum (° C)	Soil temperature, minimum (° C)
1991	[1]28.5	[1]1.0
1992	27.9	1.0
1993	29.3	4.6
1994	29.3	1.7
1995	27.6	2.0
1996	24.8	-1.6
1997	22.6	0.4
1998	23.8	1.1
1999	25.3	0.6

[1] No measurements made until February 1991.

Laboratory-Determined Characteristics

The amount of sodium chloride applied to the highway varied widely at the Richland County site (table 18). Temperatures also varied widely throughout the winters. Cold temperatures often created icy conditions, but large snowfalls were uncommon. Summary statistics of the water-quality data collected at upgradient and downgradient wells for all 9 years sampled during 1991–99 are listed in table 19. These same statistics for each year individually are listed in the appendix in table A-11. Boxplots of chloride concentration data collected at upgradient and downgradient wells for each of the 9 years individually are shown in figure 49. Boxplots of specific conductance, dissolved calcium, dissolved sodium, and dissolved chloride for water from all levels of the upgradient well and the four downgradient sampling wells for 1991–99 combined are shown in figure 50. Patterns that emerge from those data are noted below.

Specific Conductance

At the upgradient well, R-21, the mean specific conductance was 258 μS/cm, and the maximum was 585 μS/cm (table 19, fig. 50A). Mean values were fairly constant throughout the four downgradient wells (mean, 357–540 μS/cm), although the maximum ranged from 626 to 1,230 μS/cm, the highest measurement was found at the third downgradient well. Therefore, 206 ft downgradient from the highway, the mean specific conductance at the fourth downgradient well was about twice the upgradient or background value.

Chloride Concentration

At the upgradient well, R-21, the mean concentration of chloride was 4 mg/L, and the maximum was 45 mg/L (table 19, fig. 50B). Concentrations were generally higher at the first two downgradient wells (mean, 38–50 mg/L; maximum, 100–150 mg/L). Concentrations remained fairly constant downgradient along the flowpath through the second downgradient well. At the third downgradient well, R-19, the mean concentration was 42 mg/L, and the maximum was 100 mg/L. By the fourth downgradient well, R-20, the mean concentration was 30 mg/L, and the maximum was 52 mg/L. Thus, 206 ft downgradient from the highway, the mean concentration at the fourth downgradient well was about 7 times the upgradient or background concentration; however, because concentrations in all wells were low, this increase is insignificant in terms of water-quality considerations. Although the concentrations are relatively low overall, a pattern of movement through the aquifer can be observed.

Dissolved-chloride concentrations at six sampling levels in each downgradient well at the site during a 7-month period in 1992–93 are represented as a series of chloride profiles in figure 51. (Each color in the profile represents an additional 25 mg/L of chloride.) This series of profiles shows how chloride moved through the aquifer in several waves after deicing chemicals were applied during the winter 1992–93 at the site. The amount and frequency of precipitation and snowmelt recharge and the soil temperature can also affect this movement during a specific time period. At this site, the vertical distribution between levels is not as varied as some of the other more heavily deiced sites, but the movement of higher-than-background chloride concentration can be followed through time. This site has a relatively high ground-water gradient, so the ground-water velocity is much higher than at the other sites. Hence, water with higher chloride concentration moves quickly throughout the saturated zone, and the chloride concentration approaches background levels between deicing-chemical applications more frequently than at the other sites.

During winter 1992–93, deicing material was applied December 1992 into March 1993 in a greater total amount than any of the other study years. Profile plots of a plume moving quickly through the aquifer at this site are shown in figure 51 (Each color in the profile represents an additional 25 mg/L of chloride.). Although the plume is of a relatively low concentration (maximum of 100 mg/L) (fig. 51C), the plots illustrate that ground water moves through the aquifer relatively quickly owing to a steep gradient, coarse, porous aquifer materials, and an aquifer thickness of 15–35 feet.

Soil samples were collected on nine occasions at this site during 1993–99 (table A-2 in the appendix). Chloride concentrations of the samples collected from the ditch along the highway were 22 to 670 mg/L and decreased to 3–610 mg/L by 80 ft downgradient from the highway. The data are shown in the appendix in table A-2.

Sodium Concentration

At the upgradient well, R-21, the mean concentration of sodium was 2 mg/L, and the maximum was 12 mg/L (table 19, fig. 50C). Concentrations were generally higher at the first downgradient well (mean, 23 mg/L; maximum, 46 mg/L). The mean concentration decreased only slightly downgradient along the flowpath through the second, third, and fourth downgradient wells; however, the upper whiskers and upper outliers in the boxplots show higher values at the second downgradient well and a decrease through the third and fourth downgradient wells. At the third downgradient well, R-19, the mean concentration was 9 mg/L, and the maximum was 29 mg/L. At the fourth downgradient well, R-20, the mean concentration was 9 mg/L, and the maximum 18 mg/L. Thus, 206 ft downgradient from the highway, the mean concentration at the fourth downgradient well was about 4 times the upgradient or background concentration; however, because concentrations in all wells were low, this increase is negligible in terms of water-quality considerations.

Calcium Concentration

In addition to sodium chloride and abrasives, liquid calcium chloride ($CaCl_2$) was applied to the highway in about 18 percent of the applications, during the study period. Calcium concentrations initially were relatively low in the upgradient well (R-21, mean, 36 mg/L) and first downgradient well (R-15,

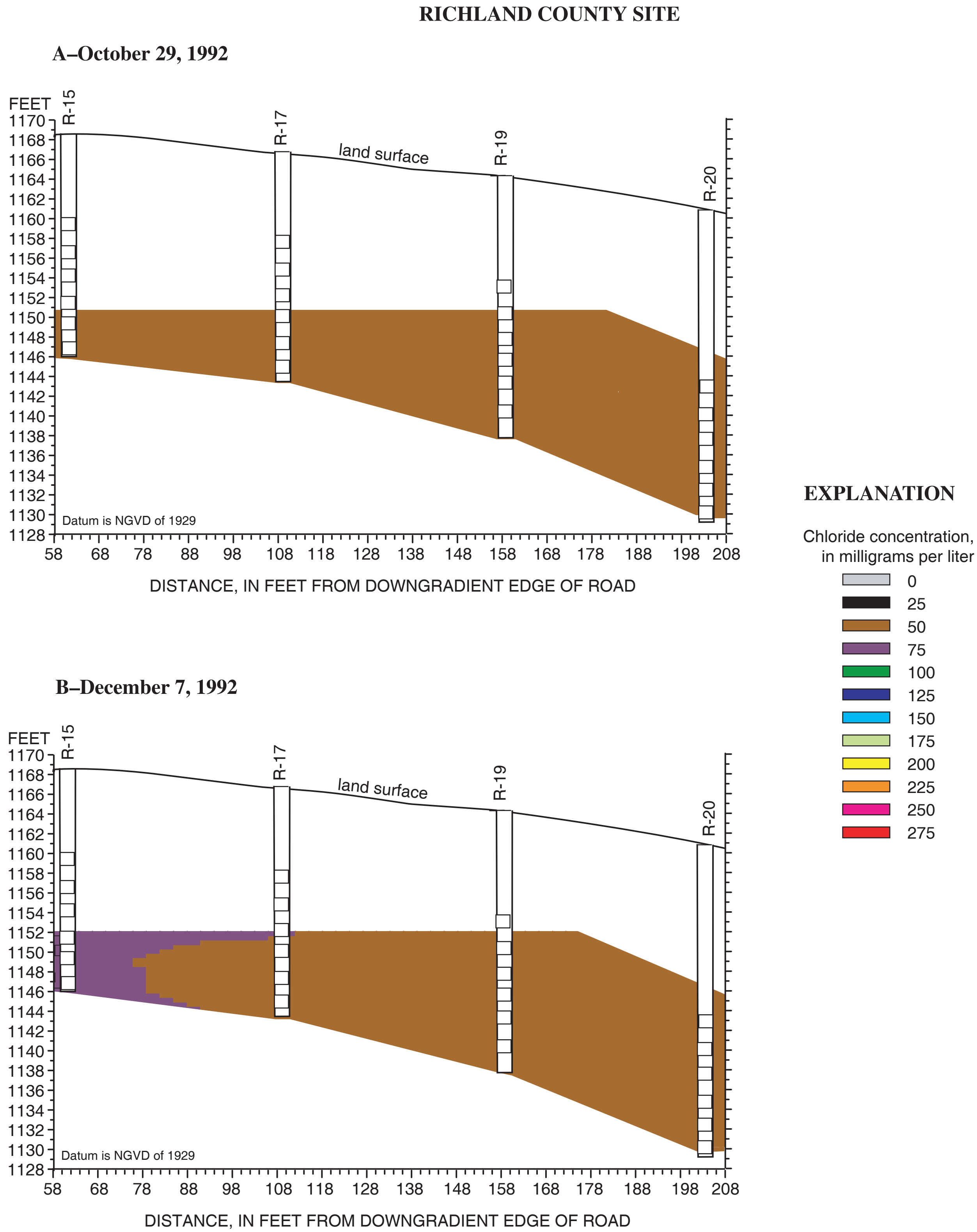


Figure 51. Profiles of chloride concentrations at the study site in Richland County, Ohio, October 29, 1992, through May 24, 1993.

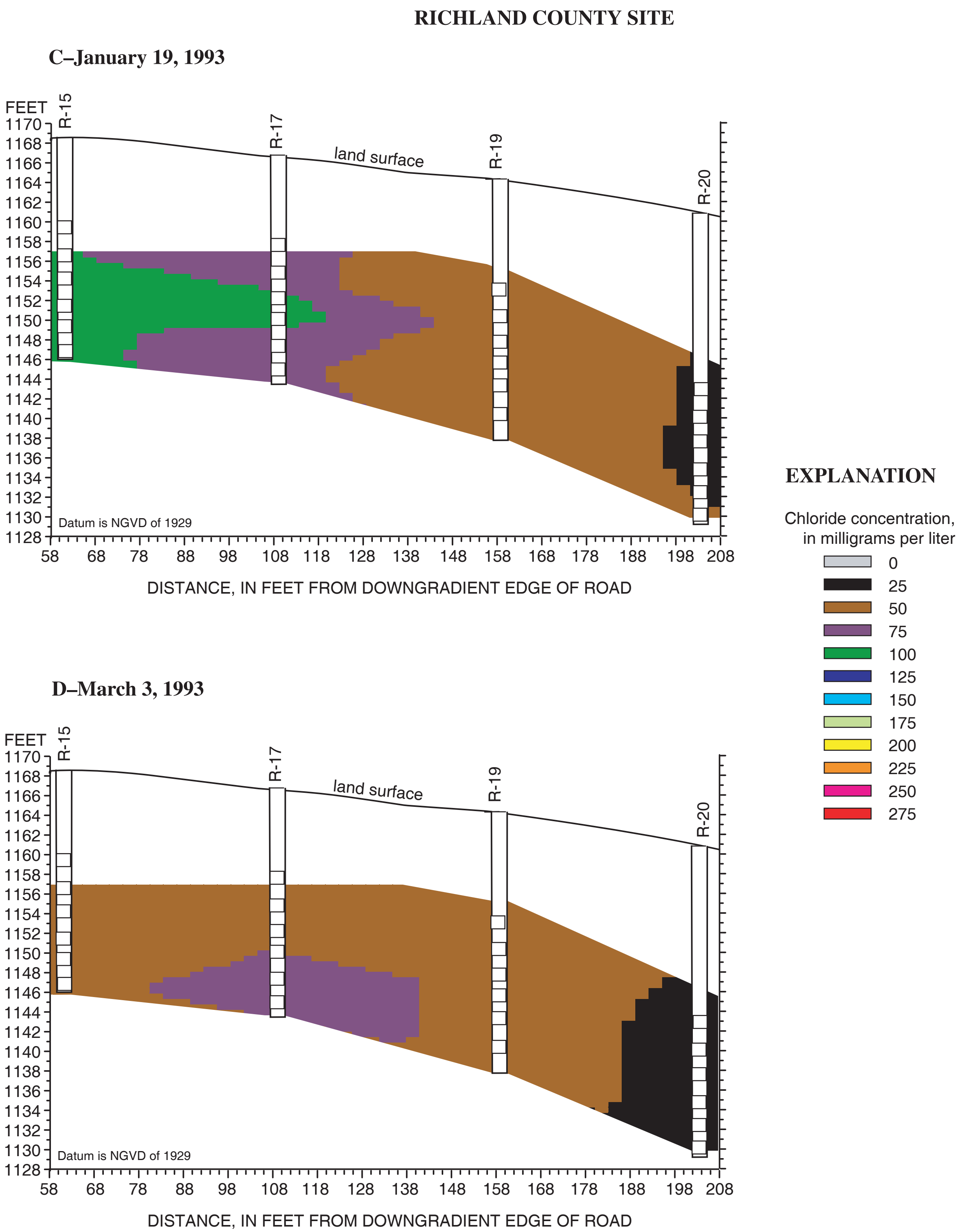


Figure 51. Profiles of chloride concentrations at the study site in Richland County, Ohio, October 29, 1992, through May 24, 1993.—Continued

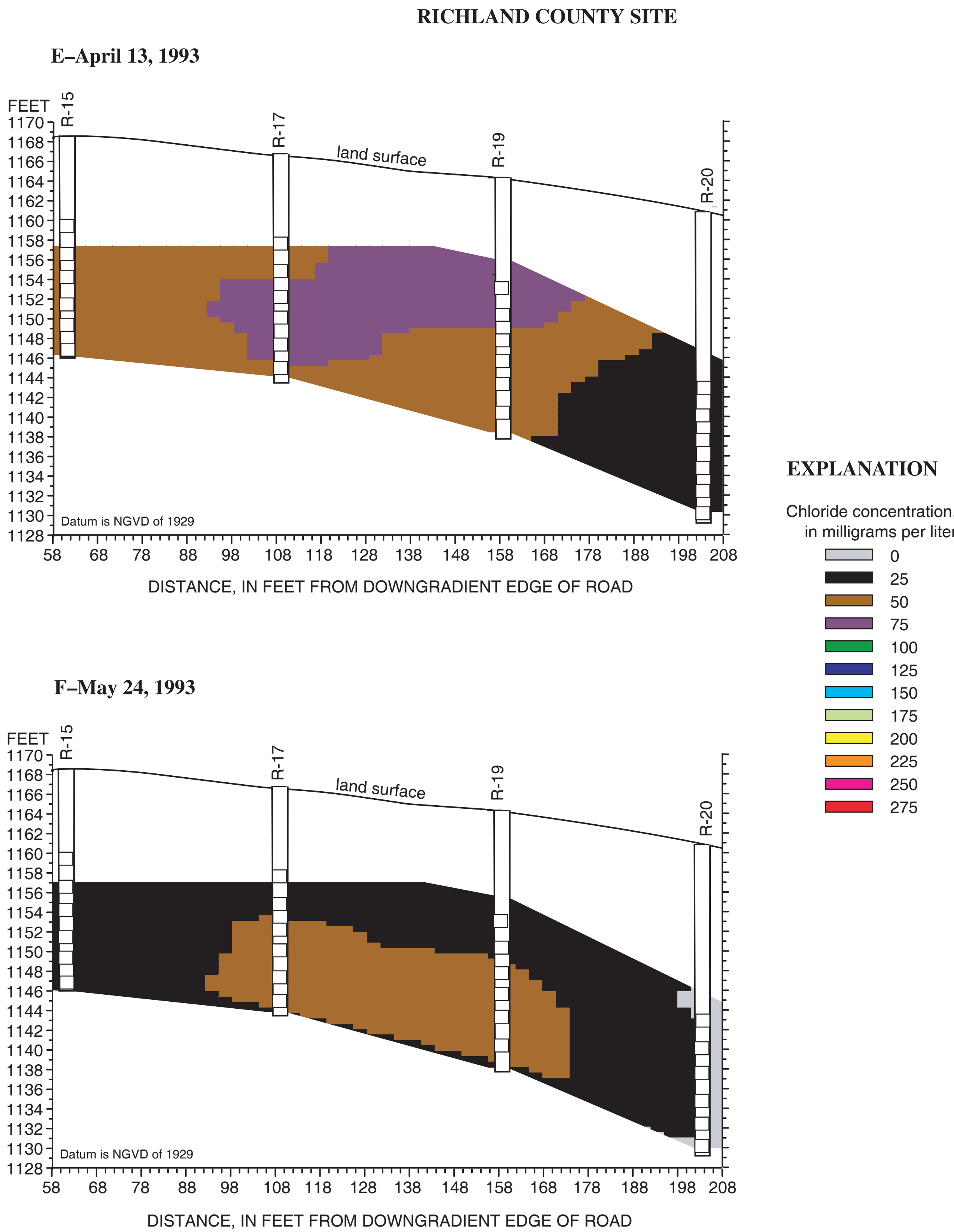


Figure 51. Profiles of chloride concentrations at the study site in Richland County, Ohio, October 29, 1992, through May 24, 1993.—Continued

mean, 30 mg/L), but steadily increased at the second (R-17, mean, 59 mg/L) through the fourth (R-20, mean, 72 mg/L) downgradient wells (table 19, fig. 50D).

Summary

The U.S. Geological Survey (USGS), in cooperation with the Ohio Department of Transportation (ODOT) and the Federal Highway Administration, studied the effects of highway deicing chemicals on shallow ground water at eight sites in Ohio from 1988 through 2002. The study was begun to gather background data from areas throughout the State representing various weather conditions, soil types, and types of unconsolidated aquifer materials.

This report is the followup to the interim report published by the USGS in 1997 that included data collected through 1993. This report includes all data collected through 1999, as well as the environmental setting and hydrogeology of each of the eight sites. However, readers should refer to the interim report (Jones and Sroka, 1997) for additional information. More than 13,100 water samples were collected during the study period. All of these data and the lithologic logs of the sampling wells are available for inspection at the USGS office in Columbus, Ohio. The data also have been published annually in the Ohio water data report. Because of the large volume of raw data, the data are not presented in either this or the interim report. Raw data can be retrieved from the USGS NWISWeb page at http://waterdata.usgs.gov/oh/nwis/. A list of well numbers and names at each site is provided in the appendix (table A-1 in the appendix) to assist in retrieving data.

Selected water-quality characteristics were monitored by use of multilevel sampling wells on the upgradient (1) and downgradient (4) sides of the highway. For this study, samples were collected every 4 to 6 weeks. Chloride concentration was used as a chemically conservative tracer to track the movement of deicing chemicals in the ground water through time.

Evidence from water-quality sampling, specific-conductance measurements, and surface-geophysical measurements indicates that five of the eight sites are potentially affected by direct application of deicing chemicals (Ashtabula County, Lucas County, Portage County, and, to a lesser extent, Ashland and Richland Counties). Snowfall and temperatures at these sites were substantially different than at the three southernmost sites (Champaign County, Clark County, and Pickaway County); specific conductance and concentrations of dissolved sodium and chloride were generally higher at Ashtabula, Lucas, and Portage County sites and did not return to background levels (generally less than 50 mg/L) on an annual cycle. Deicing events and specific-conductance values, as well as concentrations of the selected constituents, are related at these sites.

Ashland County.—The Ashland County site is on SR 3 near Loudonville, Ohio, and has second priority for ODOT deicing. This site received an annual average of 11,382 lb/2-ln mi of sodium chloride for the study period. Snowfall averages 38.4 in/yr. for nearby reporting areas. The aquifer materials range from a clayey fine sand to a coarse sand and gravel. These are underlain by bedrock at a depth of 17–43 ft. The ground-water level ranged from 0.5 to 7.2 ft below land surface during the study period. From aquifer tests, the hydraulic conductivity was computed to be 4 ft/d. Assuming an average water-table gradient of 0.010 and an effective porosity of 40 percent, ground-water velocity is 0.10 ft/d at this site.

At the upgradient well, AS-43, the mean concentration of chloride was 41 mg/L and the maximum was 360 mg/L. Samples from this well could possibly include some contamination from salt spray because the mean concentration at the upgradient well was slightly higher than that at the fourth downgradient well. Concentrations were generally higher at the first three downgradient wells (mean, 59–84 mg/L; maximum, 130–220 mg/L). Concentrations remained fairly constant downgradient along the flowpath through the third downgradient well. At the fourth downgradient well, AS-48, the mean concentration was 20 mg/L, and the maximum was 53 mg/L. Thus, 162 ft downgradient from the highway, the mean concentration at the fourth downgradient well was slightly lower than the upgradient or background concentration.

Ashtabula County.—The Ashtabula County site is on SR 84 near Kingsville, Ohio, and has second priority for ODOT deicing. This site, which is in the snow belt of northeastern Ohio, received the most deicing chemicals of all of the study sites (an annual average of about 37,503 lb/2-ln mi for the study period). Snowfall averages 51.0 in/yr for nearby reporting areas. The aquifer underlying the site consists of layers of sand, silt, clay, and gravel underlain by a silty clay till at a depth of 15–20 ft and bedrock at a depth of 20–30 ft below land surface. The ground-water level ranged from 2.1 to 10.7 ft below land surface during the study period. From aquifer tests, the hydraulic conductivity was computed to be 2 ft/d. Assuming an average water-table gradient of 0.036 and an effective porosity of 42 percent, ground-water velocity was computed to be 0.20 ft/d at this site.

At the upgradient well, AB-139, the mean concentration of chloride was 37 mg/L, and the maximum was 544 mg/L. Concentrations were highest at the first downgradient well, AB-133 (mean, 652 mg/L; maximum, 1,500 mg/L). Concentrations generally decreased downgradient along the flowpath through the second and third downgradient wells. At the fourth downgradient well, AB-137, the mean concentration was 100 mg/L, and the maximum was 280 mg/L. Thus, 158 ft downgradient from the highway, mean concentration at the fourth downgradient well was about 3 times the upgradient or background concentration.

Champaign County.—The Champaign County site is on SR 29 near Urbana, Ohio, and has second priority for ODOT deicing. This site received an annual average of 5,094 lb/2-ln mi of sodium chloride for the study period. Snowfall averages 13.4 in/yr. Aquifer materials consist of fine to coarse sand with small gravel and medium to large cobbles. Limestone and shale bedrock is present at a depth of about 240 ft

below land surface. The ground-water level ranged from 4.6 to 10.6 ft below land surface during the study period. From aquifer tests, the hydraulic conductivity was computed to be 47 ft/d. Assuming an average water-table gradient of 0.002 and an effective porosity of 35 percent, ground-water velocity was computed to be 0.27 ft/d at this site.

At the upgradient well, CH-40, the mean concentration of chloride was 23 mg/L and the maximum was 39 mg/L. Mean concentrations were 1.5 to 2 times greater at the downgradient wells (36–47 mg/L). Maximum concentrations at the four downgradient wells ranged from 96 to 150 mg/L. Thus, 228 ft downgradient from the highway, the mean concentration at the fourth downgradient well (47 mg/L) was about twice the upgradient or background concentration.

Clark County.—The Clark County site is on SR 4 near Springfield, Ohio, and has first priority for ODOT deicing. This site received an annual average of 5,478 lb/2-ln mi of sodium chloride for the study period. Snowfall averages 13.4 in/yr for nearby reporting areas. The aquifer materials underlying the site consist of medium to coarse sand with gravel and large cobbles. Dolomite bedrock is present at a depth of about 160 ft below land surface. The ground-water level ranged from 17 to 23 ft below land surface during the study period. From aquifer tests, the hydraulic conductivity was computed to be 36 ft/d. Assuming an average water-table gradient of 0.003 and an effective porosity of 35 percent, ground-water velocity was computed to be 0.31 ft/d at this site.

At the upgradient well, CL-136, the mean concentration of chloride was 13 mg/L, and the maximum was 45 mg/L. Concentrations were slightly higher at all four downgradient wells than at the upgradient well (mean, 16–32 mg/L; maximum, 54–83 mg/L). Concentrations increased along the flowpath from the first to the third downgradient well. At the fourth downgradient well, CL-143, concentrations decreased to background levels (mean, 16 mg/L; maximum, 54 mg/L). Thus, 158 ft downgradient from the highway, the mean concentration was about the same as the upgradient or background concentration.

Lucas County.—The Lucas County site is on SR 2 near Holland, Ohio, and has first priority for ODOT deicing. This site received an annual average of 16,928 lb/2-ln mi for the study period. Snowfall averages 38.8 in/yr for nearby reporting areas. The aquifer underlying the site consists of fine to medium grained sand to a depth of 31–35 ft. Dolomite bedrock is present at a depth of about 70 ft. The ground-water level ranged from 3.2 to 8.1 ft below land surface during the study period. From aquifer tests, the hydraulic conductivity was computed to be 6 ft/d. Assuming an average water-table gradient of 0.003 and an effective porosity of 43 percent, ground-water velocity was computed to be 0.04 ft/d at this site.

At the upgradient well, LU-21, the mean concentration of chloride was 31 mg/L, and the maximum was 150 mg/L. The lowest level (level 1) in the upgradient well was uncharacteristically high in chloride during specific times each year; none of the other levels showed this pattern. The maximum concentrations shown for LU-21 reflect this pattern. Therefore, the median concentrations may be more representative of the upgradient conditions. Concentrations from the first downgradient well, LU-22 (mean, 145 mg/L; maximum, 1,020 mg/L) and the second downgradient well, LU-25 (mean, 137 mg/L; maximum 674 mg/L) were generally similar to each other, although values at LU-22 were more extreme. At the third downgradient well, LU-27, the mean concentration dropped to 103 mg/L, and the maximum was 567 mg/L. At the fourth downgradient well, the mean concentration was similar to that at the third downgradient well (110 mg/L; maximum 513 mg/L). Thus, 228 ft downgradient from the highway, the median concentration at the fourth downgradient well was about 3.5 times the upgradient or background concentration. Concentrations may approach background farther down the flowpath, but no wells were in that area.

Pickaway County.—The Pickaway County site is on SR 104 near Circleville, Ohio, and has second priority for ODOT deicing. This site received an annual average of 8,228 lb/2-ln mi of sodium chloride for the study period. Snowfall averages 16.4 in/yr for nearby reporting areas. Aquifer materials underlying the site consist of fine to coarse sand and gravel until a varying thickness of gray silty clay is encountered at a depth of 30–36 ft. Below this clay layer, sand and gravel are present to a depth of about 100 ft. The top of shale bedrock is at about 100 ft below land surface. The ground-water level ranged from 6.5 to 13 ft below land surface during the study period. From aquifer tests, the hydraulic conductivity was computed to be 18 ft/d. Assuming an average water-table gradient of 0.003 and an effective porosity of 40 percent, ground-water velocity was computed to be 0.14 ft/d at this site.

At the upgradient well, PK-53, the mean concentration of chloride was 14 mg/L, and the maximum was 27 mg/L. Concentrations were slightly higher at the downgradient wells (mean, 21–32 mg/L; maximum, 53–130 mg/L). Concentrations remained fairly constant downgradient along the flowpath through the fourth downgradient well. Thus, 168 ft downgradient from the highway, the mean concentration at the fourth downgradient well was about 2.3 times the upgradient or background concentration; however, because concentrations in all wells were low, this increase is neglible in terms of water-quality considerations. The pattern observed at most of the other sites was not observed here because of low chloride concentrations resulting from a low deicing-chemical input into the aquifer in most years.

Portage County.—The Portage County site is on SR 14 near Ravenna, Ohio, and has first priority for ODOT deicing. This site received an annual average of 28,667 lb/2-ln mi of sodium chloride for the study period. Snowfall averages 62.9 in/yr for nearby reporting areas. Aquifer materials underlying the site consist of medium to very coarse sand and gravel underlain by a thick, gray clayey silt at a depth of about 15 ft. This silt is at least 20 ft thick in most areas. Bedrock is sandstone at a depth of about 40 ft below land surface. The ground-water level ranged from 4.4 to 9.5 ft below land surface during the study period. From aquifer tests, the hydraulic conductivity was computed to be 20 ft/d. Assuming an average water-table gradient of 0.006 and an effective porosity of 38 percent, ground-water velocity was computed to be 0.32 ft/d at this site.

At the upgradient well, PO-114, the mean concentration of chloride was 7 mg/L, and the maximum was 94 mg/L. At the first two downgradient wells, however, concentrations were 20–50 times higher than background. At the first downgradient well, the mean concentration was 406 mg/L, and the maximum was 1,630 mg/L. At the second downgradient well, the mean concentration was 534 mg/L and the maximum was 1,910 mg/L. Concentrations rose steadily downgradient along the flowpath through the second downgradient well. At the third downgradient well, PO-119, and the fourth downgradient well, PO-120, concentrations were near background (mean, 5–18 mg/L; maximum, 27–106 mg/L). These wells are completed just above a clay confining unit but are slightly shallower than the first two downgradient wells. At the alternate third downgradient well, PO-122, the mean concentration was 90 mg/L, and the maximum was 140 mg/L (Dec. 1994–Sept. 1999). The fate of the ground water with elevated chloride found in the first and second downgradient wells is unknown at this time beyond a distance of about 100 ft downgradient from the highway.

Richland County.—The Richland County site is on SR 97 near Lexington, Ohio, and has second priority for ODOT deicing. This site received an annual average of 12,402 lb/2-ln mi of sodium chloride for the study period. Snowfall averages 42.6 in/yr from nearby reporting areas. The aquifer materials underlying the site range from a silty fine sand to a very coarse sand and gravel until a dense gray clay till is encountered at a depth of 22–30 ft below land surface. Sandstone is present at a depth of 15–30 ft below land surface. The ground-water level ranged from 11 to 18 ft below land surface during the study period. From aquifer tests, the hydraulic conductivity was computed to be 5 ft/d. Assuming an average water-table gradient of 0.052 and an effective porosity of 40 percent, ground-water velocity was computed to be 0.65 ft/d at this site.

At the upgradient well, R-21, the mean concentration of chloride was 4 mg/L, and the maximum was 45 mg/L. Concentrations were generally higher at the first two downgradient wells (mean, 38–50 mg/L; maximum, 100–150 mg/L). Concentrations remained fairly constant downgradient along the flowpath through the second downgradient well. At the third downgradient well, R-19, the mean concentration was 42 mg/L, and the maximum was 100 mg/L. By the fourth downgradient well, R-20, the mean concentration was 30 mg/L, and the maximum was 52 mg/L. Thus, 206 ft downgradient from the highway, the mean concentration at the fourth downgradient well was about 7 times the upgradient or background concentration; however, because concentrations in all wells were low, this increase is negligible in terms of water-quality considerations. Although the concentrations are relatively low overall, a pattern of movement through the aquifer can be observed.

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Appendix

Table A-1. List of well numbers and names at each site.

Well number (latitude-longitude)	Well name
Ashland County	
403631082152100	AS-9 near Loudonville, Ohio[1]
403631082152200	AS-6 near Loudonville, Ohio[1]
403633082152400	AS-10 near Loudonville, Ohio
403634082152300	AS-7 near Loudonville, Ohio
403635082152100	AS-48 near Loudonville, Ohio
403635082152200	AS-47 near Loudonville, Ohio
403635082152300	AS-45 near Loudonville, Ohio
403635082152400	AS-46 near Loudonville, Ohio
403635082152500	AS-44 near Loudonville, Ohio
403635082152600	AS-49 near Loudonville, Ohio
403635082152700	AS-43 near Loudonville, Ohio
403635082152800	AS-8 near Loudonville, Ohio
403636082152200	AS-42 near Loudonville, Ohio
403636082152300	AS-41 near Loudonville, Ohio
403636082152600	AS-5 near Loudonville, Ohio
Ashtabula County	
415305080414200	AB-139 near Kingsville, Ohio
415305080414300	AB-132 near Kingsville, Ohio
415307080414200	AB-133 near Kingsville, Ohio
415307080414300	AB-129 near Kingsville, Ohio
415307080414400	AB-130 near Kingsville, Ohio
415307080414500	AB-134 near Kingsville, Ohio
415307080414600	AB-140 near Kingsville, Ohio
415308080414300	AB-135 near Kingsville, Ohio
415308080414400	AB-131 near Kingsville, Ohio
415309080414300	AB-136 near Kingsville, Ohio
415309080414400	AB-138 near Kingsville, Ohio
415310080414400	AB-137 near Kingsville, Ohio
Champaign County	
400947083480000	CH-44 near Urbana, Ohio
400948083475800	CH-46 near Urbana, Ohio
400948083480000	CH-45 near Urbana, Ohio
400948083480100	CH-43 near Urbana, Ohio
400948083480200	CH-41 near Urbana, Ohio
400949083480100	CH-42 near Urbana, Ohio
400950083480600	CH-38 near Urbana, Ohio
400952083475400	CH-37 near Urbana, Ohio[1]
400952083480800	CH-40 near Urbana, Ohio
400952083480900	CH-39 near Urbana, Ohio[1]
400954083475900	CH-36 near Urbana, Ohio[1]
Clark County	
395854083440500	CL-132 near Springfield, Ohio[1]
395858083440100	CL-133 near Springfield, Ohio[1]
395859083440200	CL-141 near Springfield, Ohio
395859083440300	CL-143 near Springfield, Ohio

Table A-1. List of well numbers and names at each site.—Continued

Well number (latitude-longitude)	Well name
Clark County—continued	
395859083440400	CL-142 near Springfield, Ohio
395859083440500	CL-140 near Springfield, Ohio
395859083440600	CL-137 near Springfield, Ohio
395859083440700	CL-138 near Springfield, Ohio
395859083440800	CL-139 near Springfield, Ohio
395901083440600	CL-135 near Springfield, Ohio
395901083440700	CL-136 near Springfield, Ohio
395902083440600	CL-134 near Springfield, Ohio[1]
Lucas County	
413546083480900	LU-28 near Holland, Ohio
413547083481000	LU-26 near Holland, Ohio
413547083481100	LU-27 near Holland, Ohio
413547083481200	LU-25 near Holland, Ohio
413547083481300	LU-22 near Holland, Ohio
413547083481400	LU-23 near Holland, Ohio
413547083481500	LU-24 near Holland, Ohio
413548083480400	LU-17 near Holland, Ohio
413549083481500	LU-21 near Holland, Ohio
413551083481200	LU-20 near Holland, Ohio
413553083480600	LU-18 near Holland, Ohio
413553083480900	LU-19 near Holland, Ohio
Pickaway County	
393540083001200	PK-46 near Circleville, Ohio
393541083000700	PK-44 near Circleville, Ohio
393541083000800	PK-50 near Circleville, Ohio
393541083000900	PK-49 near Circleville, Ohio
393541083001000	PK-47 near Circleville, Ohio
393541083001100	PK-48 near Circleville, Ohio
393541083001200	PK-53 near Circleville, Ohio
393542083000500	PK-52 near Circleville, Ohio
393542083000700	PK-51 near Circleville, Ohio
393542083000900	PK-45 near Circleville, Ohio[1]
Portage County	
411135081172600	PO-113 near Ravenna, Ohio
411136081172400	PO-122 near Ravenna, Ohio
411136081172500	PO-119 near Ravenna, Ohio
411136081172600	PO-120 near Ravenna, Ohio
411137081172100	PO-114 near Ravenna, Ohio
411137081172300	PO-118 near Ravenna, Ohio
411137081172400	PO-117 near Ravenna, Ohio
411137081172500	PO-112 near Ravenna, Ohio
411138081172100	PO-111 near Ravenna, Ohio
411138081172400	PO-115 near Ravenna, Ohio
411138081172500	PO-116 near Ravenna, Ohio
411138081172600	PO-121 near Ravenna, Ohio

Table A-1. List of well numbers and names at each site.—Continued

Well number (latitude-longitude)	Well name
Richland County	
403922082325700	R-11 near Lexington, Ohio
403922082325900	R-19 near Lexington, Ohio
403922082330000	R-20 near Lexington, Ohio
403923082325400	R-21 near Lexington, Ohio
403923082325500	R-16 near Lexington, Ohio
403923082325600	R-15 near Lexington, Ohio
403923082325700	R-18 near Lexington, Ohio
403923082325800	R-12 near Lexington, Ohio
403923082325900	R-17 near Lexington, Ohio
403923082330000	R-13 near Lexington, Ohio
403925082325600	R-14 near Lexington, Ohio

[1] These wells do not appear on the topography and well-location site maps. These were test observation wells used only to obtain initial water level. No samples were collected from these wells.

Table A-2. Chloride concentration of soil-water samples, collected at each study site.

[mg/L, milligrams per liter]

Soil collection date	Distance downgradient from road (feet)	Depth of sample (feet)	Dissolved chloride (mg/L)
Ashland County			
08/04/93	12	0-1	40.8
08/04/93	12	1-2	69.0
08/04/93	80	0-1	7.1
04/18/94	10	0-1	3.0
04/18/94	10	1-2	210.0
04/18/94	80	0-1	5.8
04/14/95	12	0-1	71.0
04/14/95	40	0-1	14.0
04/14/95	80	0-1	47.0
10/26/95	10	0-1	45.0
10/26/95	80	0-1	23.0
Ashtabula County			
08/05/93	10	0-1	131.7
08/05/93	10	1-2	115.8
08/05/93	80	0-1	6.1
04/18/94	10	0-1	806.0
04/18/94	80	0-1	5.7
04/13/95	10	0-1	620.0
04/13/95	80	0-1	6.2
06/13/96	10	0-1	170.0
06/13/96	10	1-2	140.0

Table A-2. Chloride concentration of soil-water samples, collected at each study site.—Continued

[mg/L, milligrams per liter]

Soil collection date	Distance downgradient from road (feet)	Depth of sample (feet)	Dissolved chloride (mg/L)
Ashtabula County—continued			
06/13/96	80	0-1	12.0
11/19/96	10	0-1	150.0
11/19/96	80	0-1	310.0
02/23/98	10	0-1	768.3
02/23/98	80	0-1	37.6
11/16/98	10	0-1	194.4
11/16/98	10	1-2	302.7
11/16/98	80	0-1	11.0
04/29/99	10	0-1	65.0
04/29/99	10	1-2	204.5
04/29/99	80	0-1	9.9
Champaign County			
08/12/93	15	0-1	5.1
08/12/93	15	1-2	37.8
08/12/93	80	0-1	6.9
04/19/94	10	0-1	17.0
04/19/94	10	1-2	91.0
04/19/94	80	0-1	14.0
04/10/95	14	0-1	230.0
04/10/95	14	1-2	140.0
04/10/95	40	0-1	86.0
04/10/95	80	0-1	16.0
11/08/95	10	0-1	39.0
11/08/95	80	0-1	17.0
06/11/96	10	0-1	14.0
06/11/96	10	1-2	42.0
06/11/96	80	0-1	4.2
03/05/98	10	0-1	171.8
03/05/98	80	0-1	17.5
11/18/98	15	0-1	34.0
11/18/98	15	1-2	22.9
11/18/98	120	0-1	15.4
05/04/99	10	0-1	17.7
05/04/99	10	1-2	62.6
05/04/99	80	0-1	3.5
Clark County			
08/12/93	10	0-1	15.0
08/12/93	10	1-2	18.2
08/12/93	80	0-1	4.1
04/19/94	10	0-1	90.0
04/19/94	10	1-2	160.0
04/19/94	80	0-1	5.6
04/10/95	15	0-1	75.0

Table A-2. Chloride concentration of soil-water samples, collected at each study site.—Continued

[mg/L, milligrams per liter]

Soil collection date	Distance downgradient from road (feet)	Depth of sample (feet)	Dissolved chloride (mg/L)
Clark County—continued			
04/10/95	15	1-2	210.0
04/10/95	40	0-1	11.0
04/10/95	80	0-1	9.9
11/07/95	10	0-1	60.0
11/07/95	80	0-1	9.1
06/10/96	10	0-1	4.0
06/10/96	10	1-2	52.0
06/10/96	80	0-1	5.5
11/04/96	10	0-1	32.0
11/04/96	10	1-2	18.0
11/04/96	80	0-1	10.0
03/05/98	10	0-1	16.9
03/05/98	80	0-1	19.0
11/18/98	10	0-1	14.3
11/18/98	10	1-2	11.6
11/18/98	80	0-1	7.6
05/07/99	10	0-1	21.3
05/07/99	10	1-2	21.3
05/07/99	80	0-1	6.8
Lucas County			
08/06/93	6	0-1	32.3
08/06/93	6	1-2	33.4
08/06/93	80	0-1	3.6
04/19/94	10	0-1	16.0
04/19/94	10	1-2	15.0
04/19/94	80	0-1	4.7
04/11/95	8	0-1	15.0
04/11/95	40	0-1	18.0
04/11/95	80	0-1	9.1
11/02/95	10	0-1	54.0
11/02/95	80	0-1	5.7
06/12/96	10	0-1	12.0
06/12/96	10	1-2	18.0
06/12/96	80	0-1	2.7
11/14/96	10	0-1	10.0
11/14/96	80	0-1	7.7
03/12/98	10	0-1	26.7
11/17/98	10	0-1	19.9
11/17/98	10	1-2	22.9
11/17/98	100	0-1	13.5
05/05/99	10	0-1	5.5
05/05/99	10	1-2	6.2
05/05/99	80	0-1	2.1

Table A-2. Chloride concentration of soil-water samples, collected at each study site.—Continued

[mg/L, milligrams per liter]

Soil collection date	Distance downgradient from road (feet)	Depth of sample (feet)	Dissolved chloride (mg/L)
Pickaway County			
08/12/93	13	0-1	13.5
08/12/93	13	1-2	6.8
08/12/93	80	0-1	4.8
04/20/94	10	1-2	54.0
04/20/94	80	0-1	13.0
04/19/95	9	0-1	92.0
04/19/95	40	0-1	21.0
04/19/95	80	0-1	29.0
010/31/95	10	0-1	23.0
010/31/95	80	0-1	6.9
06/17/96	10	0-1	7.8
06/17/96	10	1-2	6.7
06/17/96	80	0-1	8.2
11/04/96	10	0-1	49.0
11/04/96	80	0-1	30.0
03/04/98	10	0-1	61.8
03/04/98	80	0-1	56.1
11/13/98	10	0-1	12.9
11/13/98	10	1-2	9.1
11/13/98	80	0-1	8.1
05/12/99	10	0-1	31.8
05/12/99	10	1-2	36.9
05/12/99	80	0-1	9.2
Portage County			
08/05/93	12	0-1	16.6
08/05/93	12	1-2	21.3
08/05/93	80	0-1	12.5
04/18/94	12	0-1	10.0
04/18/94	80	0-1	10.0
04/12/95	12	0-1	120.0
04/12/95	46	0-1	42.0
04/12/95	86	0-1	20.0
010/27/95	10	0-1	21.0
010/27/95	80	0-1	27.0
06/13/96	10	0-1	6.6
06/13/96	80	0-1	11.0
11/05/96	10	0-1	14.0
11/05/96	80	0-1	14.0
02/24/98	10	0-1	122.9
02/24/98	80	0-1	24.0
11/16/98	10	0-1	154.3
11/16/98	10	1-2	149.5
11/16/98	80	0-1	9.8

Table A-2. Chloride concentration of soil-water samples, collected at each study site.—Continued

[mg/L, milligrams per liter]

Soil collection date	Distance downgradient from road (feet)	Depth of sample (feet)	Dissolved chloride (mg/L)
Portage County—continued			
04/30/99	10	0-1	48.7
04/30/99	10	1-2	42.2
04/30/99	80	0-1	16.5
Richland County			
08/04/93	15	0-1	22.5
08/04/93	15	0-2	39.4
08/04/93	70	0-1	3.3
04/18/94	10	0-1	49.0
04/18/94	80	0-1	6.8
04/26/95	10	0-1	120.0
04/26/95	40	0-1	24.0
04/26/95	80	0-1	16.0
010/25/95	10	0-1	36.0
010/25/95	80	0-1	13.0

Table A-2. Chloride concentration of soil-water samples, collected at each study site.—Continued

[mg/L, milligrams per liter]

Soil collection date	Distance downgradient from road (feet)	Depth of sample (feet)	Dissolved chloride (mg/L)
Richland County—continued			
06/14/96	10	0-1	57.0
06/14/96	10	1-2	88.0
06/14/96	80	0-1	5.2
11/13/96	10	0-1	670.0
11/13/96	80	0-1	610.0
02/23/98	10	0-1	37.3
02/23/98	80	0-1	13.2
11/16/98	20	0-1	13.3
11/16/98	20	1-2	9.0
11/16/98	100	0-1	11.4
04/28/99	10	0-1	76.8
04/28/99	10	1-2	128.0
04/28/99	80	0-1	6.4

Table A-3. Water-table gradient and flow angle to roadway.

[*, wells are too linear to determine flow angle of water table by triangulation method]

Site	Maximum water-table gradient (in feet per foot)	Minimum water-table gradient (in feet per foot)	Average gradient	Maximum angle to roadway (in degrees)	Minimum angle to roadway (in degrees)	Average angle to roadway (in degrees)
Ashland	0.013	0.007	0.010	104	66	83
Ashtabula	.064	.027	.036	*	*	*
Champaign	.002	.001	.002	27	19	23
Clark	.004	.002	.003	88	84	86
Lucas	.003	.002	.003	65	45	60
Pickaway	.004	.003	.003	81	45	70
Portage	.0085	.002	.006	87	48	75
Richland	.071	.029	.052	62	59	60

Table A-4. Water-quality data for multilevel wells by water year, 1991-95, Ashland County, Ohio, study site.

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
			Water year 1991			
AS-43	Upgradient	Maximum	709	130	21	22
		Minimum	223	41	7	4
		Mean	538	96	15	13
		Median	560	100	15	13
		N	26	21	21	26
AS-44	1st downgradient	Maximum	886	92	77	85
		Minimum	517	63	22	21
		Mean	641	79	53	52
		Median	602	79	51	50
		N	24	26	25	26
AS-46	2nd downgradient	Maximum	837	99	53	64
		Minimum	501	65	27	30
		Mean	674	86	40	50
		Median	662	86	40	53
		N	30	28	28	30
AS-47	3rd downgradient	Maximum	855	94	61	95
		Minimum	543	53	39	48
		Mean	711	83	51	73
		Median	722	86	51	75
		N	30	30	30	31
AS-48	4th downgradient	Maximum	676	91	28	47
		Minimum	331	56	5	8
		Mean	505	74	17	24
		Median	511	73	16	22
		N	41	35	35	42
			Water year 1992			
AS-43	Upgradient	Maximum	707	130	32	74
		Minimum	374	42	10	6
		Mean	608	90	19	27
		Median	654	92	20	25
		N	13	17	17	21
AS-44	1st downgradient	Maximum	737	87	56	69
		Minimum	592	32	24	15
		Mean	666	68	38	36
		Median	663	73	42	35
		N	9	17	17	21
AS-46	2nd downgradient	Maximum	1,000	130	48	64
		Minimum	595	42	40	33
		Mean	887	100	43	46
		Median	938	100	43	42
		N	10	15	15	19
AS-47	3rd downgradient	Maximum	821	92	56	98
		Minimum	605	79	44	65
		Mean	767	84	50	79
		Median	781	83	49	76

Table A-4. Water-quality data for multilevel wells by water year, 1991-95, Ashland County, Ohio, study site.—Continued

[μS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (μS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
		Water year 1992—continued				
		N	11	10	10	16
AS-48	4th downgradient	Maximum	693	88	24	53
		Minimum	402	27	13	9
		Mean	552	65	18	26
		Median	536	66	19	22
		N	19	29	29	30
		Water year 1993				
AS-43	Upgradient	Maximum	959	120	28	82
		Minimum	385	86	14	8
		Mean	705	106	21	40
		Median	709	110	22	36
		N	18	14	14	18
AS-44	1st downgradient	Maximum	894	93	67	100
		Minimum	572	65	31	10
		Mean	734	82	51	56
		Median	738	82	52	56
		N	18	13	13	18
AS-46	2nd downgradient	Maximum	877	99	50	77
		Minimum	671	79	32	45
		Mean	797	91	42	63
		Median	812	92	44	62
		N	17	15	15	17
AS-47	3rd downgradient	Maximum	893	91	75	110
		Minimum	653	46	53	47
		Mean	829	82	58	90
		Median	845	88	56	94
		N	13	10	10	14
AS-48	4th downgradient	Maximum	613	110	26	37
		Minimum	453	58	12	7
		Mean	509	67	17	15
		Median	490	64	14	14
		N	22	20	20	22
		Water year 1994				
AS-43	Upgradient	Maximum	1,050	130	38	130
		Minimum	341	88	14	11
		Mean	650	105	23	57
		Median	679	110	22	46
		N	22	18	18	22
AS-44	1st downgradient	Maximum	904	93	74	140
		Minimum	462	66	20	22
		Mean	742	83	54	84
		Median	782	85	64	86
		N	25	25	25	25

Table A-4. Water-quality data for multilevel wells by water year, 1991-95, Ashland County, Ohio, study site.—Continued

[μS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (μS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
			Water year 1994—continued			
AS-46	2nd downgradient	Maximum	1,040	140	60	130
		Minimum	322	74	29	20
		Mean	765	101	49	71
		Median	802	100	52	70
		N	25	20	20	26
AS-47	3rd downgradient	Maximum	957	100	73	140
		Minimum	528	84	48	35
		Mean	778	94	60	99
		Median	784	96	61	100
		N	22	16	16	22
AS-48	4th downgradient	Maximum	569	76	25	38
		Minimum	336	55	9	8
		Mean	477	65	15	16
		Median	480	64	14	13
		N	31	30	30	31
			Water year 1995			
AS-43	Upgradient	Maximum	1,560	130	210	360
		Minimum	320	51	6	2
		Mean	666	94	31	61
		Median	630	97	26	44
		N	31	26	26	32
AS-44	1st downgradient	Maximum	1,690	100	100	220
		Minimum	368	61	19	13
		Mean	728	76	48	64
		Median	678	73	45	60
		N	32	27	27	32
AS-46	2nd downgradient	Maximum	957	130	68	110
		Minimum	529	64	32	18
		Mean	825	99	52	70
		Median	848	98	51	66
		N	32	26	26	33
AS-47	3rd downgradient	Maximum	986	120	68	120
		Minimum	581	63	45	42
		Mean	781	83	59	85
		Median	782	80	59	84
		N	27	20	20	28
AS-48	4th downgradient	Maximum	654	71	25	53
		Minimum	294	54	11	5
		Mean	487	63	15	15
		Median	496	63	14	12
		N	40	34	34	41

Table A-5. Water-quality data for multilevel wells by water year, 1991-99, Ashtabula County, Ohio, study site.

[μS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (μS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
		Water year 1991				
AB-139	Upgradient	Maximum	1,020	120	79	87
		Minimum	375	48	4	1
		Mean	539	76	11	8
		Median	495	74	9	5
		N	33	28	28	34
AB-133	1st downgradient	Maximum	3,590	160	580	620
		Minimum	778	57	290	120
		Mean	2,015	88	346	448
		Median	1,910	73	320	460
		N	17	17	17	17
AB-135	2nd downgradient	Maximum	1,140	100	91	260
		Minimum	575	64	32	62
		Mean	846	87	53	156
		Median	843	86	52	150
		N	40	39	39	41
AB-136	3rd downgradient	Maximum	1,620	85	220	360
		Minimum	989	48	130	170
		Mean	1,309	70	184	284
		Median	1,290	70	190	285
		N	48	48	48	46
AB-137	4th downgradient	Maximum	813	89	46	280
		Minimum	606	60	34	81
		Mean	708	79	39	110
		Median	686	78	37	100
		N	38	37	37	37
		Water year 1992				
AB-139	Upgradient	Maximum	816	110	44	120
		Minimum	286	23	4	4
		Mean	522	73	13	24
		Median	538	75	10	16
		N	30	34	34	41
AB-133	1st downgradient	Maximum	3,890	190	760	1400
		Minimum	1,440	53	200	220
		Mean	2,224	98	368	612
		Median	2,140	79	335	560
		N	25	42	42	45
AB-135	2nd downgradient	Maximum	2,800	180	330	750
		Minimum	875	88	35	190
		Mean	1,497	113	132	320
		Median	1,390	110	110	300
		N	31	38	38	45

Table A-5. Water-quality data for multilevel wells by water year, 1991-99, Ashtabula County, Ohio, study site.—Continued

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
		Water year 1992—continued				
AB-136	3rd downgradient	Maximum	1,540	88	220	360
		Minimum	1,210	53	140	210
		Mean	1,404	74	190	306
		Median	1,420	72	190	310
		N	40	42	42	54
AB-137	4th downgradient	Maximum	875	100	53	130
		Minimum	672	76	39	100
		Mean	802	90	44	114
		Median	818	91	44	110
		N	28	44	44	45
		Water year 1993				
AB-139	Upgradient	Maximum	611	95	20	24
		Minimum	205	39	4	2
		Mean	422	64	9	6
		Median	446	62	8	3
		N	38	29	29	41
AB-133	1st downgradient	Maximum	2,380	150	330	660
		Minimum	808	33	130	120
		Mean	1,556	64	242	374
		Median	1,720	61	265	390
		N	45	42	42	44
AB-135	2nd downgradient	Maximum	1,280	110	110	280
		Minimum	883	82	62	150
		Mean	1,040	91	82	196
		Median	1,040	90	78	190
		N	43	46	46	45
AB-136	3rd downgradient	Maximum	1,590	78	220	360
		Minimum	1,040	52	140	210
		Mean	1,353	65	187	294
		Median	1,370	65	190	300
		N	46	43	43	46
AB-137	4th downgradient	Maximum	875	98	50	130
		Minimum	682	74	41	20
		Mean	776	84	45	98
		Median	778	84	45	98
		N	38	29	29	39
		Water year 1994				
AB-139	Upgradient	Maximum	560	94	12	35
		Minimum	267	14	5	3
		Mean	431	66	7	10
		Median	414	64	6	5
		N	37	32	32	38

Table A-5. Water-quality data for multilevel wells by water year, 1991-99, Ashtabula County, Ohio, study site.—Continued

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
			Water year 1994—continued			
AB-133	1st downgradient	Maximum	4,040	210	690	1100
		Minimum	1,040	23	180	220
		Mean	2,257	92	352	581
		Median	2,290	85	360	590
		N	51	47	47	51
AB-135	2nd downgradient	Maximum	2,010	180	210	520
		Minimum	643	89	82	190
		Mean	1,276	107	116	279
		Median	1,210	100	105	250
		N	52	50	50	53
AB-136	3rd downgradient	Maximum	1,730	93	260	430
		Minimum	1,050	56	160	290
		Mean	1,559	80	211	362
		Median	1,555	82	210	360
		N	52	49	49	53
AB-137	4th downgradient	Maximum	936	110	63	110
		Minimum	666	19	44	89
		Mean	778	85	49	100
		Median	766	86	48	99
		N	42	42	42	43
			Water year 1995			
AB-139	Upgradient	Maximum	580	88	34	51
		Minimum	273	49	5	3
		Mean	462	68	11	13
		Median	463	69	7	6
		N	36	27	27	37
AB-133	1st downgradient	Maximum	2,760	140	400	720
		Minimum	748	24	120	150
		Mean	1,859	88	282	454
		Median	1,980	98	315	480
		N	45	40	40	45
AB-135	2nd downgradient	Maximum	1,150	110	98	240
		Minimum	886	75	61	150
		Mean	1,009	94	75	187
		Median	994	95	73	180
		N	48	46	47	48
AB-136	3rd downgradient	Maximum	1,690	86	240	400
		Minimum	1,160	61	150	220
		Mean	1,516	76	207	345
		Median	1,580	79	220	370
		N	47	46	46	47

Table A-5. Water-quality data for multilevel wells by water year, 1991-99, Ashtabula County, Ohio, study site.—Continued

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
Water year 1995—continued						
AB-137	4th downgradient	Maximum	807	98	51	110
		Minimum	682	73	42	83
		Mean	748	84	46	92
		Median	744	83	46	91
		N	40	38	38	40
Water year 1996						
AB-139	Upgradient	Maximum	598	73	55	49
		Minimum	222	31	3	1
		Mean	363	51	9	8
		Median	345	48	6	6
		N	33	22	22	34
AB-133	1st downgradient	Maximum	4,960	260	770	1400
		Minimum	1,760	26	100	480
		Mean	2,649	101	419	713
		Median	2,330	77	400	600
		N	38	33	32	39
AB-135	2nd downgradient	Maximum	1,410	120	130	330
		Minimum	953	66	68	170
		Mean	1,102	95	90	218
		Median	1,100	92	86	215
		N	41	37	37	42
AB-136	3rd downgradient	Maximum	1,650	95	230	410
		Minimum	1,080	57	120	210
		Mean	1,411	71	189	317
		Median	1,410	69	200	320
		N	42	37	37	42
AB-137	4th downgradient	Maximum	784	98	50	100
		Minimum	677	68	42	68
		Mean	717	78	46	85
		Median	712	76	46	85
		N	34	35	35	35
Water year 1997						
AB-139	Upgradient	Maximum	1,010	80	115	164
		Minimum	122	24	4	2
		Mean	363	42	21	21
		Median	306	38	7	4
		N	38	32	32	40
AB-133	1st downgradient	Maximum	4,200	140	673	1,220
		Minimum	1,180	32	150	240
		Mean	2,627	79	395	711
		Median	2,575	77	393	692
		N	48	44	44	48

Table A-5. Water-quality data for multilevel wells by water year, 1991-99, Ashtabula County, Ohio, study site.—Continued

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
		Water year 1997—continued				
AB-135	2nd downgradient	Maximum	1,190	115	104	287
		Minimum	930	83	68	165
		Mean	1,002	91	76	189
		Median	991	89	75	180
		N	47	45	45	47
AB-136	3rd downgradient	Maximum	2,150	112	278	571
		Minimum	1,180	68	142	262
		Mean	1,571	80	204	373
		Median	1,550	77	200	362
		N	48	46	46	48
AB-137	4th downgradient	Maximum	724	86	53	106
		Minimum	593	61	42	68
		Mean	670	70	47	84
		Median	670	69	46	83
		N	40	34	34	40
		Water year 1998				
AB-139	Upgradient	Maximum	947	93	131	151
		Minimum	222	29	4	2
		Mean	479	45	39	40
		Median	312	38	7	5
		N	39	29	29	40
AB-133	1st downgradient	Maximum	4,260	171	646	1,140
		Minimum	1,740	40	259	483
		Mean	2,962	99	475	799
		Median	3,125	103	501	828
		N	44	39	39	44
AB-135	2nd downgradient	Maximum	1,930	140	190	844
		Minimum	1,200	93	104	242
		Mean	1,452	110	127	338
		Median	1,395	104	122	302
		N	48	45	45	48
AB-136	3rd downgradient	Maximum	2,590	153	349	705
		Minimum	1,730	90	207	401
		Mean	2,214	114	280	567
		Median	2,200	113	282	566
		N	47	43	43	48
AB-137	4th downgradient	Maximum	872	104	52	119
		Minimum	648	66	38	78
		Mean	760	79	47	101
		Median	770	77	48	104
		N	40	36	36	40

Table A-5. Water-quality data for multilevel wells by water year, 1991-99, Ashtabula County, Ohio, study site.—Continued

[μS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (μS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
			Water year 1999			
AB-139	Upgradient	Maximum	2,130	163	284	544
		Minimum	82	49	24	3
		Mean	1,065	95	124	210
		Median	875	84	125	140
		N	35	21	21	36
AB-133	1st downgradient	Maximum	4,890	209	748	1,500
		Minimum	1,650	65	524	454
		Mean	3,855	132	618	1,119
		Median	3,630	122	608	1,050
		N	39	28	28	39
AB-135	2nd downgradient	Maximum	2,140	146	236	553
		Minimum	1,390	80	45	318
		Mean	1,668	120	156	397
		Median	1,645	120	155	380
		N	42	40	40	46
AB-136	3rd downgradient	Maximum	2,430	127	330	657
		Minimum	1,500	65	172	106
		Mean	1,981	103	256	501
		Median	2,050	109	276	537
		N	47	39	39	48
AB-137	4th downgradient	Maximum	834	120	173	135
		Minimum	456	72	2	10
		Mean	745	82	53	109
		Median	749	81	50	110
		N	36	35	35	40

Table A-6. Water-quality data for multilevel wells by water year, 1991-99, Champaign County, Ohio, study site.

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
			Water year 1991			
CH-40	Upgradient	Maximum	787	130	13	31
		Minimum	515	40	6	7
		Mean	663	101	7	25
		Median	668	100	7	28
		N	49	45	51	54
CH-41	1st downgradient	Maximum	1,030	120	120	110
		Minimum	571	90	6	26
		Mean	747	105	20	40
		Median	742	110	11	38
		N	50	47	53	54
CH-43	2nd downgradient	Maximum	964	120	65	73
		Minimum	670	96	12	31
		Mean	837	109	30	50
		Median	836	110	31	50
		N	42	41	46	46
CH-45	3rd downgradient	Maximum	980	130	55	80
		Minimum	524	71	8	20
		Mean	775	110	25	43
		Median	785	110	21	39
		N	43	40	44	45
CH-46	4th downgradient	Maximum	1,210	150	38	83
		Minimum	602	96	20	35
		Mean	814	111	27	50
		Median	802	110	27	48
		N	44	40	44	45
			Water year 1992			
CH-40	Upgradient	Maximum	783	160	11	32
		Minimum	642	47	7	17
		Mean	734	108	8	28
		Median	734	110	7	28
		N	40	43	43	52
CH-41	1st downgradient	Maximum	898	120	48	86
		Minimum	487	41	11	31
		Mean	776	99	21	38
		Median	789	110	14	36
		N	37	52	52	54
CH-43	2nd downgradient	Maximum	1,020	130	63	81
		Minimum	682	43	12	38
		Mean	870	104	28	51
		Median	872	110	23	49
		N	36	39	39	45

Table A-6. Water-quality data for multilevel wells by water year, 1991-99, Champaign County, Ohio, study site.—Continued

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
		Water year 1992—continued				
CH-45	3rd downgradient	Maximum	1,060	140	43	150
		Minimum	635	47	10	31
		Mean	848	106	22	56
		Median	839	110	18	45
		N	29	32	32	37
CH-46	4th downgradient	Maximum	967	160	37	88
		Minimum	627	46	14	31
		Mean	837	110	22	49
		Median	842	110	19	42
		N	33	39	39	45
		Water year 1993				
CH-40	Upgradient	Maximum	790	130	10	25
		Minimum	490	79	6	10
		Mean	708	105	7	20
		Median	715	110	7	22
		N	45	46	47	47
CH-41	1st downgradient	Maximum	971	110	59	72
		Minimum	474	64	6	18
		Mean	798	104	18	35
		Median	803	110	13	34
		N	47	44	44	48
CH-43	2nd downgradient	Maximum	1,050	150	63	71
		Minimum	644	91	12	29
		Mean	919	111	39	48
		Median	905	110	40	50
		N	43	38	38	44
CH-45	3rd downgradient	Maximum	1,080	120	59	110
		Minimum	633	88	12	24
		Mean	865	106	34	47
		Median	861	110	33	43
		N	37	36	37	39
CH-46	4th downgradient	Maximum	1,070	120	59	98
		Minimum	774	95	24	36
		Mean	891	109	34	50
		Median	894	110	35	46
		N	38	39	39	40
		Water year 1994				
CH-40	Upgradient	Maximum	873	120	28	39
		Minimum	573	64	6	19
		Mean	707	108	7	22
		Median	707	110	7	21
		N	43	47	47	47

Table A-6. Water-quality data for multilevel wells by water year, 1991-99, Champaign County, Ohio, study site.—Continued

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
Water year 1994—continued						
CH-41	1st downgradient	Maximum	957	120	81	63
		Minimum	544	96	7	17
		Mean	752	107	20	30
		Median	753	110	12	24
		N	47	46	46	48
CH-43	2nd downgradient	Maximum	1,060	120	80	56
		Minimum	542	82	12	17
		Mean	801	106	43	36
		Median	794	110	42	39
		N	45	40	40	45
CH-45	3rd downgradient	Maximum	1,020	130	71	66
		Minimum	548	86	12	17
		Mean	771	109	30	35
		Median	774	110	24	35
		N	38	37	37	39
CH-46	4th downgradient	Maximum	982	120	45	71
		Minimum	540	74	20	22
		Mean	789	109	30	43
		Median	776	110	28	38
		N	38	34	34	38
Water year 1995						
No samples collected.						
Water year 1996						
CH-40	Upgradient	Maximum	782	110	10	25
		Minimum	562	70	5	8
		Mean	687	100	6	21
		Median	706	100	6	23
		N	18	16	16	18
CH-41	1st downgradient	Maximum	1,170	120	42	88
		Minimum	627	98	6	16
		Mean	802	106	17	37
		Median	764	110	7	19
		N	20	18	18	18
CH-43	2nd downgradient	Maximum	947	120	45	96
		Minimum	650	93	7	17
		Mean	808	106	25	52
		Median	804	110	26	45
		N	17	16	16	17
CH-45	3rd downgradient	Maximum	987	110	42	79
		Minimum	582	72	8	15
		Mean	802	101	27	51
		Median	824	105	31	62
		N	14	14	14	14

Table A-6. Water-quality data for multilevel wells by water year, 1991-99, Champaign County, Ohio, study site.—Continued

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
Water year 1996—continued						
CH-46	4th downgradient	Maximum	830	110	27	57
		Minimum	627	91	19	35
		Mean	786	101	24	47
		Median	802	100	25	48
		N	15	14	14	15
Water year 1997						
CH-40	Upgradient	Maximum	841	150	9	24
		Minimum	611	100	6	22
		Mean	714	113	7	23
		Median	736	110	6	24
		N	9	7	7	8
CH-41	1st downgradient	Maximum	980	110	100	67
		Minimum	672	100	8	20
		Mean	803	106	29	42
		Median	793	110	13	40
		N	11	9	9	12
CH-43	2nd downgradient	Maximum	924	120	34	62
		Minimum	694	110	10	26
		Mean	823	114	19	50
		Median	840	110	19	51
		N	10	9	9	10
CH-45	3rd downgradient	Maximum	980	110	42	88
		Minimum	646	100	8	21
		Mean	830	106	25	55
		Median	864	110	26	56
		N	8	8	8	8
CH-46	4th downgradient	Maximum	970	110	45	92
		Minimum	680	95	16	18
		Mean	871	108	32	60
		Median	874	110	31	58
		N	10	10	10	10
Water year 1998						
No samples collected.						
Water year 1999						
CH-40	Upgradient	Maximum	671	137	7	22
		Minimum	521	105	6	19
		Mean	616	110	6	20
		Median	627	106	6	21
		N	20	16	16	20
CH-41	1st downgradient	Maximum	954	112	102	67
		Minimum	543	90	8	18
		Mean	702	105	20	33
		Median	700	104	11	26
		N	30	30	30	29

Table A-6. Water-quality data for multilevel wells by water year, 1991-99, Champaign County, Ohio, study site.—Continued

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
			Water year 1999—continued			
CH-43	2nd downgradient	Maximum	874	118	46	59
		Minimum	577	91	12	18
		Mean	715	107	25	35
		Median	694	107	25	32
		N	27	24	24	27
CH-45	3rd downgradient	Maximum	799	125	46	52
		Minimum	426	46	11	9
		Mean	654	101	23	26
		Median	661	104	21	26
		N	24	18	18	24
CH-46	4th downgradient	Maximum	793	113	34	53
		Minimum	413	97	15	22
		Mean	675	106	20	32
		Median	697	106	19	30
		N	25	21	21	25

Table A-7. Water-quality data for multilevel wells by water year, 1991-99, Clark County, Ohio, study site.

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
			Water year 1991			
CL-136	Upgradient	Maximum	772	130	8	45
		Minimum	509	68	4	2
		Mean	638	105	5	11
		Median	639	110	5	10
		N	31	29	29	31
CL-137	1st downgradient	Maximum	828	140	21	43
		Minimum	426	98	5	6
		Mean	688	115	11	17
		Median	708	120	10	16
		N	36	41	41	42
CL-141	2nd downgradient	Maximum	885	150	29	41
		Minimum	545	60	4	12
		Mean	723	115	11	21
		Median	728	115	9	20
		N	37	38	38	41
CL-142	3rd downgradient	Maximum	880	140	24	54
		Minimum	457	94	11	13
		Mean	715	109	16	28
		Median	709	110	17	27
		N	35	33	33	34

Table A-7. Water-quality data for multilevel wells by water year, 1991-99, Clark County, Ohio, study site.—Continued

[μS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (μS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
		Water year 1991—continued				
CL-143	4th downgradient	Maximum	831	140	14	30
		Minimum	356	69	3	4
		Mean	622	103	8	15
		Median	615	100	9	16
		N	41	40	40	41
		Water year 1992				
CL-136	Upgradient	Maximum	832	130	8	27
		Minimum	422	45	5	8
		Mean	655	101	7	15
		Median	706	100	7	15
		N	9	11	11	14
CL-137	1st downgradient	Maximum	836	130	14	43
		Minimum	488	46	6	7
		Mean	725	112	8	20
		Median	762	110	7	18
		N	17	15	15	24
CL-141	2nd downgradient	Maximum	881	130	20	41
		Minimum	553	45	6	13
		Mean	775	108	11	28
		Median	782	110	10	28
		N	16	24	24	30
CL-142	3rd downgradient	Maximum	869	130	20	46
		Minimum	518	46	11	23
		Mean	708	105	14	34
		Median	732	110	14	34
		N	15	22	22	24
CL-143	4th downgradient	Maximum	862	140	12	26
		Minimum	317	42	4	3
		Mean	669	99	8	16
		Median	692	100	9	18
		N	18	26	26	29
		Water year 1993				
		No samples collected.				
		Water year 1994				
CL-136	Upgradient	Maximum	772	52	25	26
		Minimum	413	52	25	15
		Mean	660	52	25	21
		Median	714	52	25	20
		N	6	1	1	6
CL-137	1st downgradient	Maximum	864	120	26	50
		Minimum	747	110	6	14
		Mean	781	112	14	28
		Median	764	110	9	18
		N	7	8	8	8

Table A-7. Water-quality data for multilevel wells by water year, 1991-99, Clark County, Ohio, study site.—Continued

[μS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (μS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
		Water year 1994—continued				
CL-141	2nd downgradient	Maximum	884	110	16	32
		Minimum	637	99	8	18
		Mean	792	109	12	24
		Median	806	110	12	23
		N	11	9	9	11
CL-142	3rd downgradient	Maximum	884	110	25	44
		Minimum	700	100	18	28
		Mean	828	103	21	37
		Median	848	100	20	36
		N	6	7	7	8
CL-143	4th downgradient	Maximum	839	100	13	31
		Minimum	490	81	5	4
		Mean	662	90	9	14
		Median	658	90	10	16
		N	10	8	9	10
		Water year 1995				
		No samples collected.				
		Water year 1996				
CL-136	Upgradient	Maximum	806	120	15	31
		Minimum	500	90	4	5
		Mean	667	103	6	13
		Median	623	100	5	8
		N	11	10	10	11
CL-137	1st downgradient	Maximum	914	110	34	65
		Minimum	594	96	11	11
		Mean	717	104	20	28
		Median	704	100	17	22
		N	15	13	13	15
CL-141	2nd downgradient	Maximum	825	110	36	83
		Minimum	681	95	11	15
		Mean	758	103	25	38
		Median	768	100	28	32
		N	14	11	11	14
CL-142	3rd downgradient	Maximum	890	99	36	59
		Minimum	585	89	9	14
		Mean	719	93	28	40
		Median	723	93	32	44
		N	12	12	12	12
CL-143	4th downgradient	Maximum	816	110	25	54
		Minimum	483	82	3	4
		Mean	615	90	9	19
		Median	582	88	8	15
		N	15	14	14	15

Table A-7. Water-quality data for multilevel wells by water year, 1991-99, Clark County, Ohio, study site.—Continued

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
Water year 1997						
CL-136	Upgradient	Maximum	791	110	13	27
		Minimum	585	77	4	6
		Mean	690	103	6	9
		Median	671	110	4	6
		N	8	5	5	8
CL-137	1st downgradient	Maximum	792	130	34	29
		Minimum	674	85	6	10
		Mean	729	108	12	14
		Median	728	110	8	12
		N	6	8	8	8
CL-141	2nd downgradient	Maximum	841	120	16	23
		Minimum	617	100	8	12
		Mean	741	112	12	18
		Median	736	110	12	19
		N	9	8	8	10
CL-142	3rd downgradient	Maximum	863	110	28	43
		Minimum	663	110	20	17
		Mean	782	110	24	33
		Median	804	110	24	34
		N	7	4	4	7
CL-143	4th downgradient	Maximum	897	110	21	49
		Minimum	473	69	3	5
		Mean	633	87	9	18
		Median	600	87	10	14
		N	8	9	9	10
Water year 1998						
No samples collected.						
Water year 1999						
CL-136	Upgradient	Maximum	696	135	14	17
		Minimum	343	35	4	7
		Mean	546	97	8	12
		Median	530	106	4	11
		N	14	13	13	15
CL-137	1st downgradient	Maximum	779	114	32	56
		Minimum	514	94	8	11
		Mean	660	106	16	29
		Median	671	107	14	26
		N	24	21	21	24
CL-141	2nd downgradient	Maximum	844	114	26	62
		Minimum	533	99	11	22
		Mean	692	107	19	39
		Median	704	108	18	39
		N	24	22	22	24

Table A-7. Water-quality data for multilevel wells by water year, 1991-99, Clark County, Ohio, study site.—Continued

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
			Water year 1999—continued			
CL-142	3rd downgradient	Maximum	819	106	25	51
		Minimum	474	80	5	7
		Mean	626	98	14	28
		Median	635	98	12	27
		N	20	15	15	19
CL-143	4th downgradient	Maximum	702	119	14	27
		Minimum	423	76	3	2
		Mean	542	96	8	15
		Median	528	99	8	17
		N	22	21	21	22

Table A-8. Water-quality data for multilevel wells by water year, 1991-99, Lucas County, Ohio, study site.

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
			Water year 1991			
LU-21	Upgradient	Maximum	831	140	8	130
		Minimum	107	10	2	3
		Mean	348	56	4	36
		Median	239	40	3	8
		N	40	42	42	41
LU-22	1st downgradient	Maximum	1,570	110	210	500
		Minimum	446	36	6	27
		Mean	732	69	57	125
		Median	566	72	16	57
		N	33	36	36	39
LU-25	2nd downgradient	Maximum	983	110	130	220
		Minimum	435	22	6	16
		Mean	563	66	32	70
		Median	492	73	11	42
		N	38	39	39	40
LU-27	3rd downgradient	Maximum	1,300	160	140	340
		Minimum	311	34	4	5
		Mean	662	83	31	80
		Median	578	79	17	42
		N	34	39	39	41
LU-28	4th downgradient	Maximum	1,040	110	170	240
		Minimum	263	25	6	6
		Mean	538	60	38	55
		Median	474	63	13	34
		N	44	45	45	46

Table A-8. Water-quality data for multilevel wells by water year, 1991-99, Lucas County, Ohio, study site.—Continued

[μS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (μS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
		Water year 1992				
LU-21	Upgradient	Maximum	903	160	9	150
		Minimum	145	14	2	4
		Mean	380	57	5	38
		Median	252	36	4	10
		N	34	38	39	44
LU-22	1st downgradient	Maximum	2,250	200	310	670
		Minimum	370	17	5	24
		Mean	735	71	61	122
		Median	603	76	27	74
		N	41	37	37	44
LU-25	2nd downgradient	Maximum	1,570	100	210	400
		Minimum	358	26	5	17
		Mean	673	67	54	111
		Median	571	72	22	63
		N	37	40	40	45
LU-27	3rd downgradient	Maximum	1,530	160	120	390
		Minimum	418	26	6	1
		Mean	666	78	32	71
		Median	565	73	18	51
		N	35	42	42	43
LU-28	4th downgradient	Maximum	1,430	110	180	350
		Minimum	363	15	8	14
		Mean	620	67	42	83
		Median	566	74	14	53
		N	33	41	41	44
		Water year 1993				
LU-21	Upgradient	Maximum	893	150	12	140
		Minimum	87	6	2	2
		Mean	273	40	5	22
		Median	181	22	5	4
		N	39	36	36	40
LU-22	1st downgradient	Maximum	1,450	110	230	330
		Minimum	323	13	5	17
		Mean	647	68	48	94
		Median	612	80	18	71
		N	39	39	39	37
LU-25	2nd downgradient	Maximum	1,730	130	200	450
		Minimum	252	15	7	28
		Mean	782	73	62	149
		Median	668	83	38	100
		N	42	41	41	42

Table A-8. Water-quality data for multilevel wells by water year, 1991-99, Lucas County, Ohio, study site.—Continued

[μS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (μS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
		Water year 1993—continued				
LU-27	3rd downgradient	Maximum	1,340	140	170	330
		Minimum	303	26	6	1
		Mean	619	62	50	81
		Median	530	58	38	48
		N	38	36	36	38
LU-28	4th downgradient	Maximum	1,230	120	110	280
		Minimum	134	25	6	4
		Mean	578	68	31	72
		Median	577	76	16	67
		N	41	38	38	39
		Water year 1994				
LU-21	Upgradient	Maximum	884	160	9	130
		Minimum	133	11	2	3
		Mean	378	55	4	32
		Median	280	40	4	10
		N	42	45	44	45
LU-22	1st downgradient	Maximum	2,060	170	290	590
		Minimum	424	17	8	44
		Mean	862	94	56	163
		Median	756	92	18	140
		N	40	45	45	45
LU-25	2nd downgradient	Maximum	1,690	120	250	430
		Minimum	493	12	5	19
		Mean	726	71	53	111
		Median	646	82	27	80
		N	39	40	40	45
LU-27	3rd downgradient	Maximum	1,660	210	100	440
		Minimum	295	22	3	4
		Mean	809	96	33	99
		Median	742	91	24	63
		N	40	40	40	45
LU-28	4th downgradient	Maximum	1,400	180	120	340
		Minimum	244	33	11	12
		Mean	770	92	42	122
		Median	685	90	38	83
		N	41	43	43	44
		Water year 1995				
LU-21	Upgradient	Maximum	845	150	9	120
		Minimum	144	14	1	4
		Mean	384	58	4	35
		Median	280	40	4	13
		N	38	38	38	39

Table A-8. Water-quality data for multilevel wells by water year, 1991-99, Lucas County, Ohio, study site.—Continued

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
Water year 1995—continued						
LU-22	1st downgradient	Maximum	1,790	120	250	460
		Minimum	311	20	6	32
		Mean	726	75	59	119
		Median	615	85	20	84
		N	39	36	36	40
LU-25	2nd downgradient	Maximum	1,590	160	210	410
		Minimum	374	10	7	29
		Mean	839	80	66	152
		Median	726	90	68	120
		N	38	35	34	38
LU-27	3rd downgradient	Maximum	1,500	120	200	340
		Minimum	475	36	6	11
		Mean	861	84	62	139
		Median	787	88	46	120
		N	35	34	34	36
LU-28	4th downgradient	Maximum	1,650	98	210	390
		Minimum	450	35	10	15
		Mean	733	73	56	104
		Median	685	77	35	90
		N	39	39	39	39
Water year 1996						
LU-21	Upgradient	Maximum	870	150	8	120
		Minimum	138	15	2	6
		Mean	395	60	4	36
		Median	278	40	4	12
		N	33	33	33	35
LU-22	1st downgradient	Maximum	2,500	120	380	660
		Minimum	548	28	8	57
		Mean	857	84	62	158
		Median	745	86	20	120
		N	34	30	30	34
LU-25	2nd downgradient	Maximum	1,210	130	170	280
		Minimum	408	14	6	50
		Mean	732	75	50	128
		Median	688	83	22	120
		N	32	33	33	33
LU-27	3rd downgradient	Maximum	2,170	220	150	380
		Minimum	368	51	11	6
		Mean	1,341	136	62	97
		Median	1,550	150	62	74
		N	33	30	30	34

Table A-8. Water-quality data for multilevel wells by water year, 1991-99, Lucas County, Ohio, study site.—Continued

[μS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (μS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
Water year 1996—continued						
LU-28	4th downgradient	Maximum	1,390	140	180	350
		Minimum	446	26	9	27
		Mean	795	81	57	125
		Median	776	83	41	110
		N	34	34	34	34
Water year 1997						
LU-21	Upgradient	Maximum	869	150	17	120
		Minimum	126	7	3	5
		Mean	330	43	6	29
		Median	239	31	6	12
		N	39	38	38	40
LU-22	1st downgradient	Maximum	2,540	191	430	694
		Minimum	348	19	6	26
		Mean	710	69	57	122
		Median	564	66	36	72
		N	38	38	38	39
LU-25	2nd downgradient	Maximum	2,080	140	300	540
		Minimum	340	13	7	22
		Mean	794	67	74	145
		Median	714	66	52	108
		N	40	39	39	40
LU-27	3rd downgradient	Maximum	2,080	221	245	567
		Minimum	766	65	9	4
		Mean	1,415	130	80	136
		Median	1,385	127	64	104
		N	38	37	37	39
LU-28	4th downgradient	Maximum	1,140	110	160	248
		Minimum	376	24	8	8
		Mean	749	81	48	112
		Median	748	90	34	107
		N	40	38	38	40
Water year 1998						
LU-21	Upgradient	Maximum	853	154	11	114
		Minimum	102	5	2	2
		Mean	305	47	6	26
		Median	186	24	5	7
		N	40	32	32	40
LU-22	1st downgradient	Maximum	1,740	206	167	468
		Minimum	247	17	13	6
		Mean	728	66	52	133
		Median	670	53	42	102
		N	40	39	39	40

Table A-8. Water-quality data for multilevel wells by water year, 1991-99, Lucas County, Ohio, study site.—Continued

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
		Water year 1998—continued				
LU-25	2nd downgradient	Maximum	2,380	196	204	674
		Minimum	229	14	13	16
		Mean	868	63	83	177
		Median	740	48	54	132
		N	40	33	33	40
LU-27	3rd downgradient	Maximum	1,720	227	136	449
		Minimum	303	24	3	4
		Mean	846	95	41	100
		Median	798	94	29	66
		N	40	35	35	40
LU-28	4th downgradient	Maximum	1,910	177	257	513
		Minimum	321	16	11	8
		Mean	931	78	91	162
		Median	754	78	90	106
		N	40	38	38	40
		Water year 1999				
LU-21	Upgradient	Maximum	838	146	12	105
		Minimum	100	6	2	0
		Mean	299	47	5	25
		Median	211	32	4	7
		N	40	40	40	36
LU-22	1st downgradient	Maximum	3,520	220	484	1,020
		Minimum	306	25	21	8
		Mean	1,160	91	116	274
		Median	974	82	86	194
		N	38	35	35	37
LU-25	2nd downgradient	Maximum	2,080	243	222	562
		Minimum	291	18	16	24
		Mean	904	81	78	196
		Median	798	55	55	154
		N	38	34	34	38
LU-27	3rd downgradient	Maximum	1,530	124	183	409
		Minimum	302	22	4	4
		Mean	780	73	64	127
		Median	762	68	45	107
		N	39	36	35	38
LU-28	4th downgradient	Maximum	1,640	164	120	424
		Minimum	340	14	10	9
		Mean	913	82	67	178
		Median	902	83	74	168
		N	36	32	32	36

Table A-9. Water-quality data for multilevel wells by water year, 1991-99, Pickaway County, Ohio, study site.

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
			Water year 1991			
PK-53	Upgradient	Maximum	651	120	15	27
		Minimum	74	2	2	1
		Mean	477	80	3	15
		Median	518	86	2	15
		N	48	48	47	42
PK-47	1st downgradient	Maximum	582	170	10	22
		Minimum	14	14	3	11
		Mean	477	83	4	17
		Median	502	82	4	17
		N	42	40	39	39
PK-49	2nd downgradient	Maximum	621	88	16	31
		Minimum	16	5	3	12
		Mean	486	69	8	21
		Median	524	81	7	20
		N	36	35	31	29
PK-51	3rd downgradient	Maximum	606	110	17	22
		Minimum	12	5	2	14
		Mean	458	70	6	18
		Median	508	80	4	18
		N	29	28	25	23
PK-52	4th downgradient	Maximum	643	100	22	39
		Minimum	81	15	4	19
		Mean	516	78	10	24
		Median	566	88	6	21
		N	12	12	11	10
			Water year 1992			
PK-53	Upgradient	Maximum	684	94	15	19
		Minimum	35	2	2	7
		Mean	430	62	4	14
		Median	523	74	2	14
		N	36	36	36	29
PK-47	1st downgradient	Maximum	558	86	18	20
		Minimum	70	3	2	10
		Mean	412	52	6	17
		Median	524	72	3	19
		N	30	30	25	19
PK-49	2nd downgradient	Maximum	587	86	20	23
		Minimum	41	2	2	10
		Mean	378	46	8	17
		Median	487	71	4	18
		N	29	29	26	17

Table A-9. Water-quality data for multilevel wells by water year, 1991-99, Pickaway County, Ohio, study site.—Continued

[μS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (μS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
		Water year 1992—continued				
PK-51	3rd downgradient	Maximum	558	83	19	24
		Minimum	15	5	2	11
		Mean	377	51	9	18
		Median	526	72	8	19
		N	36	34	31	23
PK-52	4th downgradient	Maximum	867	110	23	26
		Minimum	16	4	2	10
		Mean	436	59	8	17
		Median	573	78	5	18
		N	35	34	33	25
		Water year 1993				
		No samples collected.				
		Water year 1994				
PK-53	Upgradient	Maximum	628	99	16	17
		Minimum	50	2	2	5
		Mean	511	72	3	13
		Median	530	83	2	14
		N	33	33	29	27
PK-47	1st downgradient	Maximum	666	100	32	29
		Minimum	91	7	3	13
		Mean	566	83	9	21
		Median	584	92	8	23
		N	29	29	27	26
PK-49	2nd downgradient	Maximum	763	100	28	56
		Minimum	540	15	4	15
		Mean	642	83	13	32
		Median	644	92	13	28
		N	18	18	15	14
PK-51	3rd downgradient	Maximum	787	110	24	66
		Minimum	93	9	8	16
		Mean	634	88	13	31
		Median	665	98	12	23
		N	29	29	25	24
PK-52	4th downgradient	Maximum	840	120	52	98
		Minimum	632	19	7	19
		Mean	746	82	27	56
		Median	748	100	21	58
		N	26	26	18	18
		Water year 1995				
		No samples collected.				
		Water year 1996				

Table A-9. Water-quality data for multilevel wells by water year, 1991-99, Pickaway County, Ohio, study site.—Continued

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
			Water year 1996—continued			
PK-53	Upgradient	Maximum	661	91	3	16
		Minimum	16	14	2	13
		Mean	542	75	2	14
		Median	553	79	2	15
		N	18	17	15	15
PK-47	1st downgradient	Maximum	771	97	26	44
		Minimum	51	52	9	29
		Mean	657	90	17	35
		Median	699	92	16	33
		N	17	17	17	16
PK-49	2nd downgradient	Maximum	963	100	53	130
		Minimum	623	24	11	73
		Mean	817	84	34	98
		Median	837	93	37	93
		N	9	9	7	7
PK-51	3rd downgradient	Maximum	772	100	23	56
		Minimum	642	52	12	26
		Mean	702	91	18	42
		Median	706	92	19	47
		N	18	18	17	17
PK-52	4th downgradient	Maximum	898	110	40	73
		Minimum	729	86	25	60
		Mean	820	99	32	68
		Median	813	100	30	70
		N	9	9	9	9
			Water year 1997			
PK-53	Upgradient	Maximum	671	108	14	15
		Minimum	86	2	1	13
		Mean	562	73	2	14
		Median	560	81	2	14
		N	47	47	42	41
PK-47	1st downgradient	Maximum	728	92	18	50
		Minimum	15	7	4	17
		Mean	574	70	11	27
		Median	602	80	10	24
		N	42	41	35	33
PK-49	2nd downgradient	Maximum	858	96	43	91
		Minimum	480	16	4	15
		Mean	573	71	10	22
		Median	552	80	8	19
		N	36	36	30	30

Table A-9. Water-quality data for multilevel wells by water year, 1991-99, Pickaway County, Ohio, study site.—Continued

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
Water year 1997—continued						
PK-51	3rd downgradient	Maximum	780	119	27	28
		Minimum	503	19	9	17
		Mean	619	80	15	22
		Median	612	85	14	22
		N	48	48	43	43
PK-52	4th downgradient	Maximum	872	103	64	63
		Minimum	574	16	12	16
		Mean	680	74	35	37
		Median	665	81	35	33
		N	43	43	34	34
Water year 1998						
PK-53	Upgradient	Maximum	738	122	12	18
		Minimum	84	2	2	11
		Mean	564	61	3	14
		Median	593	80	2	13
		N	43	43	30	28
PK-47	1st downgradient	Maximum	702	88	32	47
		Minimum	84	11	3	16
		Mean	587	75	9	21
		Median	606	81	6	19
		N	40	40	37	36
PK-49	2nd downgradient	Maximum	682	93	31	53
		Minimum	524	16	2	14
		Mean	606	73	9	24
		Median	608	83	5	18
		N	40	40	33	33
PK-51	3rd downgradient	Maximum	662	106	14	26
		Minimum	553	18	3	17
		Mean	614	75	8	21
		Median	617	83	8	21
		N	48	48	41	41
PK-52	4th downgradient	Maximum	749	102	35	40
		Minimum	36	16	4	16
		Mean	613	64	17	27
		Median	640	79	18	22
		N	48	47	30	28
Water year 1999						
PK-53	Upgradient	Maximum	743	113	10	14
		Minimum	73	2	2	6
		Mean	469	60	3	10
		Median	492	84	2	10
		N	42	42	31	27

Table A-9. Water-quality data for multilevel wells by water year, 1991-99, Pickaway County, Ohio, study site.—Continued

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
			Water year 1999—continued			
PK-47	1st downgradient	Maximum	632	99	11	27
		Minimum	76	3	2	9
		Mean	534	67	4	14
		Median	552	83	3	12
		N	34	34	26	25
PK-49	2nd downgradient	Maximum	601	95	8	19
		Minimum	411	12	2	11
		Mean	491	76	3	13
		Median	484	82	3	13
		N	30	30	27	27
PK-51	3rd downgradient	Maximum	703	87	10	22
		Minimum	417	10	3	9
		Mean	548	66	6	15
		Median	553	80	6	16
		N	39	39	30	30
PK-52	4th downgradient	Maximum	711	106	33	73
		Minimum	87	9	5	10
		Mean	583	59	14	30
		Median	596	84	14	29
		N	37	37	21	20

Table A-10. Water-quality data for multilevel wells by water year, 1991-99, Portage County, Ohio, study site.

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples; <, concentration or value reported is less than that indicated]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
			Water year 1991			
PO-114	Upgradient	Maximum	1,450	310	31	11
		Minimum	340	68	14	0
		Mean	634	113	20	5
		Median	514	83	20	5
		N	50	50	50	49
PO-115	1st downgradient	Maximum	3,510	150	560	1,100
		Minimum	470	42	13	26
		Mean	2,344	85	382	616
		Median	2,460	82	430	655
		N	38	34	34	38
PO-118	2nd downgradient	Maximum	3,870	170	640	1,200
		Minimum	314	24	28	18
		Mean	2,344	108	389	679
		Median	3,140	130	490	910
		N	43	39	39	41

Table A-10. Water-quality data for multilevel wells by water year, 1991-99, Portage County, Ohio, study site.—Continued

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples; <, concentration or value reported is less than that indicated]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
Water year 1991—continued						
PO-119	3rd downgradient	Maximum	992	150	33	29
		Minimum	289	49	8	3
		Mean	553	87	17	14
		Median	538	80	15	13
		N	39	35	35	37
PO-120	4th downgradient	Maximum	479	76	13	18
		Minimum	156	29	2	0
		Mean	303	48	7	4
		Median	286	46	8	2
		N	38	34	34	37
Water year 1992						
PO-114	Upgradient	Maximum	1,590	320	53	13
		Minimum	385	39	1	2
		Mean	628	117	23	7
		Median	459	68	20	7
		N	32	36	36	46
PO-115	1st downgradient	Maximum	3,500	120	530	1,000
		Minimum	475	33	28	37
		Mean	1,478	60	250	353
		Median	1,470	56	285	370
		N	32	40	40	47
PO-118	2nd downgradient	Maximum	5,230	240	770	1,600
		Minimum	329	18	33	53
		Mean	2,141	81	305	564
		Median	1,604	51	120	690
		N	32	45	45	47
PO-119	3rd downgradient	Maximum	1,640	310	26	66
		Minimum	427	60	13	3
		Mean	789	130	21	27
		Median	704	120	22	24
		N	27	30	30	36
PO-120	4th downgradient	Maximum	671	100	36	27
		Minimum	107	15	6	0
		Mean	354	51	14	10
		Median	353	51	11	6
		N	33	34	33	43
Water year 1993						
PO-114	Upgradient	Maximum	1,240	97	57	13
		Minimum	364	56	6	1
		Mean	487	77	15	5
		Median	472	77	14	5
		N	46	41	41	48

Table A-10. Water-quality data for multilevel wells by water year, 1991-99, Portage County, Ohio, study site.—Continued

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples; <, concentration or value reported is less than that indicated]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
Water year 1993—continued						
PO-115	1st downgradient	Maximum	1,900	100	260	470
		Minimum	310	34	15	1
		Mean	923	59	118	165
		Median	842	50	99	135
		N	41	30	30	42
PO-118	2nd downgradient	Maximum	3,130	100	490	840
		Minimum	212	16	11	2
		Mean	1,206	64	189	269
		Median	965	69	140	210
		N	44	36	36	47
PO-119	3rd downgradient	Maximum	1,770	100	220	106
		Minimum	218	25	7	1
		Mean	458	54	30	17
		Median	438	57	18	7
		N	36	33	33	40
PO-120	4th downgradient	Maximum	544	67	48	10
		Minimum	150	28	4	0
		Mean	293	45	10	2
		Median	288	47	9	1
		N	39	33	33	41
Water year 1994						
PO-114	Upgradient	Maximum	593	99	42	9
		Minimum	266	43	6	2
		Mean	412	68	10	6
		Median	398	60	9	5
		N	52	47	47	51
PO-115	1st downgradient	Maximum	4,560	190	720	1,300
		Minimum	438	23	29	54
		Mean	1,576	74	243	373
		Median	1,420	54	225	295
		N	51	44	44	52
PO-118	2nd downgradient	Maximum	4,880	230	710	1,400
		Minimum	377	17	50	62
		Mean	2,191	89	358	571
		Median	1,840	87	275	485
		N	50	46	46	50
PO-119	3rd downgradient	Maximum	666	110	63	47
		Minimum	229	26	6	6
		Mean	433	56	24	17
		Median	428	59	19	10
		N	40	33	34	40

Table A-10. Water-quality data for multilevel wells by water year, 1991-99, Portage County, Ohio, study site.—Continued

[μS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples; <, concentration or value reported is less than that indicated]

Well identifier	Position	Statistic	Specific conductance (μS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
		Water year 1994—continued				
PO-120	4th downgradient	Maximum	445	67	23	10
		Minimum	129	18	5	2
		Mean	269	36	14	3
		Median	256	30	14	3
		N	44	34	34	44
		Water year 1995				
PO-114	Upgradient	Maximum	603	100	21	7
		Minimum	234	34	4	4
		Mean	377	64	9	5
		Median	374	68	10	5
		N	45	37	37	45
PO-115	1st downgradient	Maximum	2,710	95	440	750
		Minimum	809	23	170	220
		Mean	1,659	56	280	386
		Median	1,690	56	275	360
		N	36	38	34	38
PO-118	2nd downgradient	Maximum	3,630	120	620	1,000
		Minimum	834	27	120	160
		Mean	2,311	75	377	605
		Median	2,670	80	430	680
		N	45	42	42	44
PO-119	3rd downgradient	Maximum	639	79	36	56
		Minimum	246	37	6	3
		Mean	422	59	17	18
		Median	436	60	16	14
		N	28	25	25	28
PO-122	3rd downgradient alternate well	Maximum	597	56	50	66
		Minimum	408	44	29	41
		Mean	538	51	36	57
		Median	538	51	36	59
		N	17	16	16	17
PO-120	4th downgradient	Maximum	476	80	19	18
		Minimum	225	30	6	3
		Mean	336	49	11	6
		Median	322	48	10	5
		N	31	28	28	31
		Water year 1996				
PO-114	Upgradient	Maximum	555	110	15	16
		Minimum	290	39	4	4
		Mean	438	77	8	9
		Median	439	82	8	8
		N	33	31	31	37

Table A-10. Water-quality data for multilevel wells by water year, 1991-99, Portage County, Ohio, study site.—Continued

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples; <, concentration or value reported is less than that indicated]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
		Water year 1996—continued				
PO-115	1st downgradient	Maximum	2,440	130	410	650
		Minimum	861	25	42	140
		Mean	1,614	81	243	385
		Median	1,610	78	245	405
		N	30	22	22	32
PO-118	2nd downgradient	Maximum	4,390	190	680	1,300
		Minimum	295	15	44	50
		Mean	1,539	80	294	503
		Median	1,170	73	260	390
		N	30	25	25	35
PO-119	3rd downgradient	Maximum	574	87	29	42
		Minimum	249	33	9	2
		Mean	378	66	19	12
		Median	394	68	18	6
		N	17	10	10	17
PO-122	3rd downgradient alternate well	Maximum	792	68	61	130
		Minimum	443	19	23	48
		Mean	574	53	33	72
		Median	531	54	27	55
		N	17	17	17	17
PO-120	4th downgradient	Maximum	451	76	18	14
		Minimum	207	25	8	2
		Mean	292	46	13	6
		Median	252	44	12	4
		N	18	12	12	18
		Water year 1997				
PO-114	Upgradient	Maximum	509	94	16	14
		Minimum	409	65	6	3
		Mean	458	78	11	7
		Median	457	78	10	7
		N	38	34	34	43
PO-115	1st downgradient	Maximum	2,640	96	487	687
		Minimum	510	33	42	34
		Mean	1,338	61	202	293
		Median	1,175	57	180	250
		N	46	43	43	47
PO-118	2nd downgradient	Maximum	3,570	129	588	1,070
		Minimum	487	25	65	89
		Mean	1,547	62	222	393
		Median	1,145	50	140	271
		N	48	39	39	48
PO-119	3rd downgradient			Wells not sampled.		

Table A-10. Water-quality data for multilevel wells by water year, 1991-99, Portage County, Ohio, study site.—Continued

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples; <, concentration or value reported is less than that indicated]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
			Water year 1997—continued			
PO-122	3rd downgradient alternate well	Maximum	794	70	64	140
		Minimum	602	60	44	88
		Mean	705	65	55	114
		Median	722	65	57	120
		N	23	23	23	23
PO-120	4th downgradient		Wells not sampled.			
			Water year 1998			
PO-114	Upgradient	Maximum	720	126	16	15
		Minimum	232	<1	1	3
		Mean	410	66	8	7
		Median	380	67	7	5
		N	45	27	27	45
PO-115	1st downgradient	Maximum	2,330	89	415	585
		Minimum	469	24	48	72
		Mean	1,649	50	267	375
		Median	1,855	46	302	424
		N	44	43	43	45
PO-118	2nd downgradient	Maximum	3,700	157	618	1,030
		Minimum	259	13	34	40
		Mean	2,031	74	341	525
		Median	2,250	74	378	572
		N	44	38	38	44
PO-119	3rd downgradient		Wells not sampled.			
PO-122	3rd downgradient alternate well	Maximum	694	66	56	105
		Minimum	444	50	5	46
		Mean	622	58	43	89
		Median	622	58	43	88
		N	28	28	28	28
PO-120	4th downgradient		Wells not sampled.			
			Water year 1999			
PO-114	Upgradient	Maximum	605	73	101	94
		Minimum	104	15	6	3
		Mean	331	46	13	10
		Median	311	52	10	8
		N	44	31	31	44
PO-115	1st downgradient	Maximum	5,200	184	908	1,630
		Minimum	403	26	51	46
		Mean	2,732	88	382	755
		Median	2,290	75	348	544
		N	43	33	33	42

Table A-10. Water-quality data for multilevel wells by water year, 1991-99, Portage County, Ohio, study site.—Continued

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples; <, concentration or value reported is less than that indicated]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
Water year 1999—continued						
PO-118	2nd downgradient	Maximum	6,360	285	976	1,910
		Minimum	263	11	42	40
		Mean	2,766	112	417	736
		Median	2,930	88	491	751
		N	40	35	35	41
PO-119	3rd downgradient	Wells not sampled.				
PO-122	3rd downgradient alternate well	Maximum	745	64	64	118
		Minimum	620	52	47	33
		Mean	695	60	59	104
		Median	694	60	60	104
		N	28	28	28	28
PO-120	4th downgradient	Wells not sampled.				

Table A-11. Water-quality data for multilevel wells by water year, 1991-99, Richland County, Ohio, study site.

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
Water year 1991						
R-21	Upgradient	Maximum	268	42	4	14
		Minimum	171	23	2	1
		Mean	223	32	2	3
		Median	228	32	2	3
		N	39	37	36	38
R-15	1st downgradient	Maximum	563	50	25	36
		Minimum	231	21	3	12
		Mean	374	35	16	20
		Median	378	33	16	17
		N	22	18	18	21
R-17	2nd downgradient	Maximum	569	71	28	80
		Minimum	373	40	6	22
		Mean	460	55	14	41
		Median	451	57	12	35
		N	29	25	25	29
R-19	3rd downgradient	Maximum	609	85	29	52
		Minimum	387	42	7	23
		Mean	519	71	10	33
		Median	556	75	9	33
		N	32	27	27	31

Table A-11. Water-quality data for multilevel wells by water year, 1991-99, Richland County, Ohio, study site.—Continued

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
Water year 1991—continued						
R-20	4th downgradient	Maximum	593	90	13	31
		Minimum	374	54	4	16
		Mean	511	71	8	23
		Median	519	72	8	22
		N	44	39	39	43
Water year 1992						
R-21	Upgradient	Maximum	369	50	9	6
		Minimum	171	24	2	1
		Mean	237	34	3	4
		Median	218	30	2	4
		N	15	15	15	19
R-15	1st downgradient	Maximum	518	58	37	93
		Minimum	291	24	18	15
		Mean	439	41	23	49
		Median	440	43	20	52
		N	20	19	19	26
R-17	2nd downgradient	Maximum	527	70	10	70
		Minimum	382	60	5	37
		Mean	492	65	6	49
		Median	495	66	6	49
		N	16	23	23	27
R-19	3rd downgradient	Maximum	1,230	89	9	56
		Minimum	384	69	5	29
		Mean	609	78	7	44
		Median	605	78	7	46
		N	27	33	33	44
R-20	4th downgradient	Maximum	703	110	10	50
		Minimum	385	73	6	28
		Mean	616	86	8	38
		Median	634	86	9	39
		N	36	44	44	54
Water year 1993						
R-21	Upgradient	Maximum	384	60	4	5
		Minimum	175	20	2	2
		Mean	270	38	2	3
		Median	278	41	2	3
		N	28	25	25	29
R-15	1st downgradient	Maximum	543	49	44	96
		Minimum	246	21	15	20
		Mean	400	34	27	49
		Median	393	34	22	43
		N	27	24	24	31

Table A-11. Water-quality data for multilevel wells by water year, 1991-99, Richland County, Ohio, study site.—Continued

[μS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (μS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
			Water year 1993—continued			
R-17	2nd downgradient	Maximum	618	69	34	100
		Minimum	249	38	5	22
		Mean	504	57	16	56
		Median	502	59	11	48
		N	27	19	19	28
R-19	3rd downgradient	Maximum	711	97	19	78
		Minimum	230	54	6	25
		Mean	594	79	10	48
		Median	598	78	9	47
		N	41	34	34	41
R-20	4th downgradient	Maximum	595	84	10	45
		Minimum	425	62	5	9
		Mean	511	72	7	26
		Median	505	72	7	22
		N	47	43	44	48
			Water year 1994			
R-21	Upgradient	Maximum	585	47	6	43
		Minimum	142	20	2	2
		Mean	236	32	3	4
		Median	214	28	3	3
		N	34	25	25	34
R-15	1st downgradient	Maximum	559	50	38	48
		Minimum	176	19	13	18
		Mean	354	29	23	32
		Median	346	25	24	34
		N	34	24	23	34
R-17	2nd downgradient	Maximum	581	80	21	73
		Minimum	321	45	5	28
		Mean	496	63	12	52
		Median	497	64	12	51
		N	31	30	30	31
R-19	3rd downgradient	Maximum	617	100	12	49
		Minimum	452	71	8	23
		Mean	561	82	9	41
		Median	577	82	9	42
		N	39	40	40	40
R-20	4th downgradient	Maximum	649	94	14	37
		Minimum	415	71	7	15
		Mean	542	80	11	27
		Median	536	78	11	27
		N	52	45	45	53

Table A-11. Water-quality data for multilevel wells by water year, 1991-99, Richland County, Ohio, study site.—Continued

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
Water year 1995						
R-21	Upgradient	Maximum	466	73	12	17
		Minimum	169	19	2	2
		Mean	282	42	3	4
		Median	277	37	2	3
		N	29	19	19	29
R-15	1st downgradient	Maximum	476	41	40	72
		Minimum	316	23	5	23
		Mean	395	29	30	56
		Median	400	28	32	68
		N	26	20	20	26
R-17	2nd downgradient	Maximum	555	77	27	63
		Minimum	276	43	4	10
		Mean	483	59	12	50
		Median	498	60	8	52
		N	27	25	25	27
R-19	3rd downgradient	Maximum	607	83	11	52
		Minimum	448	65	6	34
		Mean	554	76	8	44
		Median	564	76	7	45
		N	33	28	28	33
R-20	4th downgradient	Maximum	636	88	11	40
		Minimum	456	72	2	22
		Mean	554	80	10	32
		Median	553	81	10	34
		N	47	46	46	47
Water year 1996						
R-21	Upgradient	Maximum	401	60	4	4
		Minimum	199	24	2	2
		Mean	288	41	2	3
		Median	289	41	2	3
		N	27	17	17	27
R-15	1st downgradient	Maximum	661	50	46	150
		Minimum	119	19	11	8
		Mean	356	26	23	41
		Median	331	22	21	33
		N	23	16	16	23
R-17	2nd downgradient	Maximum	626	79	37	85
		Minimum	246	40	5	11
		Mean	495	58	19	55
		Median	496	60	18	55
		N	24	22	22	25

Table A-11. Water-quality data for multilevel wells by water year, 1991-99, Richland County, Ohio, study site.—Continued

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
		Water year 1996—continued				
R-19	3rd downgradient	Maximum	722	98	25	100
		Minimum	295	48	6	21
		Mean	522	67	15	46
		Median	500	64	17	45
		N	30	25	25	30
R-20	4th downgradient	Maximum	618	110	18	37
		Minimum	251	47	7	8
		Mean	479	74	11	22
		Median	483	68	11	22
		N	42	39	39	42
		Water year 1997				
R-21	Upgradient	Maximum	496	67	3	5
		Minimum	233	31	2	2
		Mean	310	44	2	3
		Median	310	44	2	3
		N	31	28	28	34
R-15	1st downgradient	Maximum	376	31	28	44
		Minimum	167	18	11	7
		Mean	280	23	20	25
		Median	295	21	21	27
		N	23	18	18	24
R-17	2nd downgradient	Maximum	524	71	18	54
		Minimum	353	40	6	26
		Mean	445	54	11	42
		Median	452	54	11	40
		N	29	24	24	29
R-19	3rd downgradient	Maximum	753	99	13	49
		Minimum	163	58	9	6
		Mean	489	69	11	35
		Median	500	69	10	35
		N	38	30	30	40
R-20	4th downgradient	Maximum	671	120	18	39
		Minimum	266	40	6	7
		Mean	423	61	11	23
		Median	418	61	10	24
		N	48	45	45	48
		Water year 1998				
R-21	Upgradient	Maximum	373	61	3	4
		Minimum	113	19	2	2
		Mean	248	36	2	3
		Median	239	37	2	3
		N	27	22	22	27

Table A-11. Water-quality data for multilevel wells by water year, 1991-99, Richland County, Ohio, study site.—Continued

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
Water year 1998—continued						
R-15	1st downgradient	Maximum	369	31	31	56
		Minimum	52	24	11	1
		Mean	274	26	16	26
		Median	303	26	16	25
		N	23	13	13	24
R-17	2nd downgradient	Maximum	536	70	16	55
		Minimum	431	48	5	44
		Mean	479	59	8	49
		Median	487	60	6	50
		N	25	20	20	26
R-19	3rd downgradient	Maximum	574	77	10	49
		Minimum	297	58	7	16
		Mean	523	72	8	41
		Median	538	73	8	42
		N	39	32	32	39
R-20	4th downgradient	Maximum	517	70	9	48
		Minimum	353	54	6	25
		Mean	472	62	8	38
		Median	474	62	8	40
		N	48	38	38	48
Water year 1999						
R-21	Upgradient	Maximum	554	77	7	45
		Minimum	149	17	2	2
		Mean	232	30	2	4
		Median	236	30	2	3
		N	28	20	20	28
R-15	1st downgradient	Maximum	448	32	37	80
		Minimum	46	24	12	2
		Mean	336	29	24	44
		Median	338	29	19	34
		N	22	18	18	22
R-17	2nd downgradient	Maximum	551	74	22	78
		Minimum	424	45	6	42
		Mean	506	61	11	57
		Median	512	62	9	54
		N	26	24	23	26
R-19	3rd downgradient	Maximum	575	80	10	55
		Minimum	159	26	2	2
		Mean	501	74	7	44
		Median	525	76	8	46
		N	39	32	32	39

Table A-11. Water-quality data for multilevel wells by water year, 1991-99, Richland County, Ohio, study site.—Continued

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples]

Well identifier	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)
Water year 1999—continued						
R-20	4th downgradient	Maximum	528	73	10	52
		Minimum	397	52	6	23
		Mean	466	63	8	40
		Median	470	63	8	40
		N	48	42	42	48