Effects Of Highway Deicing Chemicals On Shallow Unconsolidated Aquifers In Ohio, Interim Report, 1988-93

By Allison L. Jones and Bernard N. Sroka

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
micrometer (mm)	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)	0.3048	meter per day
gallon (gal)	3.785	liter
ton	0.9072	megagram
pound per two-lane mile (lb/2-ln mi)	0.5638	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 datum: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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).

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ABSTRACT

Effects of the application of highway deicing chemicals during winter months on ground-water quality are being studied by the U.S. Geological Survey in cooperation with the Ohio Department of Transportation and the Federal Highway Administration. Eight sites throughout the State were selected along major undivided highways where drainage is by open ditches and ground-water flow is approximately perpendicular to the highway. At these sites, records of deicer application rates are being kept and apparent movement of deicing chemicals through shallow, unconsolidated aquifers is being 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 being monitored are 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 January 1988 with background data collection, extensive literature review, and site selection. This process, including drilling of wells at the eight selected sites, lasted 3 years. Routine ground-water sampling at 4- to 6-week intervals began in January 1991. A relatively new type of 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, ground conductivity, and deicing chemical application times and rates.

For the interim reporting period, water samples were collected from January 1991 through September 1993. Evidence from water analysis, specific conductance measurements, and surface geophysical measurements indicates that four of the eight sites (Ashtabula County, Lucas County, Portage County, and Richland County sites) are potentially affected by direct application of deicing chemicals. Climatic data from the period January 1991 through September 1993 show that cold weather, and therefore deicing chemical application rates, varied widely across the State. As a consequence, only minor traces of dissolved chloride above background concentrations (mean, 12–25 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 (from the upgradient well, presumably unaffected by road salt) only intermittently (mean background concentrations of 3–25 mg/L, rising to a mean of 49–77 mg/L). For the interim reporting period, the mean dissolved chloride concentration for all downgradient wells was about 2 times the background concentration (25mg/L) at the Ashland County site (50 mg/L) and 14 times the background concentration (3 mg/L) at the Richland County site (40 mg/L). At the Lucas County, Portage County, and Ashtabula County sites, deicing-chemical application was consistent throughout the winter, and downgradient dissolved chloride concentrations rarely returned to background concentrations (mean 6–32 mg/L) throughout the period. For the interim reporting period, the mean dissolved

chloride concentration for all downgradient wells was about 3 times the background concentration at the Lucas County site (92 mg/L), 72 times the background concentration at the Portage County site (432 mg/L, 2 downgradient wells), and 21 times the background concentration at the Ashtabula County site (279 mg/L).

Other factors that may affect the movement of deicing chemicals through the aquifer were examined, such as precipitation amounts; the types of subsurface materials; ground-water velocity and gradient; hydraulic conductivity; soil type; land use; and ODOT deicing priority. A final report is planned for 2001 after a total of 9 years of data collection.

INTRODUCTION

In the northern part of the United States (including most of Ohio), where significant snowfall and ice accumulation is frequent during the winter months, highway departments encounter the problem of removing ice and snow to eliminate hazardous driving conditions. The application of salt and other chemical deicers to the highways, in conjunction with application of abrasives and plowing, is currently the most reliable and economical method. The most widely used deicing chemical is sodium chloride (NaCl), and calcium chloride ($CaCl_2$) is used to a lesser extent. Cyanide compounds are commonly added in small quantities to prevent caking of stockpiled deicing chemicals. Corrosion inhibitors also may be present. After application, chemical deicers immediately begin to melt ice and packed-snow surfaces. As the deicers dissolve and melt the upper ice, the resulting brine solution penetrates the ice and causes a break in the tight bond of ice to pavement. Deicers also help prevent the formation of new ice. The resulting salt residue is then readily washed off the pavement (Field and others, 1974).

The use of road salts has been increasing continuously since the 1940's, particularly due to the preference for the bare pavement policy by highway authorities, a policy under which salt is applied repeatedly until the pavement is bared (U.S. Environmental Protection Agency, 1971). Prior to 1978, Ohio was second among all states in the amount of road salt applied to its highways (Northeast Ohio Four County Regional Planning and Development Organization, 1978). In 1980, however, the State abandoned the bare pavement policy and published new guidelines for snow removal and the application of deicing chemicals (Ohio Department of Transportation Standard Operating Procedure PH-O-202, October 19, 1992). Under this directive, the Ohio Department of Transportation (ODOT) attempts to achieve 90 percent, 80 percent, and 60 percent clear pavement on interstate, first-priority, and second-priority roads "as soon as practical" after the cessation of a storm. Ramps, curves, bridges, and especially icy areas may be given special attention. The directive also prescribes procedures for equipment maintenance to ensure the accuracy of calibrated spreaders.

State by state data on deicing chemicals used during winter 1982–1983 (table 1) provide a general basis of comparison for use of deicers among regions. During 1982–83, Ohio used about 4.3 tons of NaCl or $CaCl_2$ per 2-lane/mi. During the winter of 1992–93, ODOT used 15.7 tons of deicing material per 2-lane/mi. Of this, 8.8 tons per 2-lane/mi was NaCl or $CaCl_2$ (Ohio Department of Transportation, written commun., 1994); the rest consisted of sand or other abrasives.

Many researchers have shown that deicing chemicals can have detrimental effects on soil, vegetation, and animal life, as well as on water resources (Schraufnagel, 1967; Hanes and others, 1970; Hutchinson, 1970; and Field and others, 1974). Evidence is growing that some applied deicing chemicals do not leave the immediate area of application, but in fact may accumulate in local ground-water basins (Hawkins, 1976; Howard and Haynes, 1993). Data from Hutchinson

(1966 and 1967) indicate elevated concentrations of sodium and chloride in soils as much as 60 ft. from the highway. At present, however, there is a lack of detailed knowledge concerning the fate and transport of deicing chemicals after they have been applied to roads. In deciding which techniques and technologies they will use to maintain highways in winter, State officials need to consider economic, health, social, and environmental costs along with the expectations of taxpayers.

Table 1. Snow- and ice-control materials used by state departments of transportation/highways in winter 1982–83
[Data based on results of a survey by the Salt Institute (1983). Dash means data not available]

State	Population, 1983 (thousands)	Total lane miles	Bare pavement miles	Sodium chloride (tons)	Calcium chloride, dry (tons)	Calcium chloride, liquid (gallons)	Abrasives (tons)
Alaska	100	1,020	900	355	250	200,000	18,225 [b]
Arizona	2,718	16,650	0	413	25	0	56,000
Arkansas	2,178	34,852	0	856	246	0	9,155
California	22,000	53,000	12,900	13,600 [a]	25 [a]	0 [a]	200,000 [a]
Colorado	2,500	32,000	32,000	10,896	0	0	434,837
Connecticut	3,100	10,160	0	51,934	600	0	169,598 [b]
Delaware	611	9,971	2,543	7,055	0	0	7,714
Florida	9,740	0	0	0	0	0	0
Georgia	5,463	41,809	13,900	8,200	60	0	7,800
Idaho	944	11,512	0	11,000	0	0	192,000
Illinois	11,114	38,515	---	206,000	520	115,150	---
Indiana	5,300	31,036	14,559	116,650	44	90	108,619
Iowa	2,900	24,300	0	60,400	2,225	9,500	116,000
Kansas	2,364	22,371	5,688	31,630	0	0	65,000
Kentucky	3,661	53,846 [d]	4,966 [d]	32,964	107	0	---
Louisiana	5,000	38,191	0	23	0	0	0
Maine	1,125	7,877	1,178	49,202	535	---	472,500 [b]
Maryland	4,500	14,600	0	82,499	978	---	30,859
Massachusetts	5,737	12,000	---	178,500	2,842	0	95,000
Michigan	9,258	13,667	4,695	229,000	267	0	10,000
Minnesota	4,077	28,724	4,162	127,957	280	0	288,893
Mississippi	2,500	23,391	0	285	---	---	---
Missouri	4,917	69,664	---	75,111	3,373	0	---
Montana	700	18,790	18,790	3,245	28	0	200,000

Table 1. Snow- and ice-control materials used by state departments of transportation/highways in winter 1982–83—Continued

State	Population, 1983 (thousands)	Total lane miles	Bare pavement miles	Sodium chloride (tons)	Calcium chloride, dry (tons)	Calcium chloride, liquid (gallons)	Abrasives (tons)
Nebraska	1,600	22,000	---	24,899	556	25,974	86,734
Nevada	799	12,608	11,340	9,831	0	0	51,000
New Hampshire	921	8,630	8,406	93,813	228	0	151,322
New Jersey	7,364	10,366	10,366	35,700	580	228,000	4,200
New Mexico	1,400	27,450	20,000	23,000	0	0	80,000
New York	17,557	29,780	29,780	300,000	300	0	460,000
North Carolina	5,847	112,573	23,342	36,573	160	0	---
North Dakota	600	15,800	---	8,719	217,800 [c]	0	38,000
Ohio	10,797	42,192	0	184,341	195	113,291	128,976
Oklahoma	3,025	25,935	0	18,770	0	---	72,000
Oregon	2,656	17,895	---	456	---	424,988	---
Pennsylvania	11,867	77,000	---	231,000	5,000	0	655,000
Rhode Island	947	3,015	3,015	29,297	132	0	45,000
South Carolina	3,122	84,450	3,450	897	286	0	4,750
South Dakota	688	18,216	---	3,697	5	0	45,002
Tennessee	4,591	25,087	25,087	51,000 [a]	740 [a]	0 [a]	51,000 [a]
Utah	2,000	22,000	---	79,720	0	0	125,000
Vermont	511	6,079	6,079	65,647	0	0	106,654 [b]
Virginia	5,347	112,814	17,350	95,000	1,000	0	255,000
Washington	4,130	16,788	0	7,500	0	0	203,531
West Virginia	1,950	70,000	21,000	52,709	314	0	178,642
Wisconsin	4,705	25,774	25,774	229,803	648	40,000	25,913
Wyoming	430	15,743	0	6,340	0	0	127,000

[a]Data shown are for winter 1981–82.

[b]Cubic yards of abrasives is converted to tons on the basis of 1 cubic yard equals 2,700 pounds.

[c]Sodium chloride solution used.

[d]Includes parkways.

In Ohio, ODOT has begun 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 the Ohio Department of Transportation (ODOT) and the Federal

Highway Administration (FHWA), began a study in 1988 to monitor the use and fate of highway deicing chemicals in shallow, unconsolidated aquifers. The data-collection phase is planned to continue through September 1999; a final report is planned to follow in 2001. 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

This interim report describes the environmental setting and hydrogeology of eight selected highway sites in Ohio and presents data collected through September 1993. Water samples were collected from January 1991 through September 1993. The sections "Deicing Chemicals," "Methods of Investigation," and "Determination of Salinity Sources" provide technical information pertaining to the overall study. The eight modules under "Effects of Highway Deicing Chemicals, by Site" present descriptive data in narrative, tabular, and graphical form; these modules, all in a common format, 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.

Previous Investigations

The effects of deicing chemicals on the environment have been studied by many researchers. Various aspects of soil, vegetation, stream, lake, and ground-water contamination potential have been investigated.

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). 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).

Springs from shallow ground water in the Toronto, Ont., lakefront area contained an average chloride concentration of 400 mg/L (Eyles and Howard, 1988). Pilon and Howard (1987) reported chloride concentrations as high as 13,000 mg/L in shallow ground water along an urban Toronto highway. Even in areas where shallow ground water is not used for public or private supply, ground- water discharge can be a major component of streamwater, 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). There is increasing evidence that a significant proportion of 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 the 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 not necessarily be flushed out each spring. Howard and others (1993) found from their model that concentrations of sodium and chloride in ground water within a few hundred meters of the highways may be three to four 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.

Acknowledgments

The authors are grateful for the information and cooperation provided by all of the ODOT maintenance employees responsible for recording salt application rates and truck calibration information. Appreciation is also expressed to the landowners who provided access to their land for the initial installation of monitoring wells and the subsequent collection of data from their property.

DEICING CHEMICALS

For the most part, deicing chemicals applied to highways are eventually carried away either to surface-water outlets or to ground water through infiltration, although the chemicals may accumulate in soils. Although a positive correlation has been found between chloride concentrations in surface water and the use of deicing chemicals, it is generally held that surface waters, particularly streams, are not significantly affected by deicing chemicals. Some lakes, however, can develop a salt-related density gradient that could adversely affect aquatic biota. In addition, salt ions through exchange processes may release mercury and other heavy metals from lake sediments (Jones and others, 1986). During periods of recharge from precipitation or snowmelt, deicing chemicals can percolate through soils and enter surficial aquifers, especially in areas of open drainage. Shallow, unconfined aquifers are known to be particularly susceptible. Estimates of the amount of chloride-laden highway runoff that reaches the shallow aquifers range from 20 percent (Frost and others, 1981) to 50 percent (McConnell and Lewis, 1972). Other researchers estimate the amount of chloride-laden runoff reaching ground water to be in the range of 10 percent (Kunkle, 1971) to 35 percent (Huling and Hollocher, 1972). The actual amount of chemicals that reach an aquifer is a function of site-specific characteristics such as vegetation cover, soil type, aquifer permeability and porosity, ground-water flow direction and gradient, depth of unsaturated zone, and highway drainage design, as well as the amount and frequency of chemical application. Deicing chemicals that infiltrate soils may affect the salinity and alkalinity of the soil and unsaturated-zone water as it percolates down toward the water table. Chemicals are also transported to soils from plowed snow piles and by splash or spray from the highway. Properties of the soil (such as permeability and moisture content), as well as land use, can affect the vegetation that grows in the soil, which in turn can control the rate of infiltration to the ground water. The amount of time that runoff spends in the soil and the unsaturated zone may also have an effect on the cation exchange rate of sodium.

Processes Affecting Concentration and Transport of Deicing Chemicals in Soils and Ground Water

Many processes can affect the chemistry of soil and ground water when deicing-chemical runoff is introduced. These processes are influenced by site characteristics such as cation exchange capacity of soil, depth to water, chemical makeup of the ambient ground water, topography, and other physical characteristics. These characteristics can play a major role in how the environment accommodates the influx of deicing-chemical runoff, especially with respect to effects on soils, ground water, and even human health.

Soils

Cation exchange capacity, the ability of a soil to exchange cations, is one of the most important chemical processes in soils. The cations in solution are attracted to the negative charge of the soil-mineral surfaces. This process is most commonly associated with fine silt, clay, and organic parts of the soil. The cation exchange capacity also varies with the pH of the soil. Under normal conditions, calcium and magnesium occupy most exchange sites, although when surplus sodium chloride is in solution, sodium will become the dominant cation replacing calcium and magnesium. Because sodium ions are not held as strongly as other ions, usually at least 50 percent of the soluble cations must be sodium before sodium adsorption will be significant (Prior and Berthouex, 1967; U.S. Department of Agriculture, 1954; Schraufnagel, 1967). Relatively high concentrations of sodium and chloride ions in soils can adversely affect plant growth. Soils containing large amounts of exchangeable sodium frequently develop undesirable physical properties such as poor drainage (Qayyum, 1962).

Ground Water

Chloride. Concentrations of dissolved chloride naturally present in ground water are usually less than 10 mg/L. Chloride can be derived from sodium chloride deposits or as an ion in solution in sedimentary bedrock that has been deposited in a marine environment (Campbell, 1973). Chloride ions form salts of high solubility; they do not significantly enter into oxidation or reduction reactions, they form no important solute complexes, they are not significantly adsorbed on mineral surfaces, and they play few biochemical roles. Chloride ions are retained in solution through most of the processes that would tend to separate out other ions (Hem, 1989). Chloride ions are highly mobile, and although movement through compacted, fine-grained sediments is somewhat restricted because of their large size, movement of chloride ions is expedited in most cases due to the properties listed above. This mobility is one of the reasons that ground-water resources can be vulnerable to highway-deicing chemicals in the form of both sodium chloride and calcium chloride.

Sodium. Concentrations of dissolved sodium naturally present in ground water not associated with saline soils commonly range from 6 to 130 mg/L (Bond and Straub, 1973). Ground water may dissolve sodium from permeable rocks; sodium from deicing-chemical drainage can add to the background sodium concentration. Water percolating through soil and aquifer materials rich in fine silts and clays and organic materials may gain sodium ions through ion exchange. The chloride ion, which is negatively charged, is a chemically conservative ion and is useful as a tracer. The rates of movement and concentration of sodium ions, however, are fairly unpredictable; hence, sodium is generally not useful as a tracer. Some important variables in the control of sodium reaching shallow ground water are ground-water flow characteristics, volume of ground water withdrawn, volume and pattern of deicing-chemical application, aquifer and soil characteristics, and precipitation patterns (Terry, 1974; Backman, 1980). Because sodium ions do not necessarily move through the ground-water system, most investigators have used chloride concentration as an indicator of the extent of ground-water flow (Jones and others, 1986).

Effects on Human Health

Most regulatory agencies have not established health-related limits for either sodium or chloride concentrations in water. However, elevated concentrations of sodium and chloride can be a health concern to some individuals. Water-quality guidelines for sodium and chloride in drinking water as defined by several agencies are listed in table 2.

Evidence indicates that elevated sodium concentrations may have serious health implications. The ion has been linked with the development of hypertension, a condition affecting perhaps 20 percent of the United States population (Moses, 1980; Craun, 1984; Tuthill and Calabrese, 1979). Elevated sodium concentrations also have 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 heath, an esthetic guideline of 200 mg/L has been issued by many agencies.

The hazard to human health from water containing elevated chloride concentrations is greatest to those with heart or kidney diseases. For everyone else the problem is more esthetic than health related because salty water generally is not palatable (Hutchinson, 1970). Most agencies maintain a chloride guideline of 250 mg/L as a taste threshold.

Table 2. Water-quality guidelines for sodium and chloride in drinking water

[Modified from Ontario Ministry of the Environment (1991). mg/L, milligrams per liter. Dash indicates no guidelines given]

Agency	Limit	Type	Chloride (mg/L)	Sodium (mg/L)
U.S. Environmental Protection Agency (USEPA)	Secondary maximum contaminant level	Esthetic	250	20[a]
State of Ohio	Secondary maximum contaminant level	Esthetic	250	20[b]
State of New York	Maximum contaminant level	Health	250	---
State of Florida	Maximum containment level	Health	---	160
Health and Welfare Canada	Esthetic objective	Esthetic	250	200
Ontario Ministry of the Environment (MOE)	Maximum desirable concentration	Esthetic	250	---
Ontario Ministry of the Environment (MOE)	Esthetic objective	Esthetic	---	200
World Health Organization (WHO)	Guideline value	Esthetic	250	200
European Economic Community (EEC)	Guideline level	Esthetic	---	20
European Economic Community (EEC)	Maximum admissible concentration	Esthetic	---	150

[a]Reporting level only. Monitoring is required and data are reported to health officials to protect individuals on highly restricted sodium diets.

[b]Health advisory only.

METHODS OF INVESTIGATION

Site Selection

Locations of the eight study sites are shown in figure 1. During the first 2 years of the study, 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 (diagram of highway section shown in fig. 2), 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 land-owners on both sides of the highway willing to participate in the study for at least 10 years. None of the highways were newly constructed. 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 8. A potential site had to meet all criteria to be acceptable. 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.

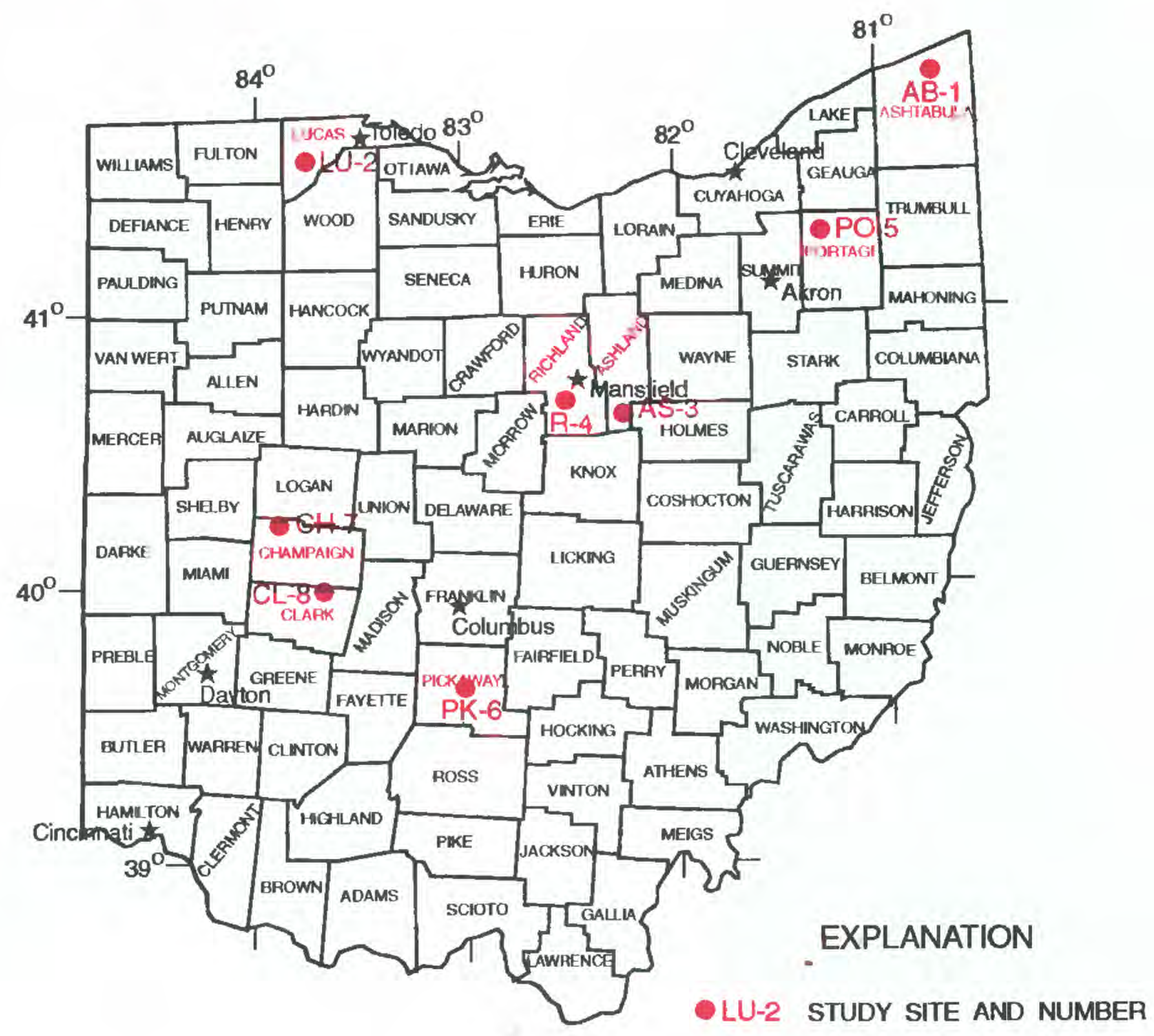
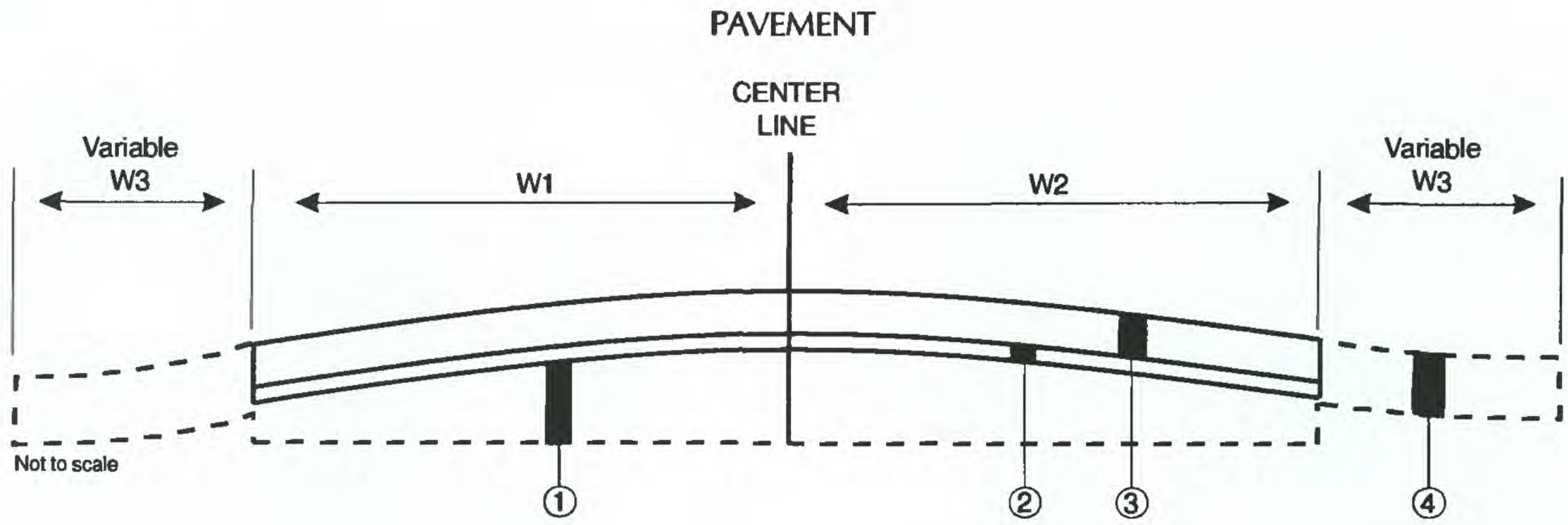


Figure 1. Location of sites monitored for effects of highway-deicing chemicals on shallow ground water in Ohio.



EXPLANATION

① EXISTING BASE PAVEMENT

② TACK COAT

③ ASPHALT OR CONCETE OVERLAY

④ AGGREGATE BERMS

W ROAD OR BERM WIDTH

Site	State Route	Number of Lanes	Pavement width (W1+W2)	Aggregate berm width (W3)	ODOT[1] deicing priority
Ashland County	3	2	23.0 feet	4 feet	Second
Ashtabula County	84	2	24.0 feet	3 feet	Second
Champaign County	29	2	25.5 feet	4 feet	Second
Clark County	4	2	25.5 feet	4 feet	First
Lucas County	2	4	70.0 feet	3 feet	First
Pickaway County	104	2	27.0 feet	4 feet	Second
Portage County	14	2	30.0 feet	4 feet	First
Richland County	97	2	22.0 feet	3 feet	Second

[1]Ohio Department of Transportation

Figure 2. A highway section and additional information on study sites in Ohio.

Electromagnetic Conductivity Surveys

Electromagnetic (EM) ground-conductivity surveys were used to characterize the general hydrogeology of potential study sites. The electromagnetic conductivity of the earth can be measured by use of the electromagnetic induction technique, whereby an EM field is imparted to the earth and the electrical response is measured (fig. 3). 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 energized with an alternating current that induces electrical currents in subsurface conductors. The electrical currents in the Earth 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.

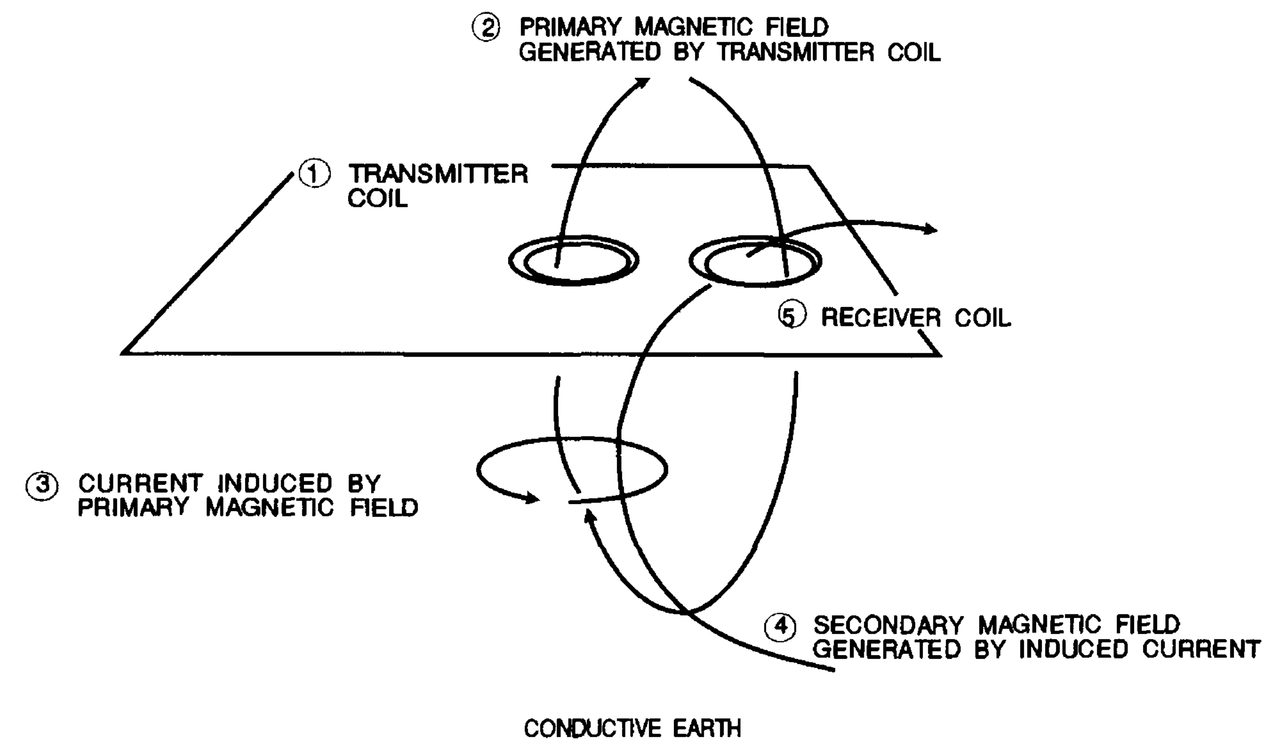


Figure 3. Operating principles of the electromagnetic induction technique. The (1) transmitter coil generates a (2) magnetic field. This primary field induces a (3) current in a mass of conductive earth. The induced current in turn generates a (4) secondary magnetic field. The (5) receiver coil senses both the primary and secondary fields. The conductivity of the earth is proportional to the primary fields. Copyright © 1985. Electric Power Research Institute. EPRI EA-4301. *Field Measurement Methods for Hydrogeologic Investigations: A Critical Review of Literature.* Reprinted with Permission.

Test Drilling

If the geophysical tests indicated the presence of unconsolidated sand and gravel, or if EM measurements were not possible, test wells were drilled by use of a hollow-stem auger. Lithologic logs from these 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 each well 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. This site-selection method was followed at each potential site until eight sites that met all the selection criteria were located (fig. 1). All test and observation wells were installed by the ODOT Foundation Exploration drilling crew or one of several private drilling firms.

Well Installation

Hollow-stem augers were used to install the wells, and split-spoon samples were collected to log the formations. Formation samples were used to measure grain size and determine the elemental composition (appendix 1). 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 ft 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 PVC casing and the protective steel casing.

At each site, one well is upgradient from the highway at a sufficient distance to prevent splash and runoff from reaching it, generally about 50 ft. The other four wells at each site are downgradient from the highway, generally in line with the ground-water flowpath, each increasingly distant from the highway. The interval between wells ranges 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.

Data Collection

Data for each site were collected from six main sources:

- The amount and type of deicing chemicals 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 samples were collected using three types of ground-water sampling devices on a regular basis.
- Geophysical data were collected periodically to monitor ground-conductivity changes attributable predominantly to changes in water quality.
- Soil samples were collected to determine the amount of dissolved chloride in soil-water extract, near the highway and beyond the splash distance.
- Physical 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 National Oceanic and Atmospheric Administration (NOAA) weather station to supplement precipitation and air temperature data collected at each site.

Deicing Material Application Data

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 then sent to the USGS office. Items recorded on the form include date and time, weather conditions, rate at which deicing material was applied from 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.

Deicing chemicals used during the winters 1981–82 through 1992-93 by each county that contained a study site are listed in table 3 (Ohio Department of Transportation, written commun., 1994). These data relate a general idea of the magnitude of use of deicing-chemicals in each study-site county, but they are not detailed enough to indicate the exact amounts of chemicals applied at each site. Therefore, data collected separately by maintenance truck drivers for each of the study sites proved to be very useful.

Table 3. Ohio Department of Transportation deicing chemical use for Ohio counties that include a study site

[Amounts are in tons. ---, data not available. For brevity winter seasons are referred to as "years"]

Winter	Ashland County	Ashtabula County	Champaign County	Clark County	Lucas County	Pickaway County	Portage County	Richland County
1981-82	5,670	16,800	1,745	3,220	6,700	1,225	8,525	4,720
82-83	3,195	10,400	700	1,275	2,056	450	5,700	2,606
83-84	11,049	19,800	2,038	2,975	7,611	2,550	13,800	8,914
84-85	6,832	18,400	2,065	3,755	6,740	3,000	9,300	5,909
85-86	7,449	24,000	2,720	3,620	6,402	2,365	12,700	6,317
86-87	6,288	15,700	1,804	2,985	3,650	810	7,500	4,558
87-88	8,027	---	2,453	2,556	4,270	829	---	6,362
88-89	8,007	16,000[a]	2,615	4,161	5,797	1,261	7,000[a]	6,129
89-90	6,353	22,000[a]	1,439	2,068	6,394	817	7,000[a]	5,126
90-91	5,754	15,000[a]	2,858	4,087	4,892	998	7,000[a]	5,220
91-92	6,510	17,000[a]	1,723	2,672	4,310	782	7,000[a]	4,712
92-93	6,974	21,000[1]	1,976	3,470	4,503	1,071	6,000[a]	4,660
12-year average	6,842	17,827[2]	2,011	3,070	5,277	1,346	8,320[b]	5,436
1990-93 average	6,413	17,667	2,186	3,410	4,568	950	6,667	4,864

[1]Estimated values.

[2]Eleven-year average (data for 1987-88 not available).

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 involved. All samples were analyzed at the USGS National Water Quality Laboratory (NWQL) in Arvada, 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.

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 4. Six passive-flow samplers 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 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 have 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 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). The tubing sections were then filled with deionized water and were clipped at both ends. Once these tubes were lowered into each of the sampling sections, diffusion of the ground water began to displace the deionized water in the dialysis cells, allowing them to come to equilibrium with the surrounding ground water. This system allows for passive sampling at many levels. This sampling device has the limitation that only a finite amount of water is available for analysis. For example, using the sampler described above, a maximum of approximately 150 ml of sample water can be obtained from each level at any one time.

An earlier version of the above sampler was used in this project for the first several months of sampling. Instead of dialysis tubing, sheets of dialysis material (cellulose acetate) were stretched across the ends of 3-in.-long clear acrylic cylinders and were secured with rubber O-rings. These were also filled with deionized water and placed, two per level, into the above mentioned screened sections of the dialysis sampler. Unfortunately, the integrity of the dialysis sheets, which were cellulose acetate (100 percent regenerated cellulose) was compromised in about 75 percent of the samples by cellulose-degrading bacteria whose main food source is cellulose. The bacteria greatly weakened or completely degraded the membranes, often leaving a black, scummy residue. For this reason, as well as the fact that tubing has a much larger surface area than the small sheets, the acrylic cylinders were abandoned in favor of the cellulose ester tubing, which is not readily biodegradable.

To determine the equilibration time of the dialysis cells in the surrounding system, laboratory tests were done on both types of dialysis cells. The cells were filled with deionized water and

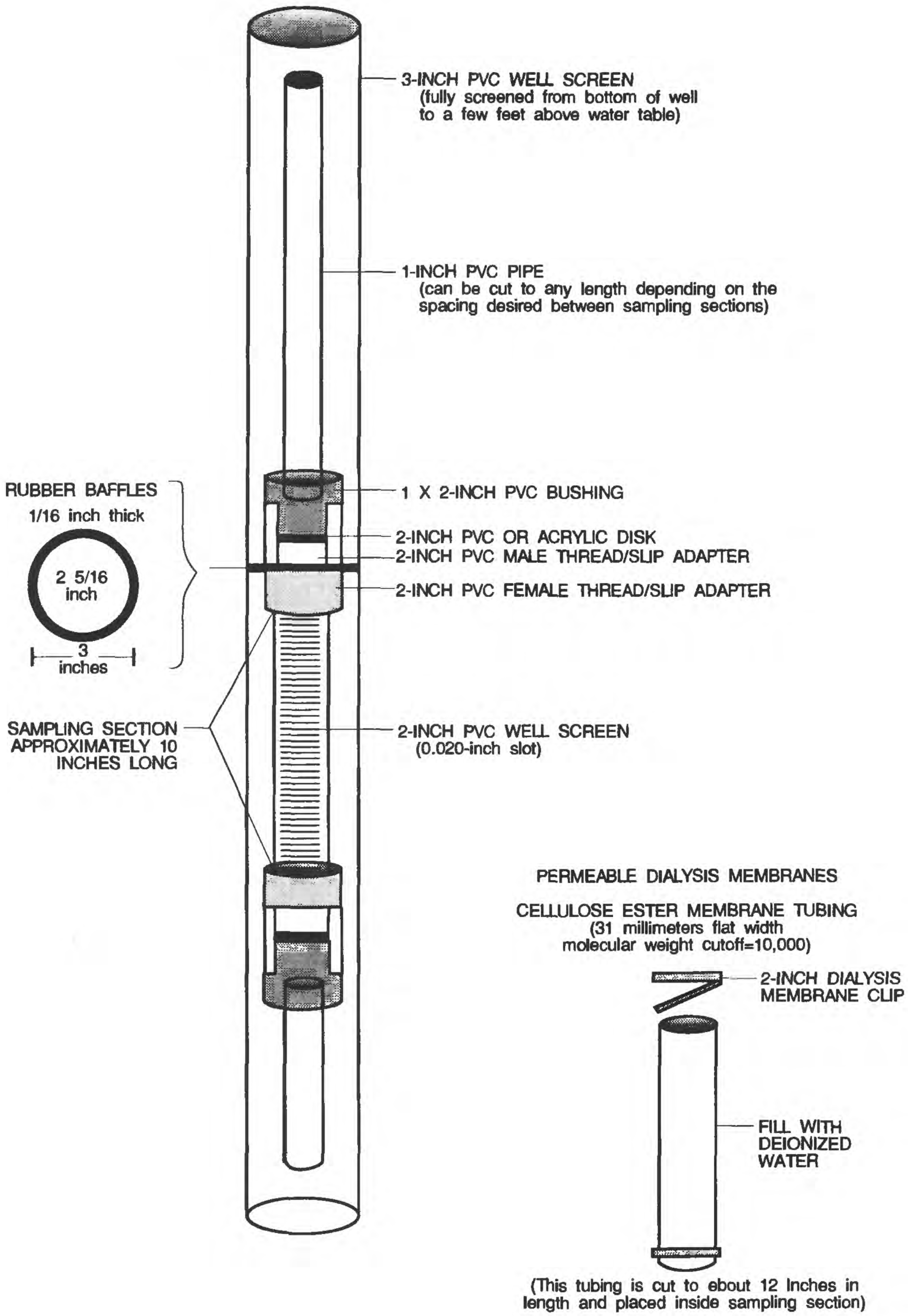


Figure 4. Screened-interval, multilevel dialysis sampler.

suspended in separate baths of 0.005M and 0.05M KCl solution. Each bath was mixed daily, and one set of cells was removed every 24 hours and analyzed for dissolved chloride concentration; specific conductance was measured concurrently. Once the specific conductance/dissolved chloride relation was established, later tests measured only specific conductance. The results of the tests, listed in table 4 and shown in figure 5, indicate that at 72 hours the deionized water was replaced with a solution of 97–99 percent of the bath water. At a sampling interval of 30–45 days, the sample should be very near equilibrium with the surrounding ground water and be representative of water from the previous several days.

Multilevel Tube Sampler. A conventional multilevel tube sampler (fig. 6) was installed adjacent to one of the downgradient multilevel dialysis samplers at each site. This sampler consisted of a 2-in.-diameter PVC casing (not screened) completed 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 from the top and inserted into 100-mesh stainless steel screened ports 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 short time until the tubing was flushed and the water was clear; and a sample was then collected. With this sampling device, only water in the immediate vicinity of the port is available for sampling. The device can also be clogged easily if the formation consists of a significant amount of very fine sand or silt.

Both types of samplers were visited according to two periodic 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 level throughout the year, some of the upper levels were dry during some sample-collection periods. Samples from the multilevel dialysis sampler were collected by removing the string of dialysis chambers 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 a filter. A sample was also collected from each of the six levels in the one multilevel tube sampler. A standard 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; and specific conductance was also measured.

In routine 2, samples were collected once 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 monitoring the stability of the pH, specific conductance, and water temperature 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 5,000 ground-water samples were collected from January 1991 through September 1993; therefore, the individual sample data are not presented in this report. They are available upon request from the USGS office in Columbus, Ohio (address given on back of title page of this report).

Table 4. Results of dialysis cell equilibration tests
[µS/cm, microsiemens per centimeter at 25 degrees Celsius]

3-inch acrylic cylinders; low-conductance bath (731 µs/cm)

Hours from initial immersion	Specific conductanca (µS/cm)	Percent of bath concentration
0	0	0
24	410	56
48	692	95
72	719	98

3-inch acrylic cylinders; high-conductance bath (6,570 µs/cm)

Hours from initial immarsion	Specific conductance (µS/cm)	Percent of bath concentration
0	0	0
24	4,700	72
48	6,470	98
72	6,495	99

12-inch cellulose-ester dialysis tubing; low-conductance bath (738 µs/cm)

Hours from initial immersion	Specific conductanca (µS/cm)	Parcant of bath concantration
0	0	0
24	592	80
48	679	92
72	734	99

12-inch cellulose-ester dialysis tubing; high-conductance bath (6,630 µs/cm)

Hours from initial immersion	Specific conductance (µS/cm)	Parcent of bath concentration
0	0	0
24	5,880	89
48	6,300	95
72	6,560	99

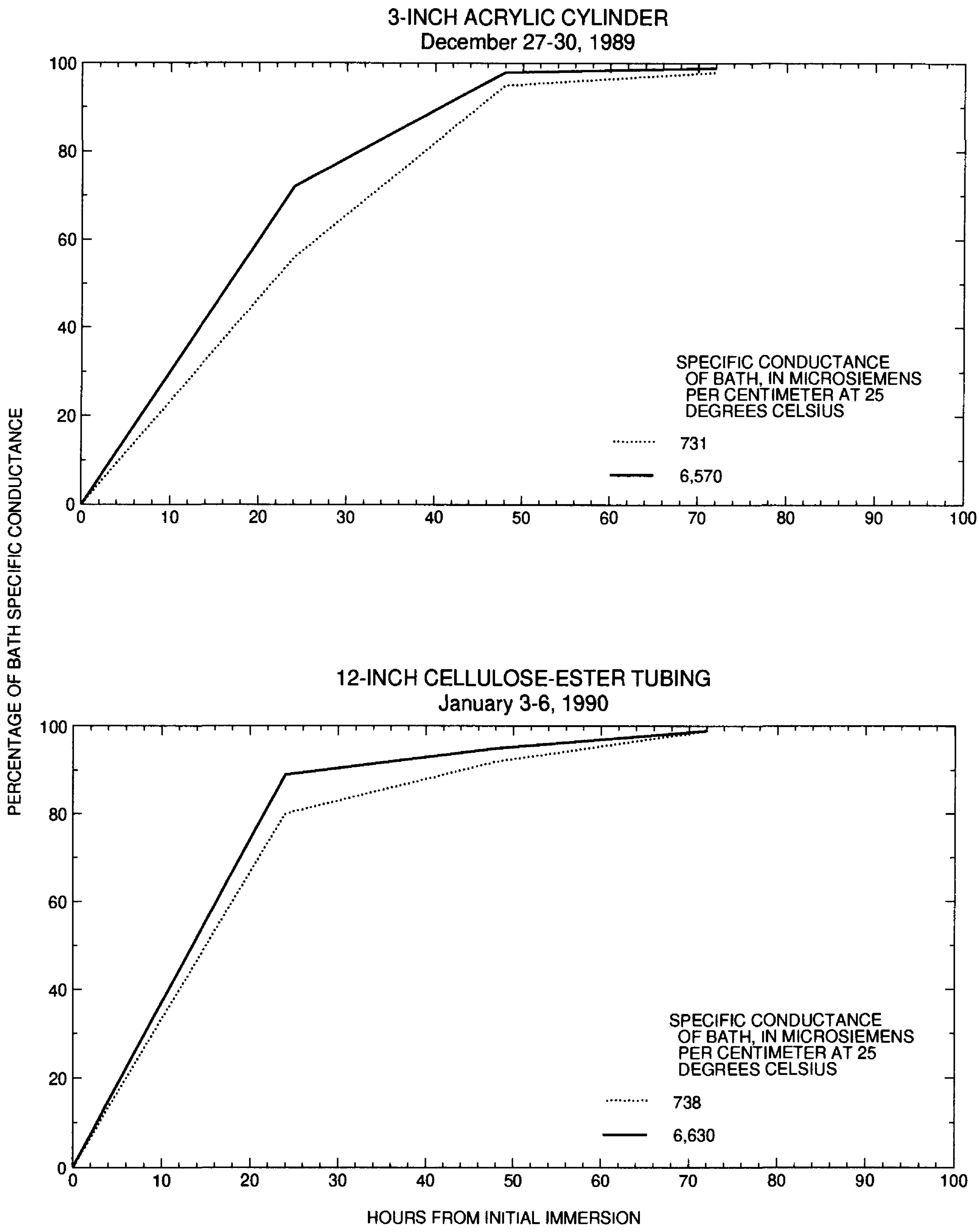


Figure 5. Results of dialysis cell equilibrium tests.

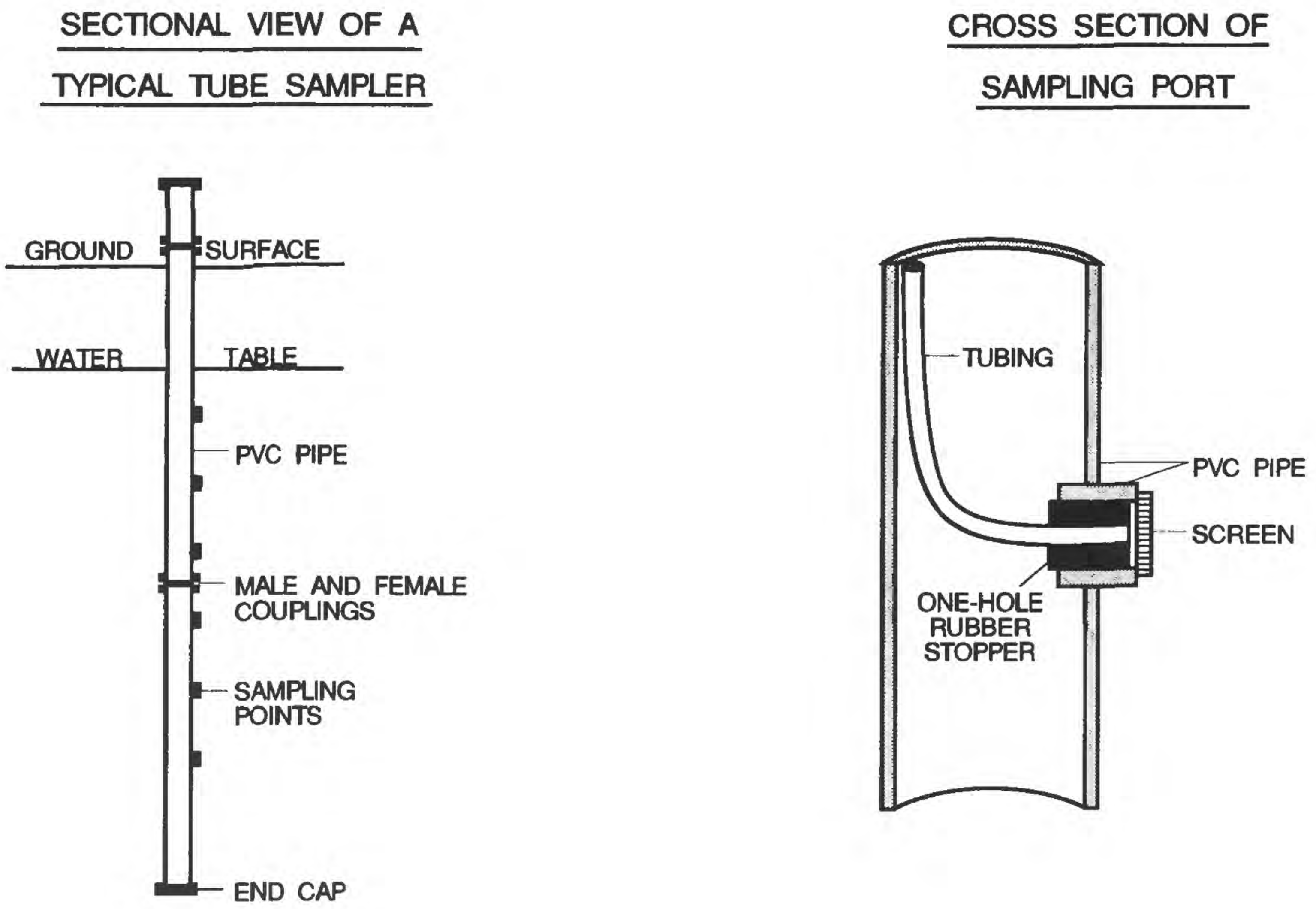


Figure 6. Multilevel tube sampler showing polyethylene tubing and screened ports. (Modified from Pickens and others, 1981, A multilevel device for ground-water sampling, Ground-Water Monitoring Review, Spring 1981.)

Geophysical Data

Electromagnetic ground conductivity surveys used in the site-selection phase of the study were also used periodically at each of the eight study sites to define changes in the ground conductivity that would be attributable primarily to changes in water quality. These surveys were reasonably successful at the three sites where deicing was the most frequent and therefore where the most distinguishable differences in conductivity developed, but interference from nearby powerlines and chain-link fences made interpretation difficult at other sites. The small changes observed in surveys at the three most heavily deiced sites are discussed later in the report section "Effects of Highway Deicing Chemicals on Shallow Unconsolidated Aquifers, by Site."

Aquifer Materials and Soils Data

At each site, aquifer materials were collected during the well-installation phase and analyzed for grain size. Several single-well aquifer tests (slug tests) were done at one of the test wells at each site to determine an average hydraulic conductivity for the site. Test wells were constructed as conventional wells by use of 2-in.-diameter casing and 5-ft-long slotted screen. The method described by Bouwer and Rice (1976) was used to analyze these data. Ground-water flow directions were determined by measurement of water levels in a series of test wells. The geology and soil type of each site was determined from test drilling and areal geophysical surveys, as well as local well logs and county soil surveys.

Soil samples were collected once during the interim reporting period, in August 1993. Three samples were collected at each site by use of a hand-driven percussion split-spoon sampler. Two samples were collected from the bottom of the ditch along the downgradient side of the road, one in the interval of 0–1 ft and one in the interval of 1–2 ft. The third sample was collected approximately 50–75 ft from the highway on the downgradient side, away from any road splash or overland runoff, in the interval of 0–1 ft. Samples were prepared by use of the saturation extract procedure described in Page and others (1982). The extract was sent to the NWQL for determination of dissolved chloride concentration.

Physical Data

An electronic data logger was installed at each site to collect data on an hourly basis for the following characteristics: precipitation, air temperature, soil temperature, ground-water level, 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 have been recorded since February 1991.

Each site was instrumented with a propane-heated rain gage, which allowed precipitation data to be compared to corresponding water-level changes in the monitoring wells. These corresponding 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 3-in. 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. Data were downloaded during each sampling trip from the data logger to a personal field computer, then downloaded once again and processed at the office in the USGS computer system.

Climatic Data

Average annual temperature and average annual precipitation data for 1951–80 were obtained from the NOAA climatographic summary for Ohio (1982). Snowfall data for 1936-65 were obtained from an Ohio Agricultural Research and Development Center (OARDC) publication (Miller and Weaver, 1971). NOAA and OARDC data from the weather sites nearest to each of the eight study sites were used (table 5).

In the discussion of the effects of highway deicing chemicals by site, average annual climatological data referenced are from NOAA or OARDC. Data referring to the site itself during the interim reporting 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; 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

Table 5. National Oceanic and Atmospheric Administration (NOAA) temperature and precipitation sites and Ohio Agricultural Research and Development Center (OARDC) snowfall site whose data were used in the highway-deicing chemicals study

Study site	Temperature site	Precipitation site	Snowfall site
Ashland County	Charles Mill Dam	Pleasant Hill Dam	Charles Mill Dam
Ashtabula County	Ashtabula	Ashtabula	Geneva
Champaign County	Urbana Sewage Plant	Urbana Sewage Plant	Urbana
Clark County	Urbana Sewage Plant	Springfield Sewage Plant	Springfield
Lucas County	Toledo Airport	Toledo Airport	Toledo
Pickaway County	Circleville	Circleville	Circleville
Portage County	Hiram	Ravenna	Ravenna
Richland County	Charles Mill Dam	Charles Mill Dam	Charles Mill Dam

(details in the "Well Installation" section of the report). As mentioned previously, one additional multilevel well at each site was constructed as a multilevel tube sampler (conventional multilevel ground-water sampler), to compare performance with that of the adjacent multilevel dialysis sampler. The data indicate that in many cases the concentrations of analytes collected by use of either well design were similar, although in some cases–especially at sites where ground water contained high concentrations of chloride–the difference between concentrations was significant. Both samplers have been shown to collect a representative water sample independently. It is possible that one simply cannot expect similar water quality at the same level, even in wells 2 or 3 ft apart, especially at sites where the subsurface materials and the resulting ground-water flowpath can be quite variable.

To determine the precision of sample-collection techniques, one sequential replicate sample was collected from one 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. A sample of the actual deicing chemicals from each of the ODOT outposts was collected, dissolved, and analyzed for trace elements for background information and to monitor any potential changes in trace-element concentration in the future.

Project personnel participate annually in the National Field Quality Assurance (NFQA) program, whereby employee skill and field-instrument accuracy are monitored.

The NWQL also routinely analyzes laboratory quality-control samples to verify the quality of analytical procedures and to determine internal corrective action (if needed). The NWQL also participates in several outside programs such as the USEPA round-robin rotation and the Standard Reference Water Sample (SRWS) program.

DETERMINATION OF SALINITY SOURCES

To determine the primary source of sodium and chloride in the ground water at each of the sites, the ratio of chloride to bromide in water samples was examined. This method has been used successfully to differentiate among salinity sources such as dissolved highway deicing-chemicals, oilfield brines, or other formation waters that have contaminated ground-water resources (Whittemore, 1984, 1988; Knuth and others, 1990). The weight ratio of Br:Cl is used as a tracer of salinity because bromide and chloride behave conservatively in the ground-water system. Conservative constituents are not affected by ion-exchange or mineral-precipitation reactions; thus, their concentrations change only in response to dilution and mixing. Moreover, the Br:Cl ratio is useful in distinguishing salinity sources because most deicing chemicals, which are derived from halite of marine origin, have Br:Cl ratios less than 10×10^{-4}, whereas oilfield and gasfield brines typically have Br:Cl ratios greater than 10×10^{-4} (Whittemore, 1988). Because the lowest Br:Cl ratios in natural waters are near 1×10^{-4}, it is convenient to express Br:Cl ratios as a value multiplied by 10,000.

Two possible salinity sources were evaluated by use of the Br:Cl ratio technique: halite-solution brine and formation brines associated with oil and gas production. Halite-solution brine is formed by either the dissolution of deicing chemicals in water or the dissolution of bedded halite within bedrock aquifers. Bedded halite is found in the Silurian Salina Group in northeastern and eastern Ohio at depths ranging from about 1,350 ft to more than 6,500 ft below land surface (Clifford, 1973). The only area in Ohio where bedded halite-solution brine has been noted in an aquifer used for water supply is in the carbonate-rock aquifer of Silurian age near Lake Erie in Sandusky County (Breen and Dumouchelle, 1991). Chloride concentrations as high as 37,000 mg/L are present in ground water in this area. Thus, it is reasonable to assume that in the shallow, unconsolidated aquifers evaluated in this study, dissolution of deicing chemicals is the only likely source of halite-solution brine.

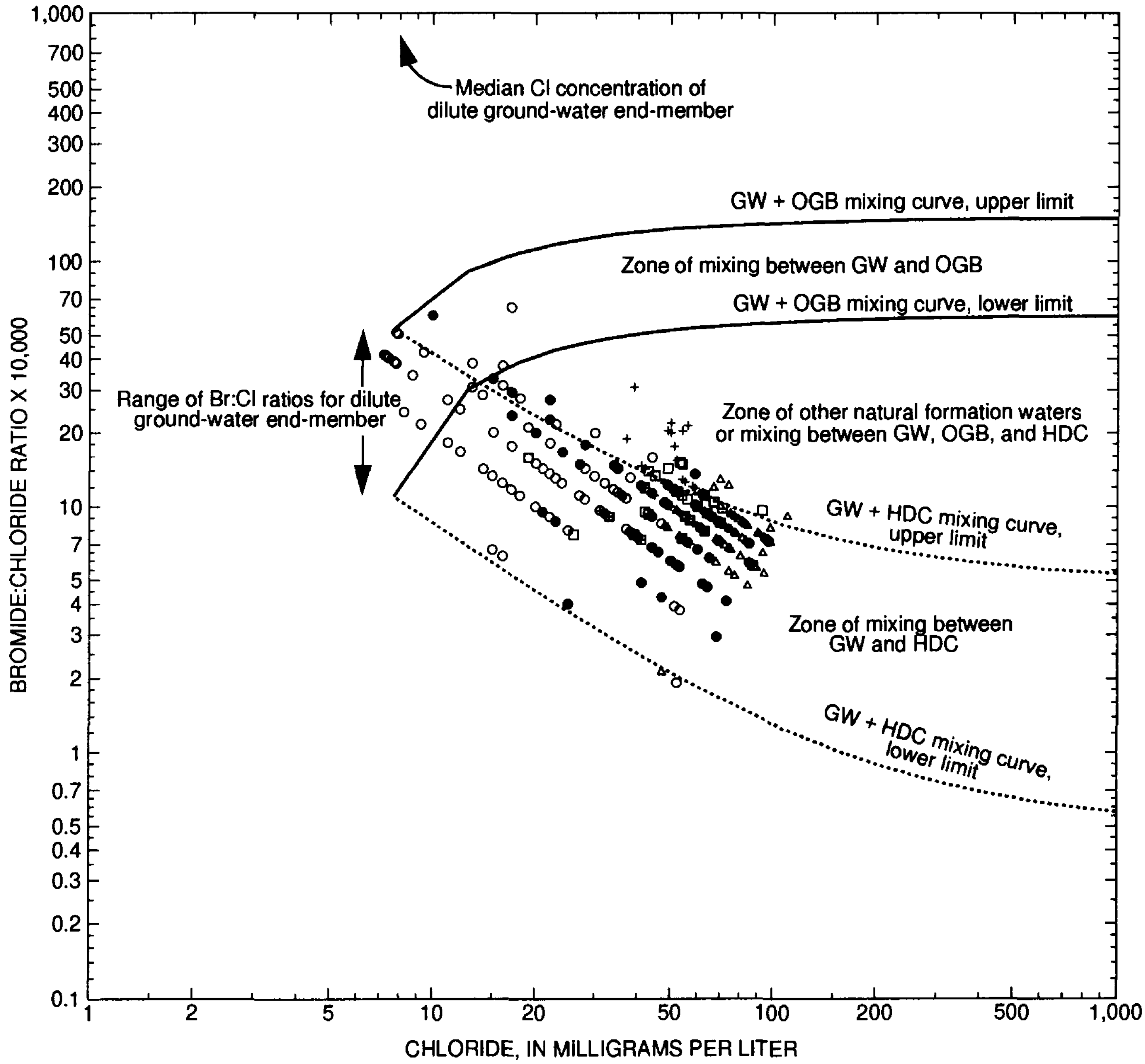
Formation brines with chloride concentrations ranging from several thousand to more than 200,000 mg/L are found in deeply buried bedrock units in Ohio. Discharge of saline water to shallow aquifers has been noted at some locations in eastern Ohio (Stout and others, 1932). Formation brines are also produced as a byproduct of oil and gas production. Contamination of shallow aquifers by oilfield or gasfield brine has been discovered in various areas of Ohio (Pettyjohn, 1971; Northeast Ohio Brine Disposal Task Force, 1984; Knuth and others, 1990; Eberts, 1991; Breen and Dumouchelle, 1991) and has been generally attributed to problems caused by the improper disposal of brine. In addition, oilfield and gasfield brine can be legally disposed of in Ohio by spreading it on roads as a means of dust and ice control (Bair and Digel, 1990). This practice, which is much less common now than in the past, was mostly used by small-town and township maintenance groups. ODOT does not spread brines on highways. Thus, in general, dissolved deicing chemicals and oilfield and gasfield brine are two possible sources of increased concentrations of chloride and sodium in shallow, unconsolidated aquifers in Ohio.

The sources of chloride in the shallow ground water at the five sites where concentrations were most consistently elevated were examined in detail. The Ashland, Ashtabula, Lucas, Portage, and Richland County sites were evaluated by use of mixing curves on a plot of the Br:Cl weight ratio against chloride concentration (figs. 7-11). Each of the mixing curves in figures 7-11 represent the continuum of theoretical solutions that result from the mixture of uncontaminated ground water with either of the two potential end-member salinity sources, (1) halite-solution brine from dissolved deicing chemicals or (2) oilfield and gasfield brine. Each pair of solid lines and dashed lines defines the boundaries of a mixing zone. The methodology for the generation of the curves and the mixing zones is presented in Whittemore (1988).

To account for the natural variation in the chemistry of ground water and oilfield and gasfield brines, mixing curves that encompass the range in Br:Cl ratios in dilute ground water and oilfield and gasfield brine were calculated and plotted on the diagrams. The dilute ground-water end-member reflects the range in chemistry for uncontaminated ground water from the upgradient well at each site. The range of Br:Cl ratios for the dilute ground-water end-member at each site encompasses the minimum and maximum Br:Cl ratios of all ground-water samples collected from the upgradient well with chloride concentrations less than 10 mg/L. The chloride concentration of the dilute ground-water end-member at each study site is the median chloride concentration for all ground-water samples collected from the upgradient well for which chloride concentrations were less than 10 mg/L. Except for the Lucas County site, the upper and lower limits of the oilfield and gasfield brine compositions were estimated from brine data for northeastern and central Ohio reported by Stout and others (1932), Lamborn (1952), Stith (1979), Breen and others (1985), and Eberts and others (1990). These reports contain bromide and chloride concentration data for brines collected from oil and gas-bearing wells completed in Devonian, Silurian, and Ordovician-Cambrian strata. For the Lucas County site, upper and lower limits on the composition of brines produced by the oil- and gas-bearing Ordovician Trenton Limestone are given by Breen and Dumouchelle (1991). The upper and lower limits of the highway deicing chemical Br:Cl ratios were set at 0.5 and 5.0, a range consistent with available data on bromide and chloride concentrations for deicing chemicals reported by Whittemore (1982, 1984, and 1988) and Knuth and others (1990).

Br:Cl ratios were computed for ground-water samples collected at the Ashland, Ashtabula, Lucas, Portage, and Richland County sites and plotted on figures 7-11 against their corresponding chloride concentrations. Data for all levels in each multilevel well are included on the plots. As figures 7-11 show, most of the data points plot in the region bounded by the upper and lower mixing curves for ground water and dissolved deicing chemicals. This pattern indicates that the origin of bromide and chloride in the ground water is most likely the chemicals being used to deice nearby roads and that oilfield and gasfield brine is not being used as a deicer. The data in figures 7-11 show linear trends that are due to the precision of the analytical determinations for bromide, which is 0.01 mg/L. A series of samples that have variable chloride concentrations but near-detection-limit concentrations of bromide would result in linear trends similar to those evident in figures 7-11. Any small change or analytical variation in the reported bromide concentration could contribute to slight change in placement of the data on the plot as well.

Ground water with a chloride concentration greater than 100 mg/L, (from the Ashtabula, Lucas, and Portage County sites) typically had a Br:Cl ratio between 1 and 10, and plotted within the zone of mixing between ground water and dissolved deicing chemicals. Ground water with a chloride concentration greater than 500 mg/L had a Br:Cl ratio between 1 and 3 and is clearly derived from mixing of ground water and dissolved deicing chemicals. Many of the samples from the third and the fourth downgradient wells at the Portage County site (fig.10) have chloride concentrations that are less than the median chloride concentration from the upgradient well and thus plot far left of the mixing zones. In addition, some of the ground-water samples from the Lucas County site (fig. 9) with chloride concentrations less than 100 mg/L plotted in the zone of other natural formation waters or mixing between ground water, oilfield and gasfield brine, and highway-deicing chemical solution. At this site, the Br:Cl ratios for dilute ground water from the downgradient wells are higher than the Br:Cl ratios for dilute ground water from the upgradient well. Thus, at chloride concentrations less than 100 mg/L, some ground waters had Br:Cl ratios higher than the upper boundary of the zone of mixing between ground water and dissolved deicing chemicals. If a wider range of Br:Cl ratios had been used to define the dilute ground-water end-member, the upper limit of the zone of mixing between ground water and dissolved deicing chemicals would have been higher and would have included all the data.



EXPLANATION

SAMPLE FROM MULTILEVEL WELLS:

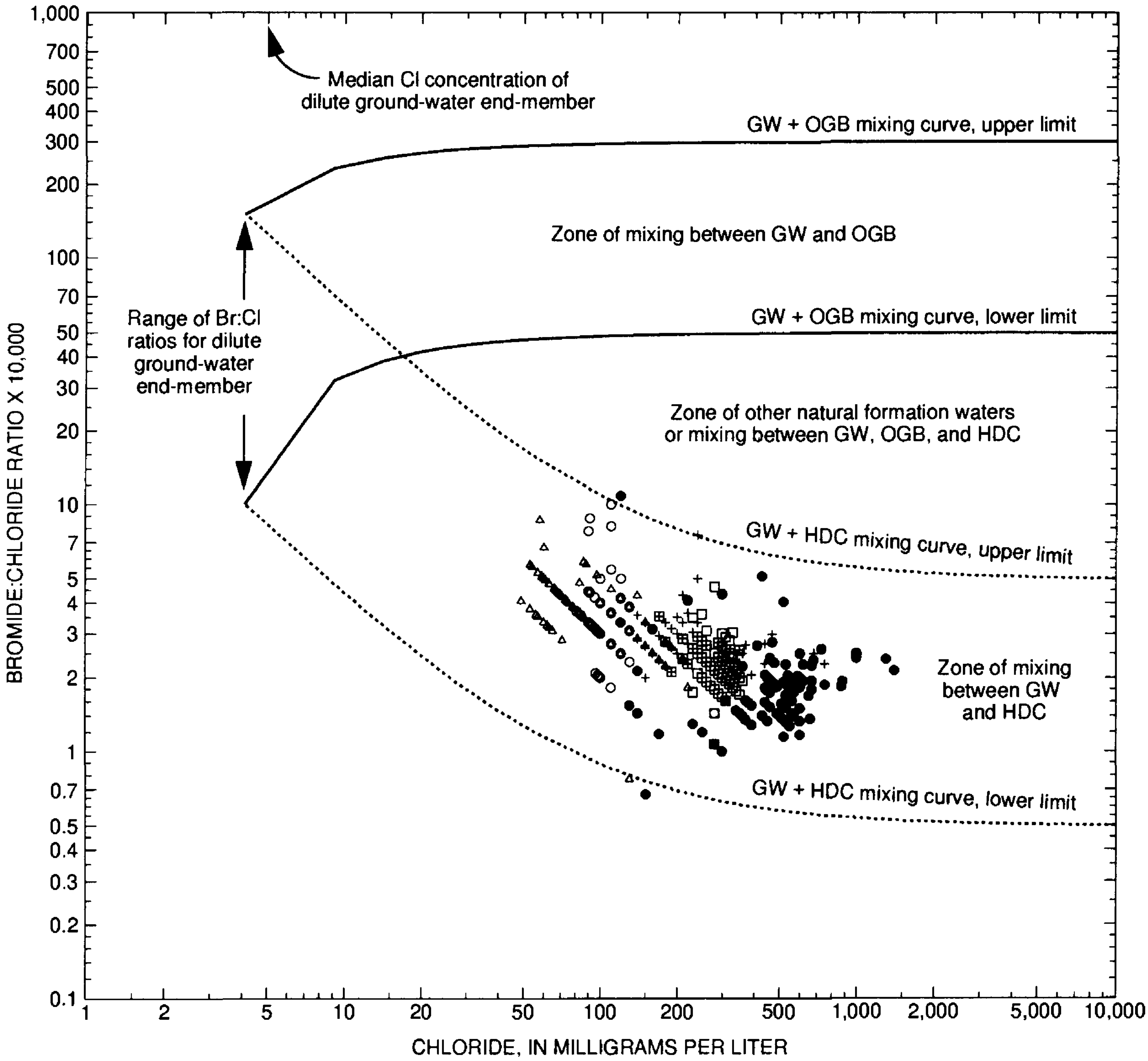
- ● WELL AS-44, FIRST DOWNGRADIENT
- + WELL AS-46, SECOND DOWNGRADIENT
- □ WELL AS-49, THIRD DOWNGRADIENT
- ▵ WELL AS-47, THIRD DOWNGRADIENT (TUBE)
- ○ WELL AS-48, FOURTH DOWNGRADIENT

GW GROUND WATER

OGB OILFIELD AND GASFIELD BRINE

HDC HIGHWAY-DEICING CHEMICAL SOLUTION

Figure 7. Bromide:chloride ratios in ground-water samples from the Ashland County study site, Ohio.



EXPLANATION

SAMPLE FROM MULTILEVEL WELLS:

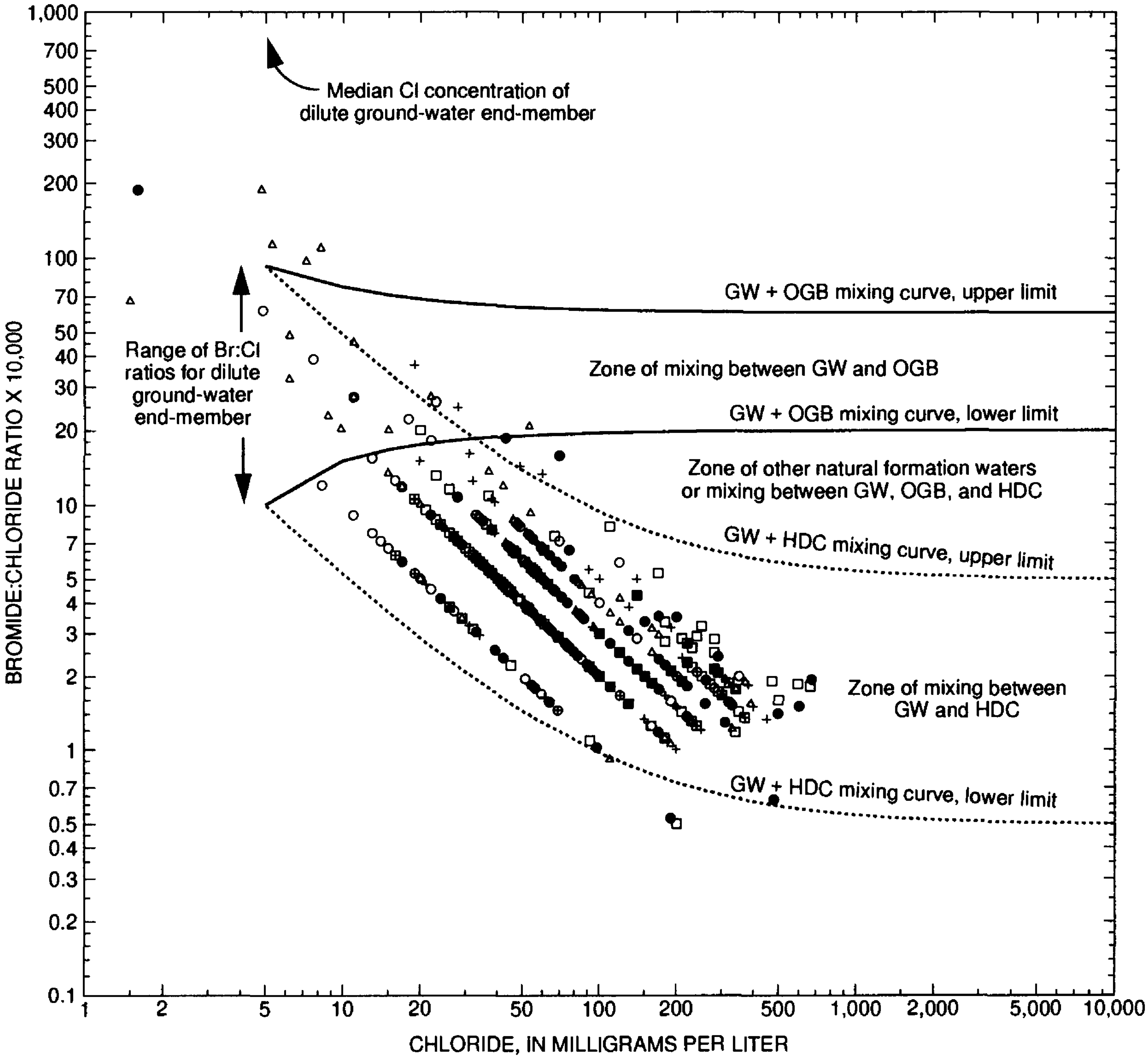
- ● WELL AB-133, FIRST DOWNGRADIENT
- + WELL AB-135, SECOND DOWNGRADIENT
- □ WELL AB-136, THIRD DOWNGRADIENT
- △ WELL AB-138, THIRD DOWNGRADIENT (TUBE)
- ○ WELL AB-137, FOURTH DOWNGRADIENT

GW GROUND WATER

OGB OILFIELD AND GASFIELD BRINE

HDC HIGHWAY-DEICING CHEMICAL SOLUTION

Figure 8. Bromide:chloride ratios in ground-water samples from the Ashtabula County study site, Ohio.



EXPLANATION

SAMPLE FROM MULTILEVEL WELLS:

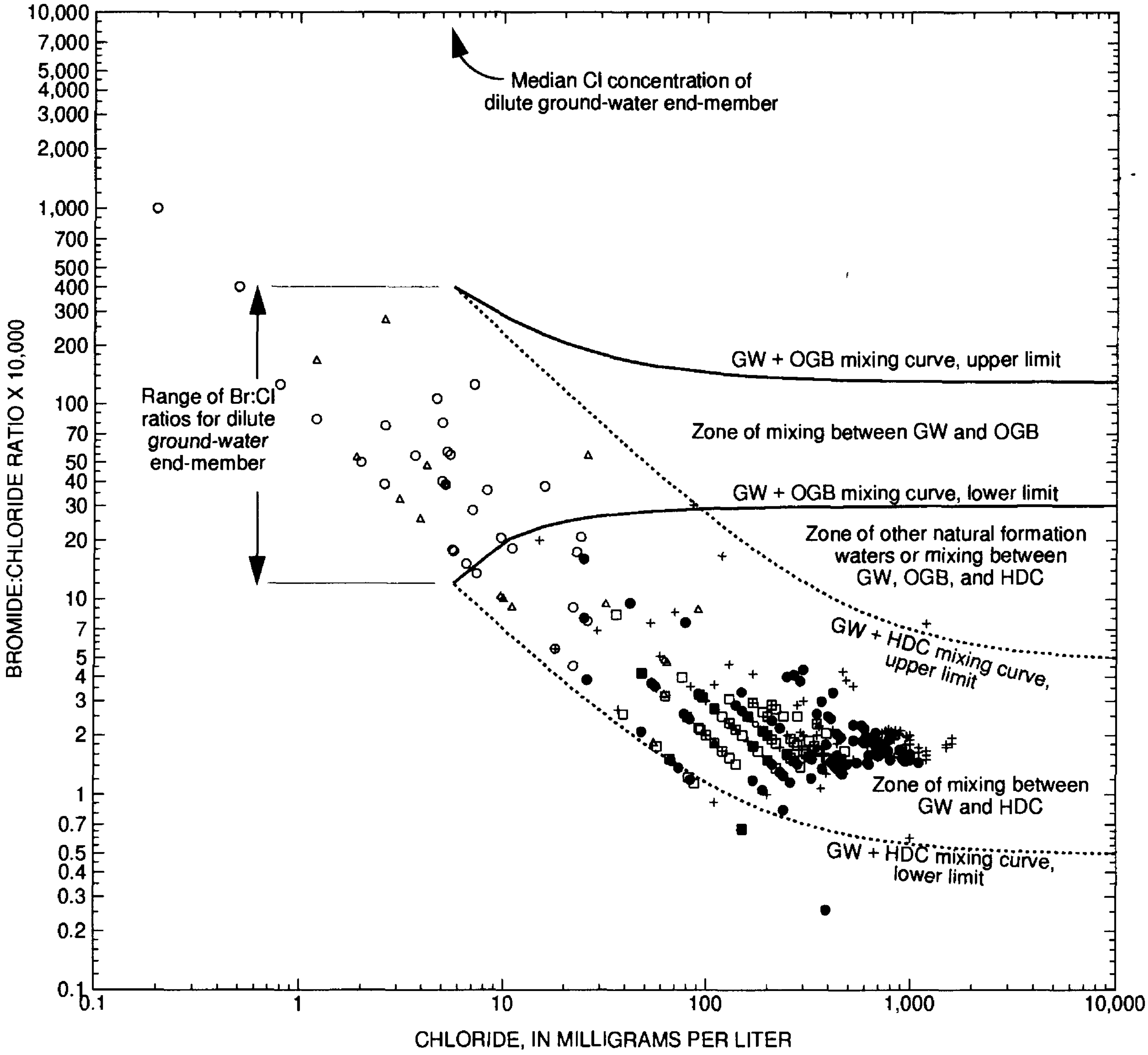
- ● WELL LU-22, FIRST DOWNGRADIENT
- + WELL LU-25, SECOND DOWNGRADIENT
- □ WELL LU-26, THIRD DOWNGRADIENT
- △ WELL LU-27, THIRD DOWNGRADIENT (TUBE)
- ○ WELLLU-28, FOURTH DOWNGRADIENT

GW GROUND WATER

OGB OILFIELD AND GASFIELD BRINE

HDC HIGHWAY-DEICING CHEMICAL SOLUTION

Figure 9. Bromide:chloride ratios in ground-water samples from the Lucas County study site, Ohio.



EXPLANATION

SAMPLE FROM MULTILEVEL WELLS:

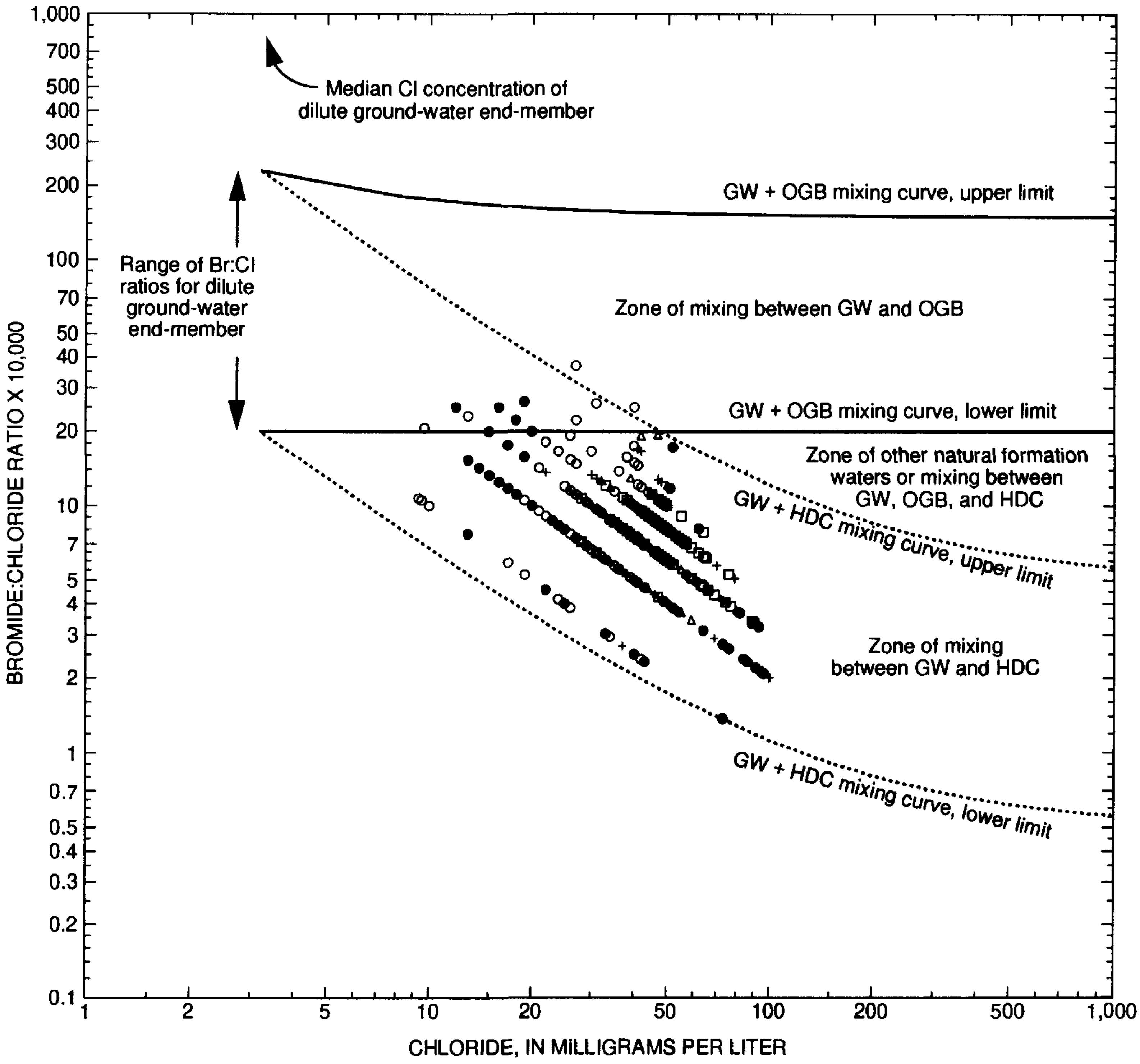
- ● WELL PO-115, FIRST DOWNGRADIENT
- + WELL PO-118, SECOND DOWNGRADIENT
- □ WELL PO-117, THIRD DOWNGRADIENT
- △ WELL PO-119, THIRD DOWNGRADIENT (TUBE)
- ○ WELL PO-120, FOURTH DOWNGRADIENT

GW GROUND WATER

OGB OILFIELD AND GASFIELD BRINE

HDC HIGHWAY-DEICING CHEMICAL SOLUTION

Figure 10. Bromide:chloride ratios in ground-water samples from the Portage County study site, Ohio.



EXPLANATION

SAMPLE FROM MULTILEVEL WELLS:

- ● WELL R-15, FIRST DOWNGRADIENT
- + WELL R-17, SECOND DOWNGRADIENT
- □ WELL R-18, THIRD DOWNGRADIENT
- △ WELL R-19, THIRD DOWNGRADIENT (TUBE)
- ○ WELL R-20, FOURTH DOWNGRADIENT

GW GROUND WATER

OGB OILFIELD AND GASFIELD BRINE

HDC HIGHWAY-DEICING CHEMICAL SOLUTION

Figure 11. Bromide:chloride ratios in ground-water samples from the Richland County study site, Ohio.

At the Ashland (fig. 7) and Richland County (fig. 11) sites, where the maximum chloride concentrations were approximately 100 mg/L, most of the data points fell in the zone of mixing between ground water and dissolved deicing chemicals. Some of the ground water from the Ashland County site falls in the zone of other natural formation waters or mixing between ground water, oilfield and gasfield brine, and highway-deicing chemical solution. This pattern may be due to the narrow range in Br:Cl ratios determined for the dilute ground-water end-member. If a wider range of Br:Cl ratios had been used, the upper limit of the zone of mixing between ground water and dissolved deicing chemicals would be higher and would include all of the data. Alternatively, the data may indicate that not only dissolved deicing chemicals but also oilfield and gasfield brine contribute chloride to ground water at this site. The Ashland County site overlies the Loudonville natural gas field, discovered in 1911 (Debrosse and Vohwinkel, 1974). Very small amounts of gasfield brine from drilling activities in the area might be present in the shallow ground water and might be contributing a minute percentage (<0.06 percent) of the ground water to the aquifer. It should be noted, however, that the chloride concentrations of the waters that plot in the zone of other natural formation waters or mixing between ground water, oilfield and gasfield brine, and highway-deicing chemical solution are fairly low, and an accurate identification of the salinity source or sources to these waters may not be possible at the site.

EFFECTS OF HIGHWAY DEICING CHEMICALS ON SHALLOW UNCONSOLIDATED AQUIFERS, BY SITE

Effects of highway deicing chemicals were evident throughout the interim reporting period at the three northernmost sites (Ashtabula, Portage, and Lucas County sites), although trace amounts of deicing chemicals were detected at the Richland and Ashland County sites during some periods. Sampling at the Champaign, Clark and Pickaway County sites was temporarily suspended at times because of the mild winters during 1991–93. As the study proceeds, the presence and movement of deicing chemicals may become more evident at the Champaign, Clark and Pickaway County sites.

Climatic data for the period January 1991 through September 1993 show that cold weather, and resultant deicing chemical application rates, varied widely across the State. As a result, only traces of dissolved chloride above background concentrations (mean 12–25 mg/L) were present in ground-water samples from the Pickaway, Clark, or Champaign 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 3–25 mg/L, rising to a mean of 49–77 mg/L). For the interim reporting period, the mean dissolved chloride concentration for all downgradient wells was about 2 times the background concentration at the Ashland County site and 14 times the background concentration at the Richland County site. At the Lucas, Portage, and Ashtabula County sites, deicing chemicals were applied frequently throughout the winter, and downgradient dissolved chloride concentrations rarely returned to background concentrations (mean 6–32 mg/L) throughout the period. For the interim reporting period, the mean dissolved chloride concentration for all downgradient wells was about 3 times the background concentration (32 mg/L) at the Lucas County site (92 mg/L), 72 times the background concentration (6 mg/L) at the Portage County site (432 mg/L - 2 wells only), and 21 times the background concentration (13 mg/L) at the Ashtabula County site (279 mg/L).

Each site is described separately in the remainder of the report. Four aspects of each site are described: site characteristics, climate, hydrogeology, and effects of highway deicing chemicals on water quality. Site characteristics include location, topography, land use, highway characteristics, geology and soil type. Climatic information includes regional and site-specific data, including snowfall. Hydrogeologic information includes aquifer properties, ground-water levels and flow direction, recharge characteristics, and ground conductivity. 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 and chloride, and specific conductance. Summary facts that supplement the individual descriptions of each site are listed in table 6. 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.

Table 6. Site information and hydrologic features of each highway study site
[ODOT, Ohio Department of Transportation]

Site	State route	ODOT deicing priority	Average annual snowfall values for nearby areas (inches)[a]	Average annual deicing chemical use for county (tons)[b]	Depth to water at site (feet)[c]	Water-table gradient at site (feet per foot)	Ground-water velocity at site (feet per day)
Ashland County	3	Second	30–40	6,842	1–7	0.011	0.11
Ashtabula County	84	Second	60–70	17,827	5–10	.035	.19
Champaign County	29	Second	20–25	2,011	6–11	.001	.14
Clark County	4	First	25–30	3,070	19–23	.011	1.13
Lucas County	2	First	30–40	5,277	4–8	.004	.06
Pickaway County	104	Second	20–30	1,346	7–13	.003	.24
Portage County	14	First	50–60	8,320	5–9	.007	.55
Richland County	97	Second	30–40	5,436	11–17	.052	.68

[a] From Miller and Weaver (1971).

[b] Twelve-winter-season average, 1981–93. Source: ODOT, written communication, 1994.

[c] Range during interim period, 1988–93.

Ashland County Site

Site Characteristics

The Ashland County site (fig. 12) is on 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 steep hills and is on the southern boundary of Ohio's glaciated area and near a glacial outwash stream (White, 1977). The slope of the area is 2.5 ft over 340 ft or 0.007, toward the Clear Fork of the Mohican River. The downgradient side of the highway is an unused field covered mostly with weeds and brush. 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 open ditches. Total pavement width, including 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 northeast and rise up a slight grade about 1,000 ft from the site.

The surficial material at the site ranges from a clayey fine sandy soil to a very coarse sand and gravel; a dense gray clay underlies these materials at about 13–16 ft below land surface. Bedrock is the Cuyahoga Shale of Mississippian age (Swinford, 1995 and Kriz, 1995). Well logs obtained from ODNR, Division of Water, indicate the depth to this formation varies from 17–43 ft within a half-mile area. The soils are of the Shoals-Lobdell Association; with the moderately well-drained Lobdell silt loam distributed throughout the site (U.S. Department of Agriculture, 1980a). 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. 13).

The 12-winter (1981–93) average annual use of deicing-chemicals in Ashland County as a whole was 6,842 tons (table 3). The maximum for this 12-winter-season period was 11,049 tons in 1983–84 and the minimum for this period was 3,195 tons in 1982–83. The 3-winter (1990–93) average annual use of deicing-chemicals during the reporting period for this county as a whole was 6,413 tons. The maximum for this 3-winter period was 6,974 tons in 1992–93 and the minimum for this period was 5,754 tons in 1990–91. For all of Ohio, the 3-winter average annual use of deicing-chemicals was 8.0 ton/2-ln mi (16,000 lb/2-ln mi) (Ohio Department of Transportation, written commun., 1994). Data collected at this site indicate the three-winter average annual use of deicing-chemicals was 5.35 ton/2-ln mi (10,700 lb/2-ln mi.), which is 33 percent less than the State average. During the interim reporting period, no calcium chloride ($CaCl_2$) was applied to the highway at this site.

Climate

The average annual precipitation for the area is 38.8 in. The average annual temperature for the area is 8.8°C (47.9°F), with the monthly normal high of 27.9°C (82.3°F) in July and the monthly normal low of -9.7°C (14.6°F) in January (National Oceanic and Atmospheric Administration, 1982). During the interim reporting period, annual precipitation based on data collected at the site averaged 29.4 in. The average annual snowfall is 30–40 in. for nearby reporting areas (Miller and Weaver, 1971).

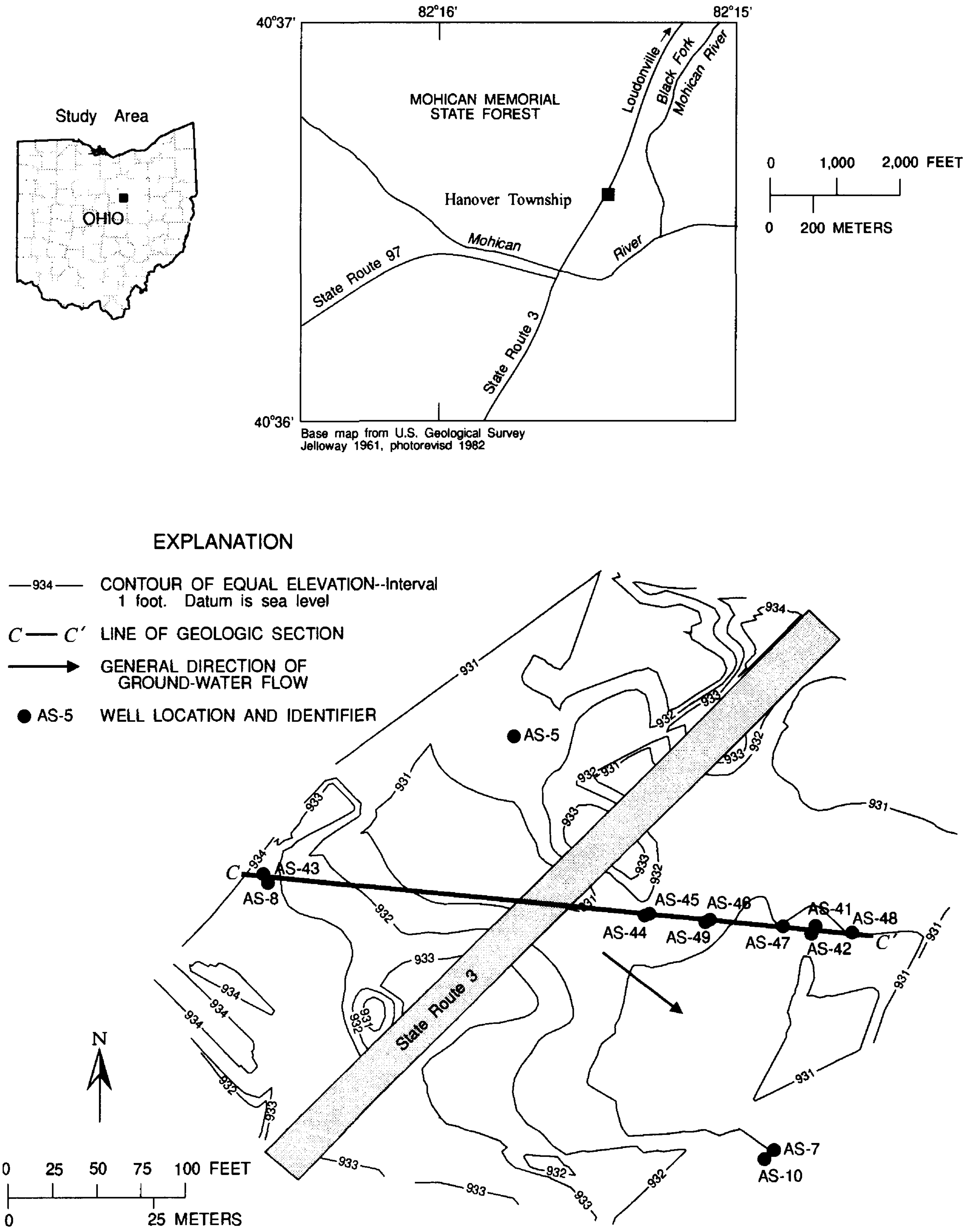
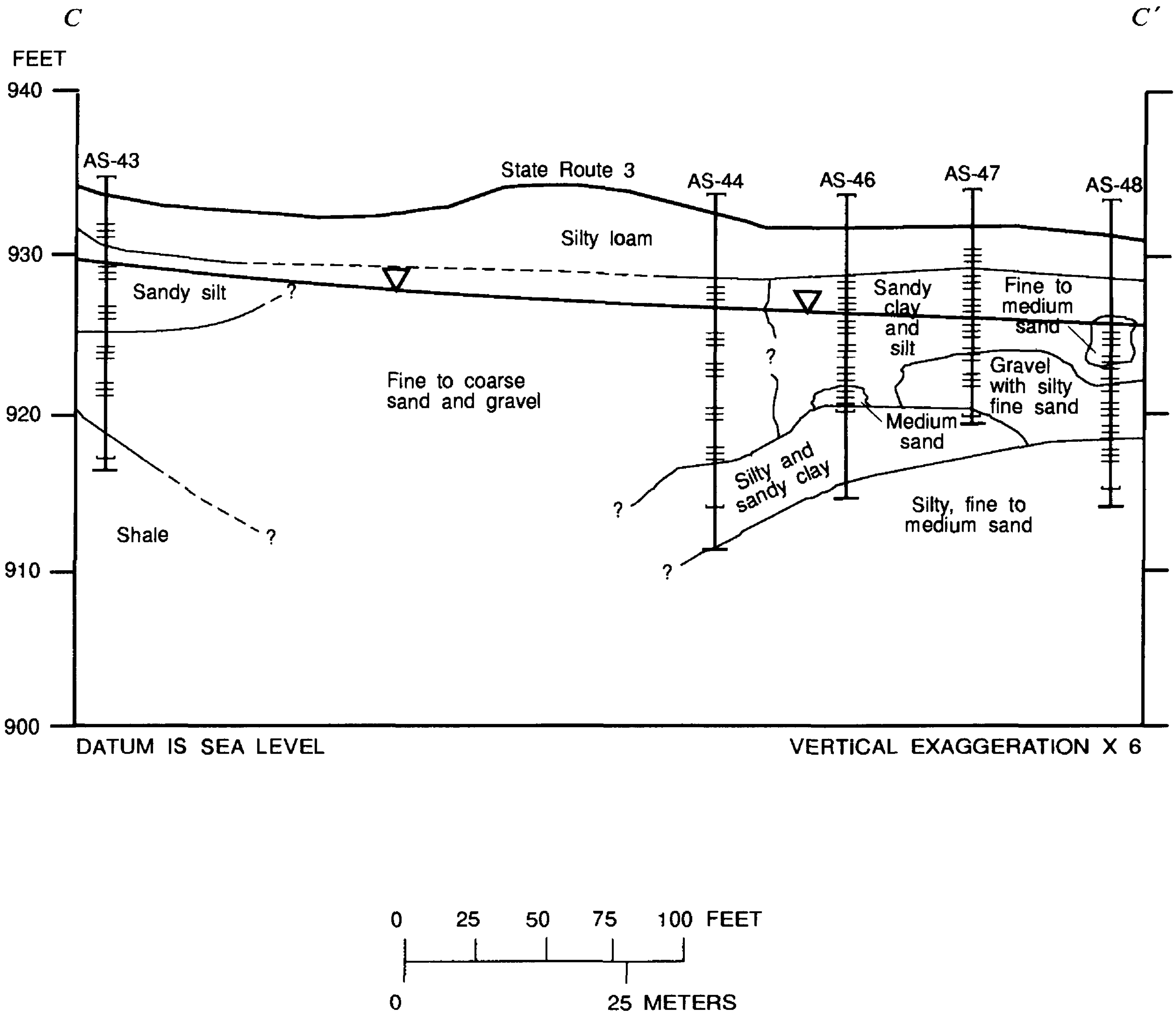


Figure 12. Topography, well locations, and ground-water flow direction at Ashland County study site.



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

Figure 13. Geologic section *C-C′*, Ashland County study site, Ohio. (Section trace shown in fig. 12.)

Hydrogeology

The ground-water level is 1–7 ft below land surface throughout the year at this site. During the interim reporting period, the direction of flow varied from about 72° to 90° to the alignment of the highway, as determined by the triangulation method using available wells; average water-table slope is about 0.011. At this site the ground-water level responds to precipitation within 1 day, owing to the porous aquifer materials at the surface and the shallow water table.

Results of single-well aquifer tests (slug tests) on the aquifer indicate that the hydraulic conductivity is 4 ft/d. Assuming an average gradient of 0.011 and an effective porosity of 40 percent, the ground-water velocity was computed to be 0.11 ft/d.

The electrical conductivity of the subsurface materials was measured at the Ashland County site on two occasions by use of the Geonics EM-34-3 at the 10-m spacing. The composition of the aquifer materials was inferred from these measurements and well logs from the site. Surveys were completed at this site in March 1992 and April 1993. Measurements downgradient from the highway ranged from 2 mS/m near the well farthest from the highway to about 14 mS/m close to the highway; this range indicates sand and gravel with some fine sand and silt and most likely low to medium specific conductance. The aquifer materials can vary significantly, especially in the amount of silt present throughout the site. Variations in electrical conductivity measurements between EM surveys define changes in the ground conductivity, that would be attributable only to changes in water quality. Measurements between surveys showed little change, possibly because during the interim reporting period, both surveys were done during the same part of the winter. Analysis of the regular ground-water samples verified that higher measurements near the highway are due, in part, to increased specific conductance of the ground water.

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 14. The 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. The movement of chloride and other deicing-related constituents from the highway with time are indicated by boxplots of laboratory-determined data (fig. 15).

Field-monitored characteristics

Specific conductance. Specific conductance of ground water varied little during the interim reporting period. A maximum of 907 μS/cmwas recorded in March 1993, and a minimum of 722 μS/cm was recorded in March 1992. Annual extremes (based on water year) ranged from 843 μS/cm in June 1991 to 811 μS/cm in September 1991 (data incomplete), from 847 μS/cm in September 1992 to 722 μS/cm in March 1992, and from 907 μS/cm in March 1993 to 798 μS/cm in November 1992. For comparison, the mean specific conductance of the upgradient well for the interim reporting period was 607 μS/cm. All increases and decreases in specific conductance were very gradual, possibly because of a combination of (1) deicing chemicals being applied somewhat regularly but in small quantities, and (2) the relatively flat water table and slow ground-water velocity, which slows down the flush of chemicals through the aquifer, thus resulting in slow, gradual changes.

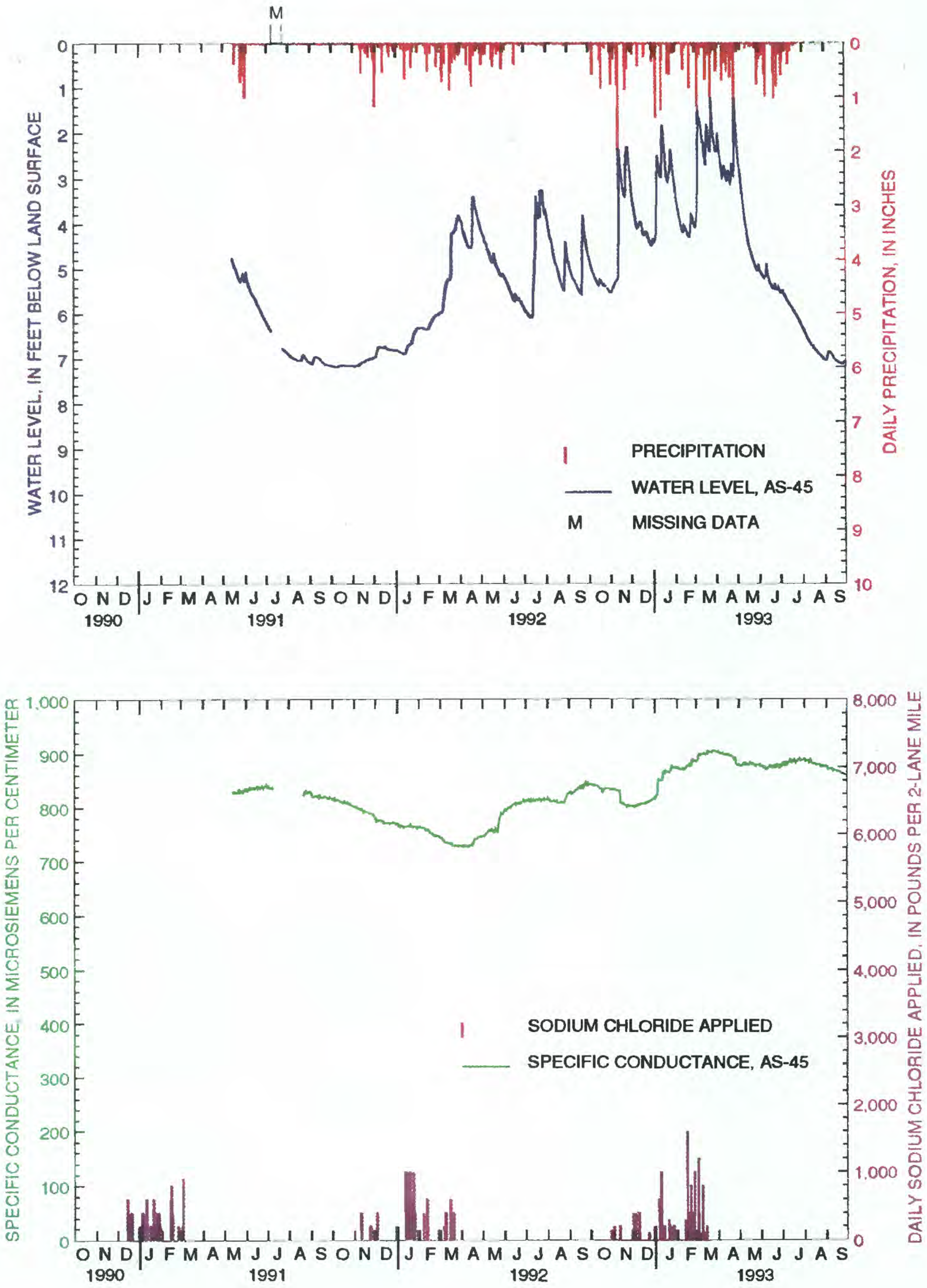


Figure 14. Ground-water levels, specific conductance, precipitation, and salt application for the Ashland County site.

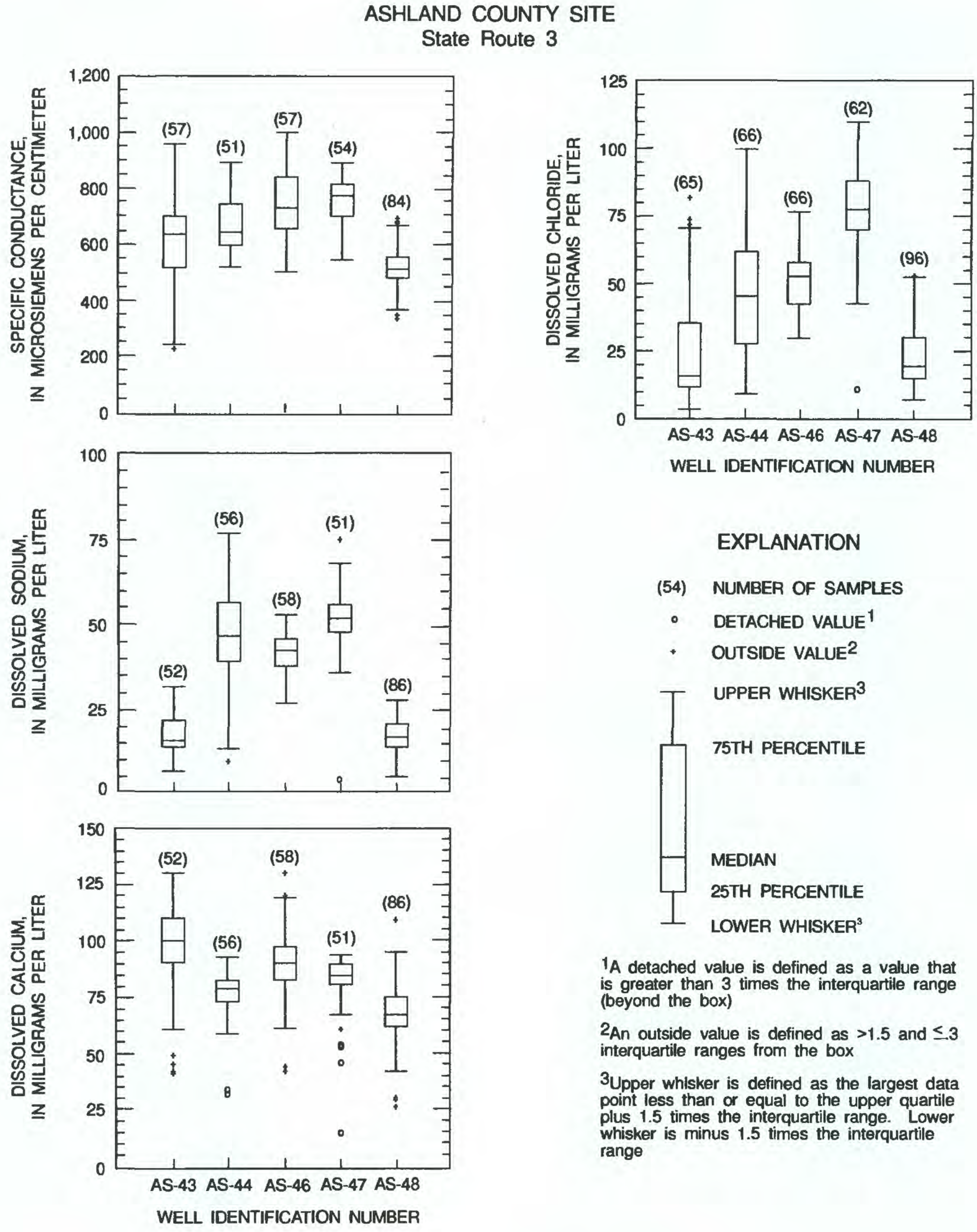


Figure 15. The distribution of specific conductance and concentrations of dissolved sodium, calcium, and chloride in ground water sampled at the Ashland County study site, Ohio, January 1991-September 1993. (Plots are shown in downgradient order from left to right. Far left plot is upgradient from highway; others are downgradient.)

Air and soil temperature. During the interim reporting period the air temperature at this site ranged from 35.5°C in July 1991 to a minimum of -23.2°C in February 1993. The annual maximum for 1991 was 35.5°C in July, but the minimum for 1991 could not be accurately determined because measurements were not made until May 1991. Annual extremes (based on water year) for the remainder of the interim reporting period ranged from a maximum of 31.7°C in June and August 1992 to a minimum of -23.1°C in January 1992 and from a maximum of 34.8°C in August 1993 to a minimum of -23.2°C in February 1993.

During the interim reporting period the soil temperature ranged from a maximum of 35.5°C in 1991 to a minimum of 3.8°C in 1993. The annual maximum for 1991 was 35.5°C in July, but the minimum for 1991 could not be accurately determined because measurements were not made until May 1991. Annual extremes (based on water year) for the remainder of the interim reporting period ranged from a maximum of 31.5°C in July 1992 to a minimum of 5.4°C in December and February 1992 and from a maximum of 31.3°C in August 1993 to a minimum of 3.8°C in February 1993. No soil temperature of 0°C or less was recorded on any day during that period; thus, frozen soil would not have inhibited infiltration of runoff water into the aquifer.

Laboratory-determined characteristics

Because of the variability in the weather patterns at the Ashland County site, deicing chemicals were not applied to the highway uniformly throughout a single winter or from year to year. Temperatures also varied widely throughout the winters 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 are listed in table 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 are shown in figure 15. Data shown are for the sampling period January 1991 through September 1993. Patterns that emerge from those data are noted below.

Chloride concentration. At the upgradient well, AS-43, the mean concentration of chloride was 25 mg/L and the maximum was 82 mg/L. Concentrations were generally higher at the first three downgradient wells (mean, 47–77 mg/L; maximum, 77–110 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 23 mg/L and the maximum was 53 mg/L. Thus, 150 ft downgradient from the highway, the mean concentration at the fourth downgradient well was about equal to the upgradient or background concentration.

Soil samples were collected at this site in August 1993. The extract from the soil sample preparation method was analyzed at the NWQL for dissolved chloride concentration. The chloride concentration of the samples collected within 12 ft of the highway was 40–69 mg/L and decreased to 7 mg/L by 80 ft downgradient from the highway.

Sodium concentration. At the upgradient well, AS-43, the mean concentration of sodium was 18 mg/L, and the maximum was 32 mg/L. Concentrations were generally higher at the first three downgradient wells (mean, 41–53 mg/L; maximum, 53–77 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 17 mg/L, and the maximum was 28 mg/L. Thus, 150 ft downgradient from the highway, the mean concentration at the fourth downgradient well was about equal to the upgradient or background concentration.

Table 7. Water-quality data for multilevel wells at the Ashland County site, Ohio, January 1991 through August 1993
[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples; UG, upgradient; DG, downgradient]

Well name	Position	Statistic	Property or constituent				
			Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)	Bromide, dissolved (mg/L)
AS-43	UG	Maximum	959	130	32	82	0.20
		Minimum	223	41	7	4	<.01
		Mean	607	97	18	25	.40
		Median	635	100	16	16	.03
		N	57	52	52	65	61
AS-44	1st DG	Maximum	894	93	77	100	0.08
		Minimum	517	32	10	9	<.01
		Mean	678	76	53	47	.04
		Median	643	79	48	46	.04
		N	51	56	56	66	65
AS-46	2d DG	Maximum	1000	130	53	77	0.12
		Minimum	501	42	27	30	<.01
		Mean	748	91	41	52	.06
		Median	729	90	42	53	.05
		N	57	58	58	66	66
AS-47	3d DG	Maximum	893	94	75	110	0.10
		Minimum	543	15	4	11	<.01
		Mean	751	82	51	77	.06
		Median	774	85	52	78	.06
		N	54	51	51	62	60
AS-48	4th DG	Maximum	693	110	28	53	0.11
		Minimum	331	27	5	7	<.01
		Mean	516	69	17	23	.03
		Median	510	68	17	20	.03
		N	84	86	86	96	95

Specific conductance. At the upgradient well, AS-43, the mean specific conductance was 607 μS/cm, and the maximum was 959 μS/cm. Values were generally highest at the first three downgradient wells (mean, 678–751 μS/cm; maximum, 893–1,000 μS/cm). Values remained fairly constant downgradient along the flowpath through the third downgradient well. At the fourth downgradient well, AS-48, the mean specific conductance was 516 μS/cm and the maximum was 693 μS/cm. Thus, 150 ft downgradient from the highway, the mean specific conductance at the fourth downgradient well was about the same as the upgradient or background concentration.

Ashtabula County Site

Site Characteristics

The Ashtabula County site (fig. 16) 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 is the northernmost site in the study area; average yearly snowfall and average yearly salt use are the highest among the eight study sites (table 6). 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 postglacial 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 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 Chagrin Shale, which is about 20–30 ft below land surface (White and Totten, 1979). 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). 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. 17).

The 12-winter (1981–93) average annual use of deicing-chemicals in Ashtabula County as a whole was 17,827 tons (table 3). The maximum for this 12-winter period was 24,000 tons in 1985–86 and the minimum for this period was10,400 tons in 1982–83. The maximum 3-winter (1990–93) average annual use of deicing-chemicals during the interim reporting period for this county as a whole was 17,667 tons. The maximum for this 3-winter period was 21,000 tons in

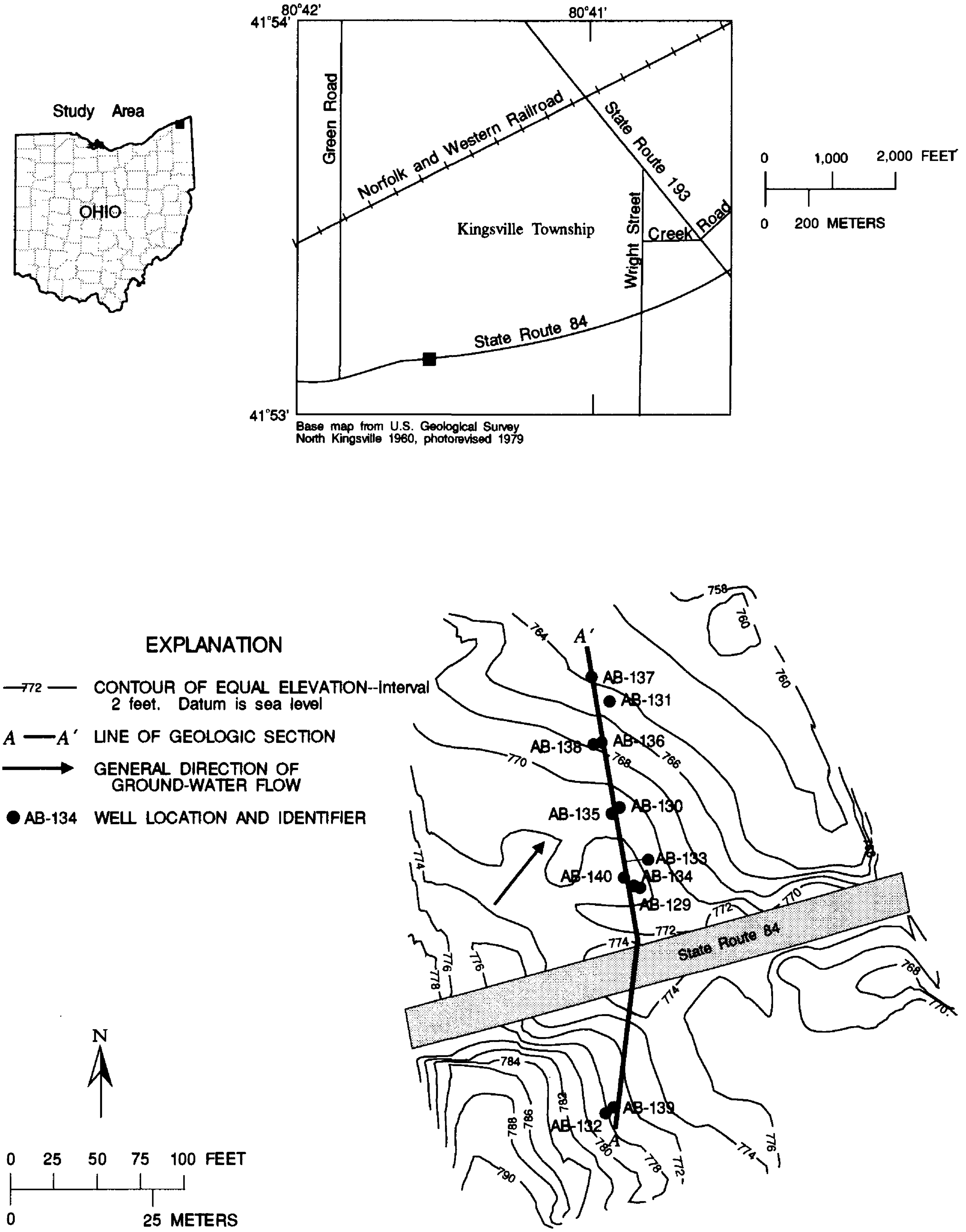
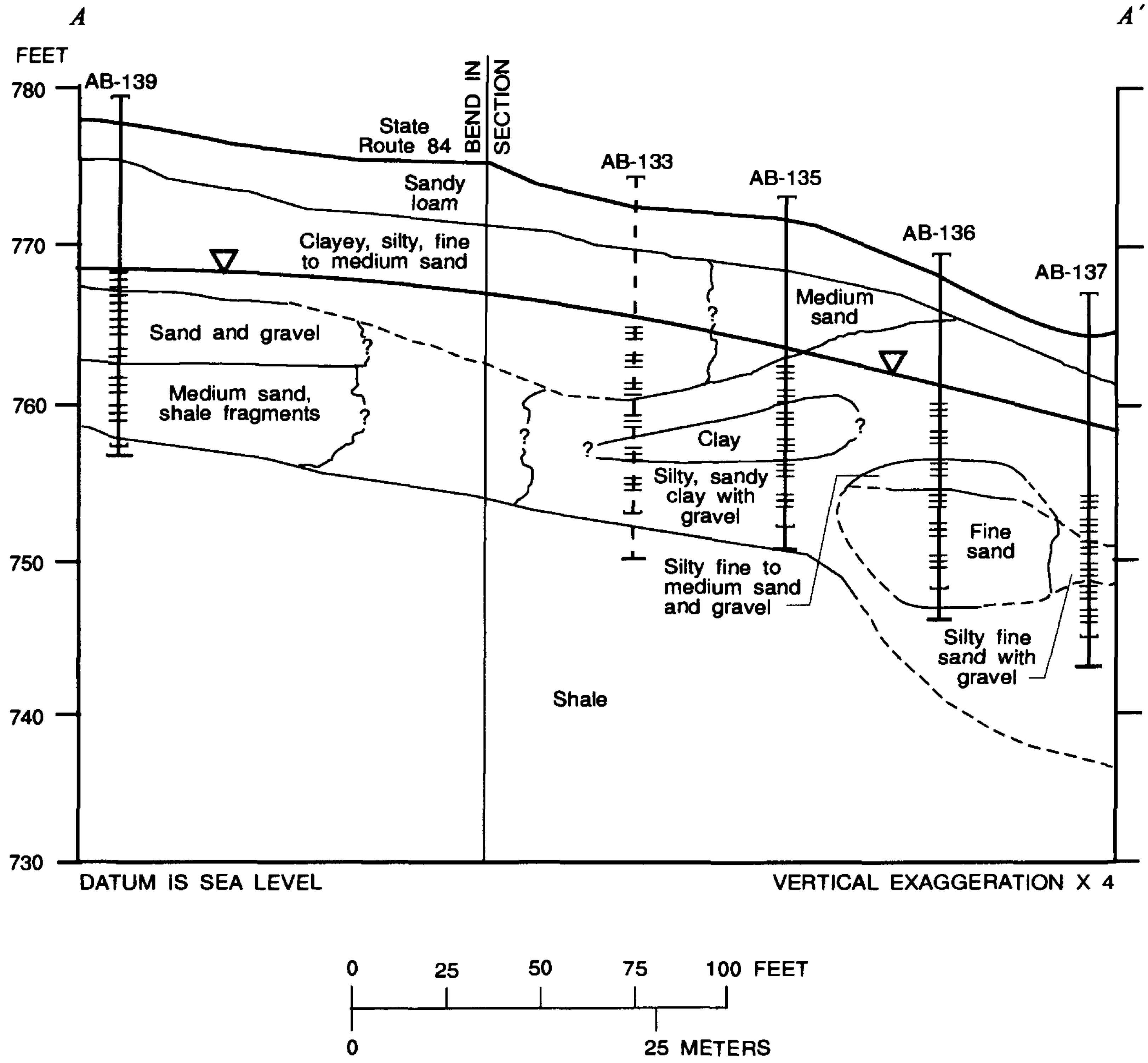


Figure 16. Topography, well locations, and ground-water flow direction at the Ashtabula County study site.



EXPLANATION

AB-136 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

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

1992–93, and the minimum for this period was 15,000 tons in 1990–91. For all of Ohio, the 3-winter average annual use of deicing-chemicals was 8.0 ton/2-ln mi (16,000 lb/2-ln mi) (Ohio Department of Transportation, written commun., 1994). Data collected at this site indicate the 3-winter average annual use of deicing-chemicals was 19.43 ton/2-ln mi (38,867 lb/2-ln mi.), which is 143 percent greater than the State average. During the interim reporting period, a small amount of liquid calcium chloride ($CaCl_2$) also was applied to the highway in 69 percent of the treatments in addition to sodium chloride and abrasives.

Climate

The average annual precipitation for the area is 38.3 in. per year. The average annual temperature for the area is 9.6°C (49.2°F), with the monthly normal high of 27.4°C (81.3°F) in July and the monthly normal low of -7.6°C (18.4°F) in January (National Oceanic and Atmospheric Administration, 1982). During the interim reporting period, annual precipitation based on data collected at the site averaged 36.1 in. The average annual snowfall is 60–70 in. for nearby reporting areas (Miller and Weaver, 1971).

Hydrogeology

The ground-water level is 5–10 ft below land surface throughout the year at this site. During the interim reporting period, the direction of flow varied from an angle of approximately 86° to about 40° to the alignment of the highway, as determined by the triangulation method using available wells; average water-table slope is about 0.035. 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.

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 0.035 and an effective porosity of 42 percent, the ground-water velocity was computed to be 0.19 ft/d.

The electrical conductivity of the subsurface materials was measured at the Ashtabula County site on four occasions by use of the Geonics EM-34-3 at the 10-m spacing. The measurements were made on the downgradient side of the highway. Powerlines and a buried gasline on the upgradient side of the highway resulted in inconclusive readings due to interference. Measurements near the highway on the downgradient side also were inconclusive due to interference; but at a distance of 10 m and greater in the field downgradient from the highway, measurements did not appear to be affected by interference. The composition of the aquifer materials was inferred from these measurements and well logs from the site. Surveys were completed at this site in July 1991, April 1993, May 1993, and August 1993. Measurements ranged from 4 to 20 mS/m, indicating a relatively wide range of aquifer materials throughout the site (sand, gravel, clay, silt, and till in varied amounts). These measurements were verified with well logs from the area. Variations in electrical conductivity measurements between EM surveys define changes in the ground conductivity that would be attributable only to changes in water quality. Analysis of the regular ground-water samples verified that downgradient from the highway, measurements were higher, for the most part because of increased specific conductance of the ground water. Contour plots of two surveys of the downgradient side of the highway, completed on July 9, 1991, and April 7, 1993, are shown in figure 18. The plots show an overall view of the distribution of the combined ground conductivity of earth materials and ground water. In general, the higher values are closer to the highway and the slight differences between the two plots are due to changes in

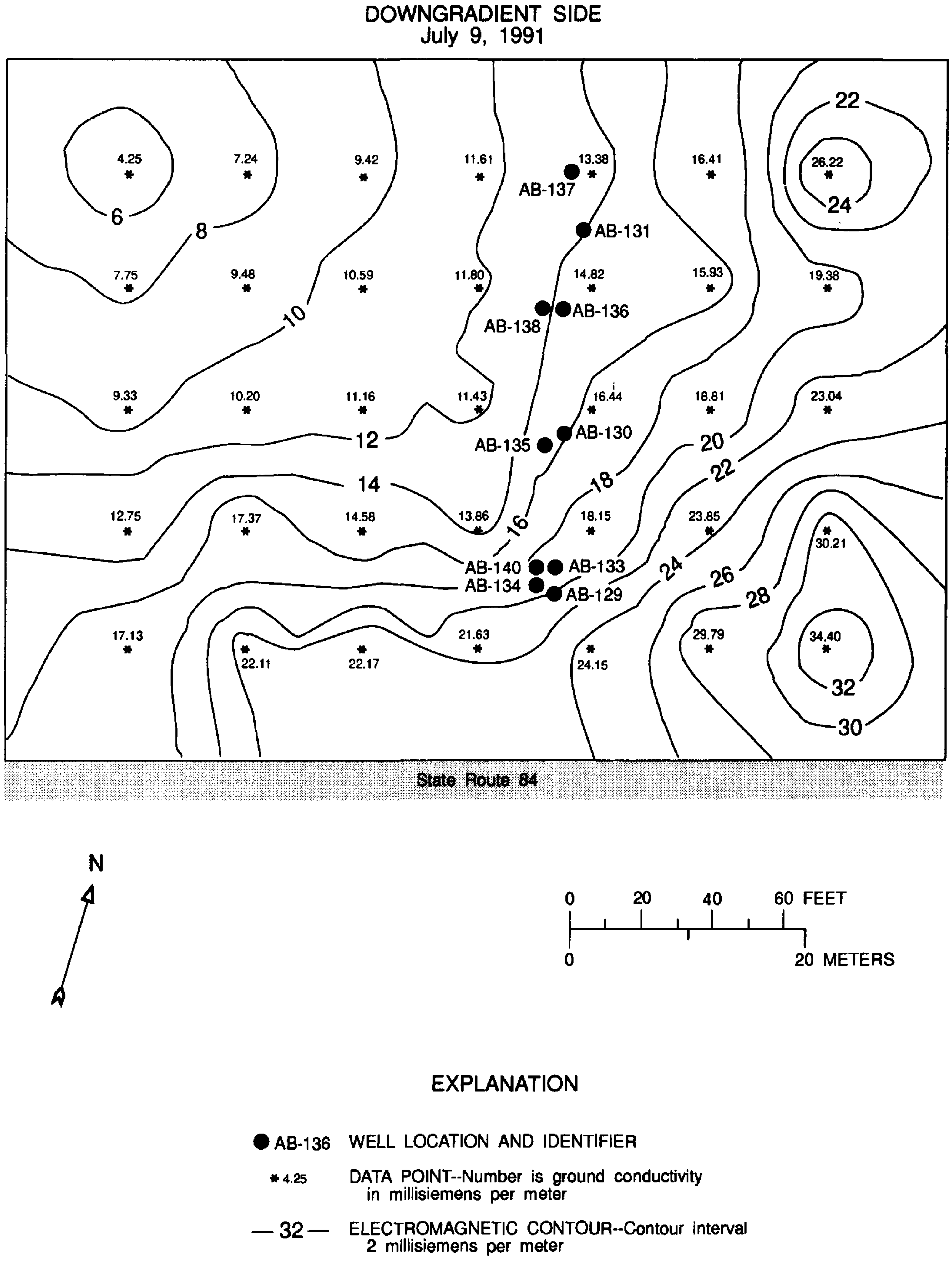
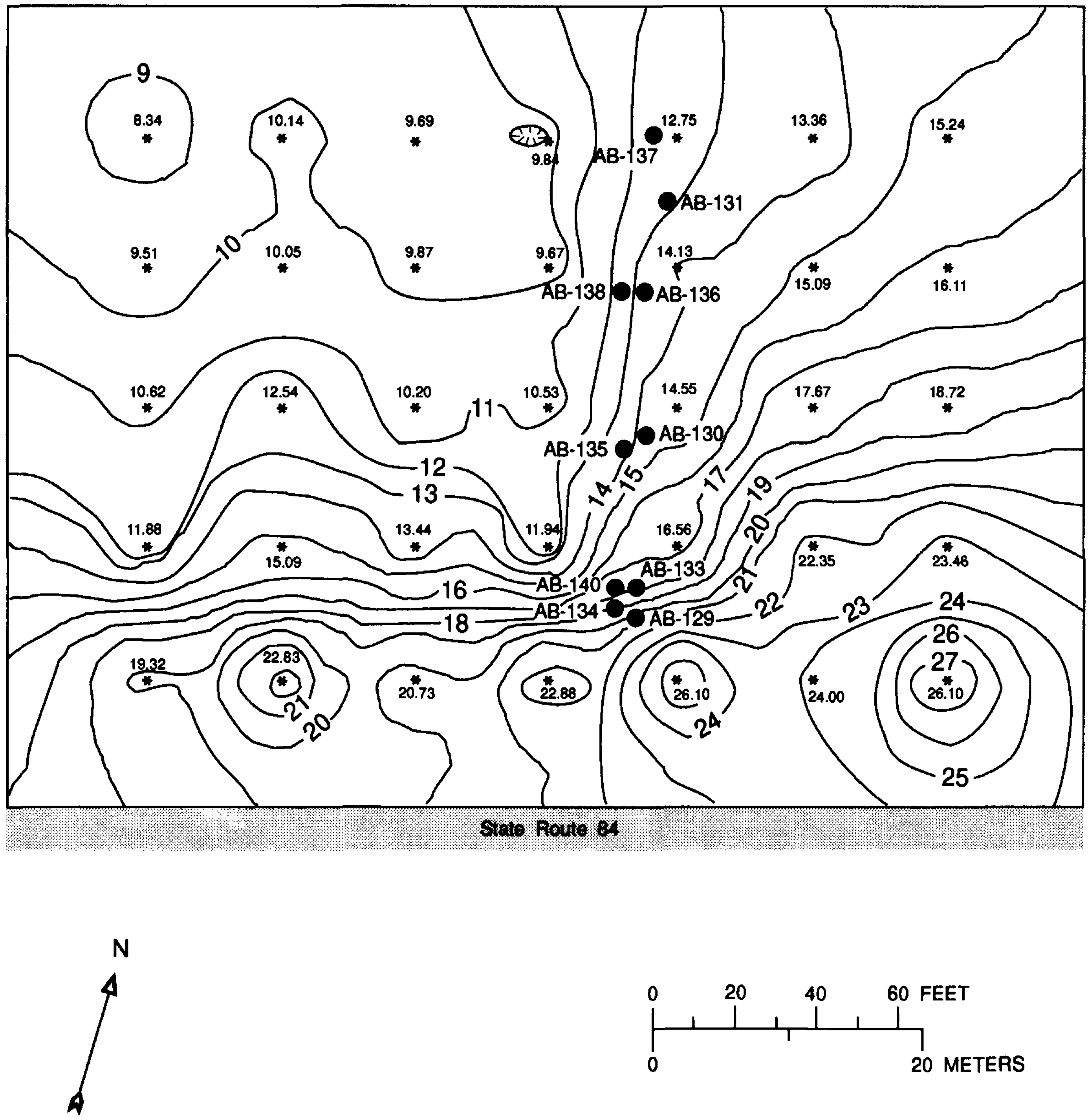


Figure 18. Contour plots of electromagnetic geophysical surveys on downgradient side of Ashtabula County study site, Ohio, July 9, 1991, and April 7, 1993. (The horizontal coplanar arrangement was used with a 10-meter spacing.)

DOWNGRADIENT SIDE
April 7, 1993



EXPLANATION

● AB-136 WELL LOCATION AND IDENTIFIER

* 8.34 DATA POINT--Number is ground conductivity in millisiemens per meter

— 24 — ELECTROMAGNETIC CONTOUR--Contour interval 1 millisiemen per meter. Hachures indicate decreasing conductivity

Figure 18. Contour plots of electromagnetic geophysical surveys on downgradient side of Ashtabula County study site, Ohio, July 9, 1991, and April 7, 1993--Continued.

quality of water in the aquifer. The small variability in ground conductivity from one survey to the next (generally, in the range of 0–5 mS/m) is not at a scale that could be detected as a distinct saline-water plume. Although baseline values are not necessarily permanently increasing each year, chloride concentrations and specific conductance rarely return to their original upgradient values during a annual cycle at this site.

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 19. The 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. The movement of chloride and other deicing-related constituents from the highway with time are indicated by boxplots of laboratory-determined data.The movement of chloride and other deicing-related constituents from the highway with time are indicated by boxplots of laboratory-determined data (fig. 20).

Field-monitored characteristics

Specific conductance. Specific conductance of ground water near the highway varied greatly during the interim reporting period. A maximum of 2,880 µS/cm was recorded in August 1992, and a minimum of 948 µS/cm was recorded in August 1991 (range, 1,920 µS/cm). Annual extremes (based on water year) ranged from 2,560 µS/cm in March 1991 to 948 µS/cm in August 1991, from 2,880 µS/cm in August 1992 to 1,300 µS/cm in April 1992, and from 2,660 µS/cm in March 1993 to 1,370 µS/cm in February, 1993. For comparison, the mean specific conductance of the upgradient well for the interim reporting period was 493 µS/cm. Fluctuations in specific conductance seem to occur fairly quickly at this site, possibly because of the relatively steep gradient of the terrain and the water table at this site. Some examples of these rapid fluctuations are declines from 2,650 to 1,540 µS/cm in 4 days, from 2,390 to 1,710 µS/cm in 4 days, from 2,100 to 948 µS/cm in 4 days, and from 2,820 to 2,330 µS/cm in 1 day. Conversely, there were periods when specific conductance of ground water remained at 2,000 µS/cm or above for a considerable time: for 86 days from February 20, 1991, to May 17, 1991; for 146 days from July 10, 1992, to December 3, 1992; and for 148 days from April 26, 1993, to September 21, 1993.

Air and soil temperature. During the interim reporting period the air temperature at this site ranged from 33.0°C in the summers of 1991 and 1993 to a minimum of -19.8°C in the winter of 1993. The annual maximum for 1991 was 33.0°C in September 1991, but the minimum for 1991 could not be accurately determined because measurements were not made until February 1991. Annual extremes (based on water year) for the remainder of the interim reporting period ranged from a maximum of 30.7°C in August 1992 to a minimum of -18.8°C in February 1992, and from a maximum of 33.0°C in July 1993 to a minimum of -19.8°C in February 1993.

During the interim reporting period, the soil-temperature record was often incomplete, but recorded data ranged from a maximum of 31.8°C in July 1993 to a minimum of -0.7°C in February 1993. Annual extremes (based on water year) for 1991 could not be accurately determined because of equipment failure. Soil-temperature records were incomplete for 1992, except for the summer, when a maximum of 27.9°C was recorded in July. No minimum for 1992

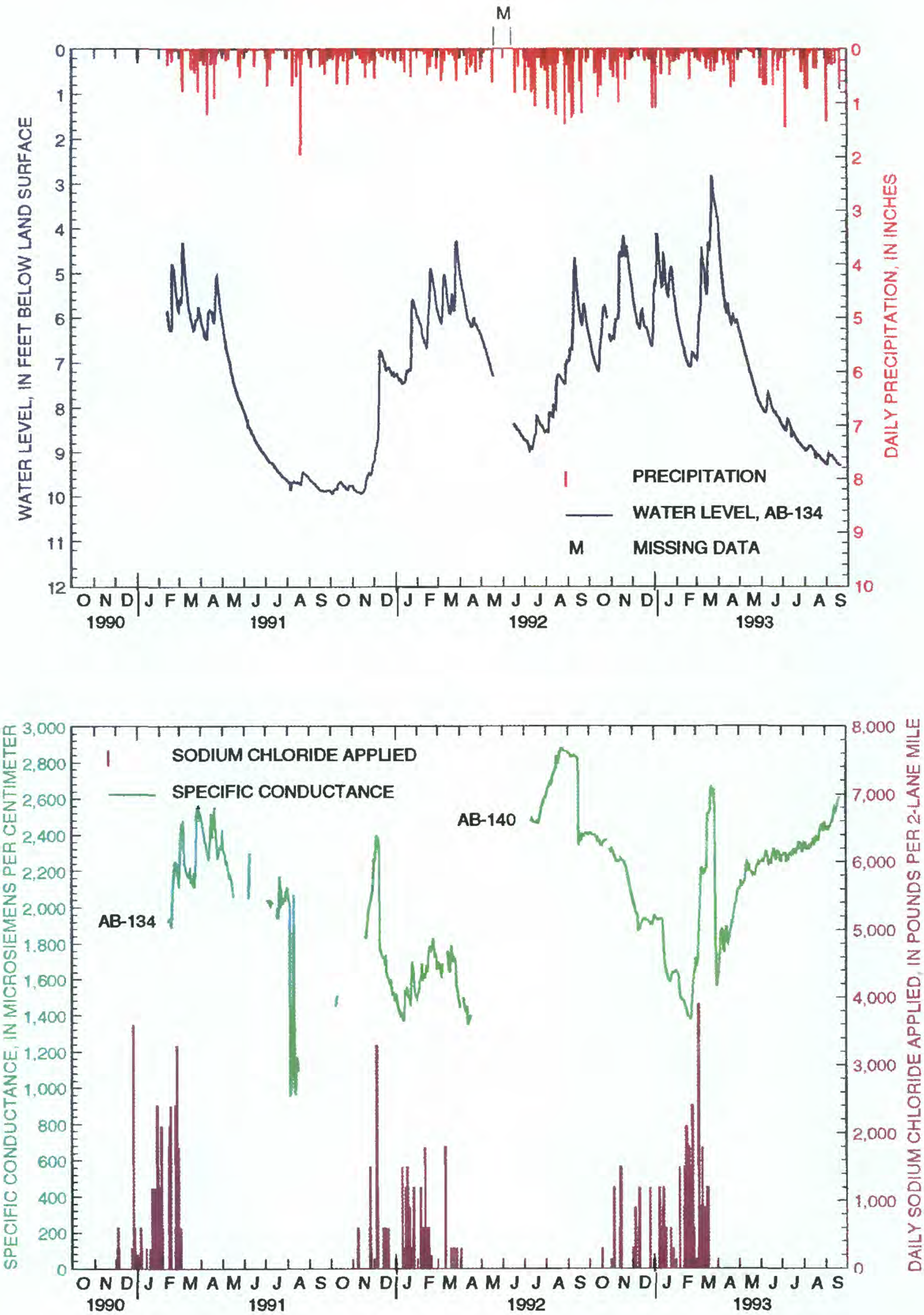


Figure 19. Ground-water levels, specific conductance of ground water, precipitation, and sodium chloride applied at the Ashtabula County study site, Ohio.

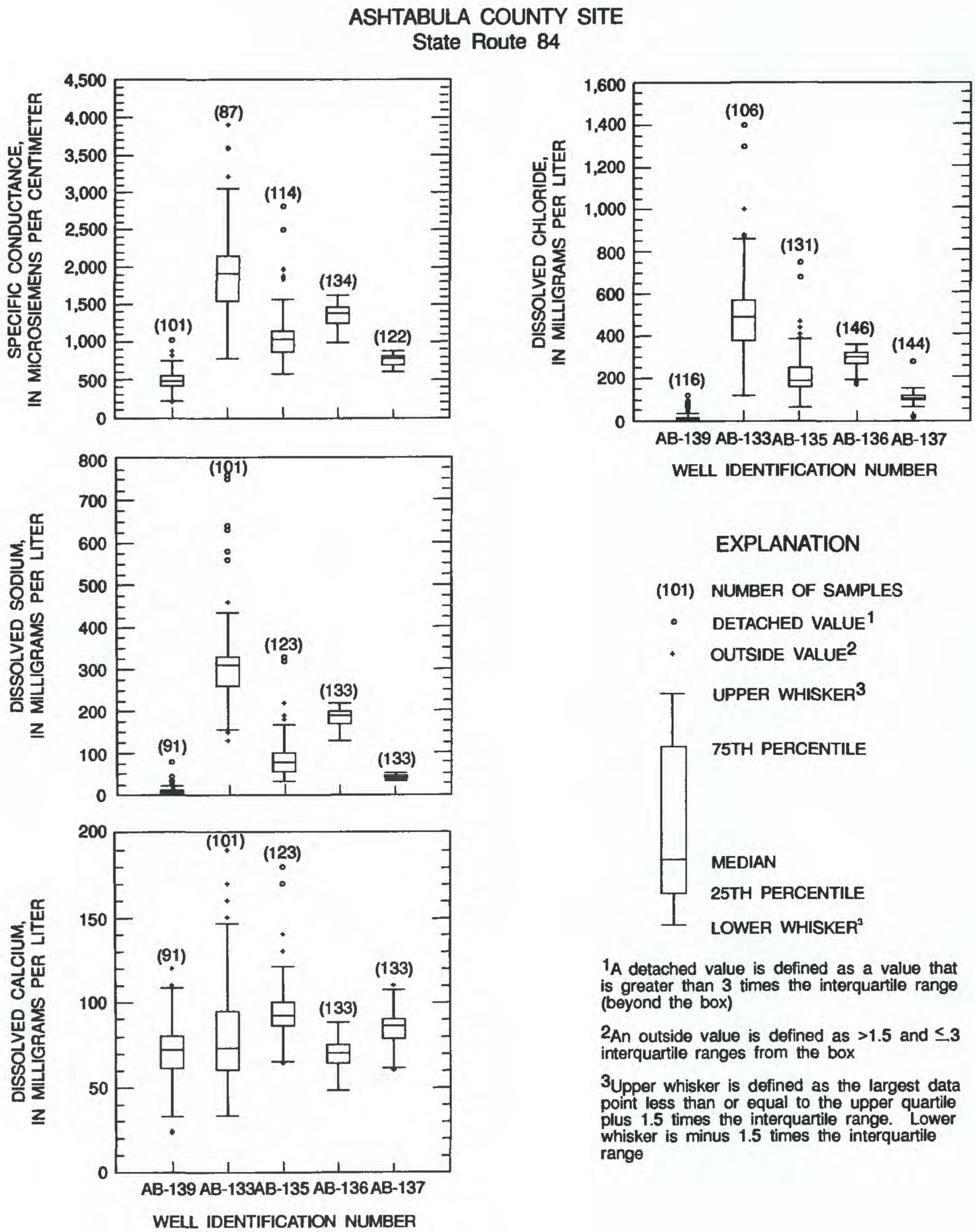


Figure 20. The distribution of specific conductance and concentrations of dissolved sodium, calcium, and chloride in ground water sampled at the Ashtabula County study site, Ohio, January 1991-September 1993. (Plots are shown in downgradient order from left to right. Far left plot is upgradient from highway; others are downgradient.)

could be determined accurately. Annual extremes (based on water year) for 1993 ranged from a maximum of 31.8°C in July to a minimum of -0.7°C in February. There appear to have been only two days during the interim reporting period (in 1993) when the soil temperature was 0°C or less, thus indicating no extended periods when frozen soil could inhibit infiltration of runoff water into the aquifer.

Laboratory-determined characteristics

The Ashtabula County site was the site most heavily treated with deicing materials during the interim reporting period. Summary statistics of the water-quality data collected at upgradient and downgradient wells are listed in table 8. 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 are shown in figure 20. Data shown are for the sampling period January 1991 through September 1993. Patterns that emerge from those data and require further discussion are noted below.

Chloride concentration. At the upgradient well, AB-139, the mean concentration was of chloride 13 mg/L and the maximum was 120 mg/L. Concentrations were highest at the first downgradient well, AB-133 (mean, 487 mg/L; maximum, 1,400 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 107 mg/L and the maximum was 280 mg/L. Thus, 150 ft downgradient from the highway, mean concentration at the fourth downgradient well was eight times the upgradient or background concentration. Dissolved chloride concentrations at each of six sampling levels in each well at the site are shown in figure 21. A vertical distribution of chloride concentrations is evident at the first downgradient well, AB-133. For example, in November 1991, the chloride concentration at level 2 reached 1,400 mg/L but was only 670 mg/L at level 5. A water sample collected from the entire screened interval of this well may have had an average concentration somewhere between these two. Preferential flowpaths can be monitored by sampling from multilevel wells, especially at sites where aquifer materials are mixed. The vertical distribution of chloride concentrations is much less apparent as distance from the highway increases.

Soil samples were collected at this site in August 1993. The extract from the soil-sample preparation method was analyzed at the NWQL for dissolved chloride concentration.The chloride concentration of the samples collected within 10 ft of the highway was 115–131 mg/L and decreased to 6 mg/L by 80 ft downgradient from the highway.

Sodium concentration. At the upgradient well, AB-139, the mean concentration of sodium was 11 mg/L and the maximum was 79 mg/L. Concentrations were highest at the first downgradient well, AB-133 (mean, 312 mg/L; maximum, 760 mg/L). At the fourth downgradient well, AB-137, the mean concentration was 43 mg/L and the maximum was 53 mg/L. Thus, 150 ft downgradient from the highway, mean concentration at the fourth downgradient well was about four times the upgradient or background concentration. Because of the steep surface gradient at this site, preferential flowpaths may result in somewhat higher concentrations in the fourth downgradient well than in the third downgradient well.

Specific conductance. At the upgradient well, AB-139, the mean specific conductance was 493 μS/cm and the maximum was 1,020 μS/cm. Values were highest at the first downgradient well, AB-133 (mean, 1,838 μS/cm; maximum, 3,890 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 757 μS/cm and the maximum was 875 μS/cm. Thus, 150 ft downgradient from the highway, the mean value at the fourth downgradient well was 1 1/2 times the upgradient or background value.

Table 8. Water-quality data for multilevel wells at the Ashtabula County site, Ohio, January 1991 through August 1993
[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples; UG, upgradient; DG, downgradient]

Well Name	Position	Statistic	Property or constituent				
			Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)	Bromide, dissolved (mg/L)
AB-139	UG	Maximum	1,020	120	79	120	0.19
		Minimum	205	23	4	1	<0.01
		Mean	493	71	11	13	0.01
		Median	479	72	9	5	<0.01
		N	101	91	91	116	115
AB-133	1st DG	Maximum	3,890	190	760	1,400	0.31
		Minimum	778	33	130	120	<0.01
		Mean	1,838	82	312	487	0.09
		Median	1,910	73	310	490	0.09
		N	87	101	101	106	104
AB-135	2nd DG	Maximum	2,800	180	330	750	0.18
		Minimum	575	64	32	62	<0.01
		Mean	1,096	97	88	226	0.06
		Median	1,030	92	78	190	0.05
		N	114	123	123	131	131
AB-136	3rd DG	Maximum	1,620	88	220	360	0.13
		Minimum	989	48	130	170	<0.01
		Mean	1,353	69	187	295	0.07
		Median	1,380	70	190	300	0.06
		N	1,34	133	133	146	147
AB-137	4th DG	Maximum	875	110	53	280	0.20
		Minimum	606	60	34	20	<0.01
		Mean	757	85	43	107	0.04
		Median	776	86	43	105	0.04
		N	122	133	133	144	143

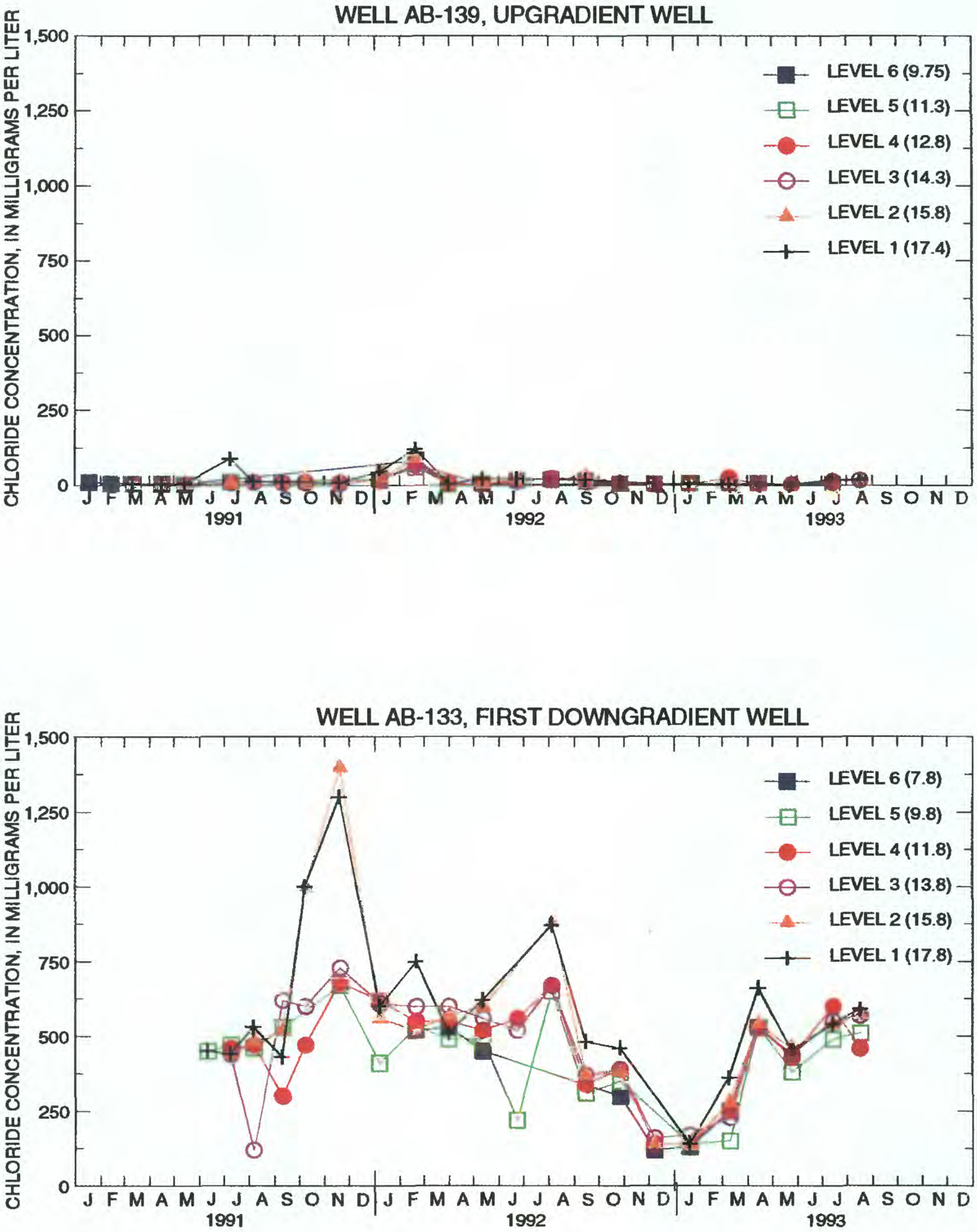
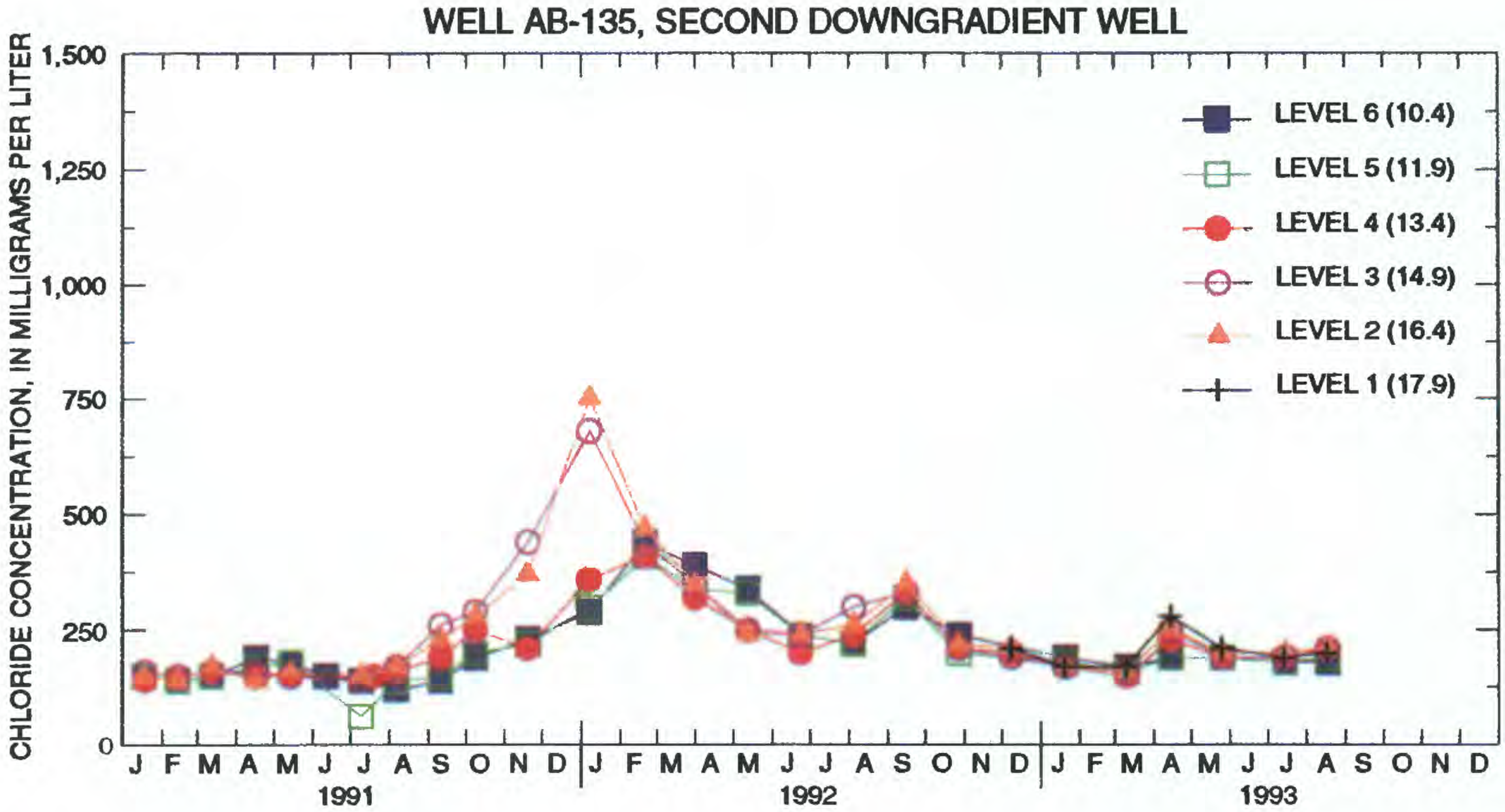


Figure 21. Dissolved chloride concentration, by level, for multilevel wells at the Ashtabula County study site, Ohio. (Number in parentheses is depth, in feet below land surface.)



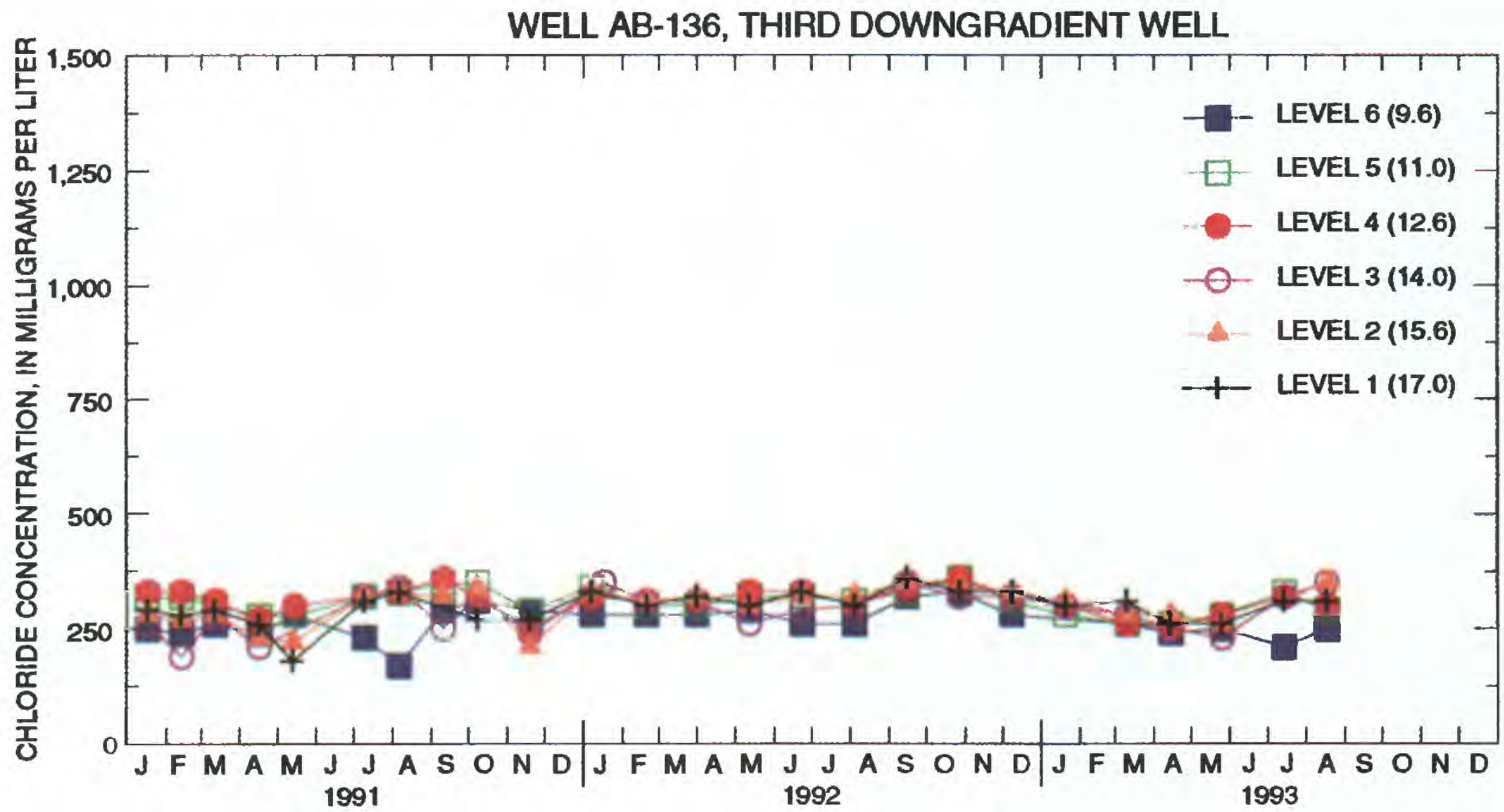


Figure 21. Dissolved chloride concentration, by level, for multilevel wells at the Ashtabula County study site, Ohio--Continued.

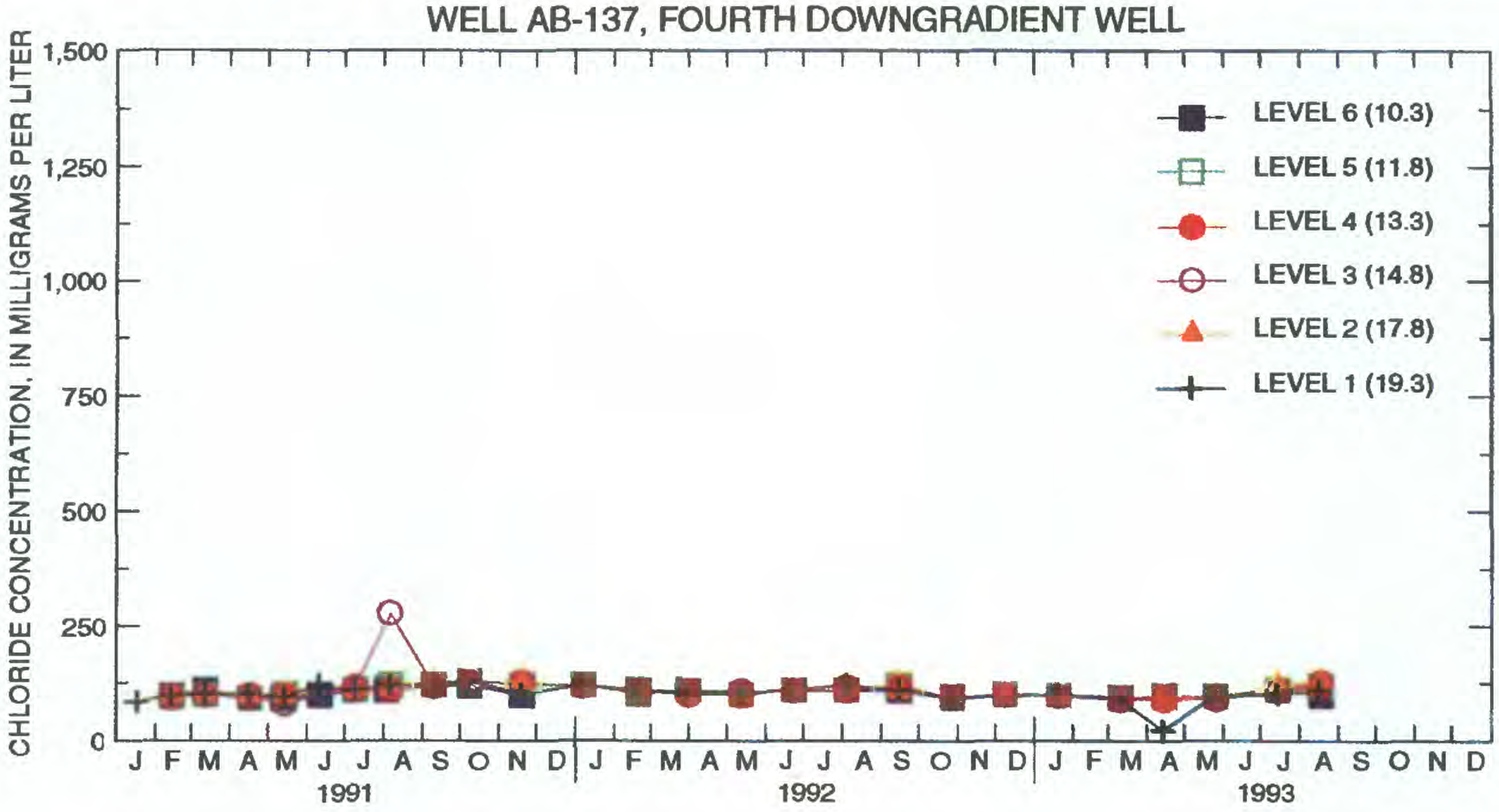


Figure 21. Dissolved chloride concentration, by level, for multilevel wells at the Ashtabula County study site, Ohio--Continued.

Champaign County Site

Site Characteristics

The Champaign County site (fig. 22) 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). It 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 towards the northwest about 0.1 mi north of the site.

The surficial material at the site is a dark silty loamy soil. 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 could be located in the area to help verify the elevation of the bedrock surface specifically at this site. However, based on seismic surveys done in the county by Feulner (1960), elevation of the bedrock surface is about 240 ft below land surface. The soil type is the Homer Silt loam upgradient and near the road downgradient, and the Lippincott Silty Clay

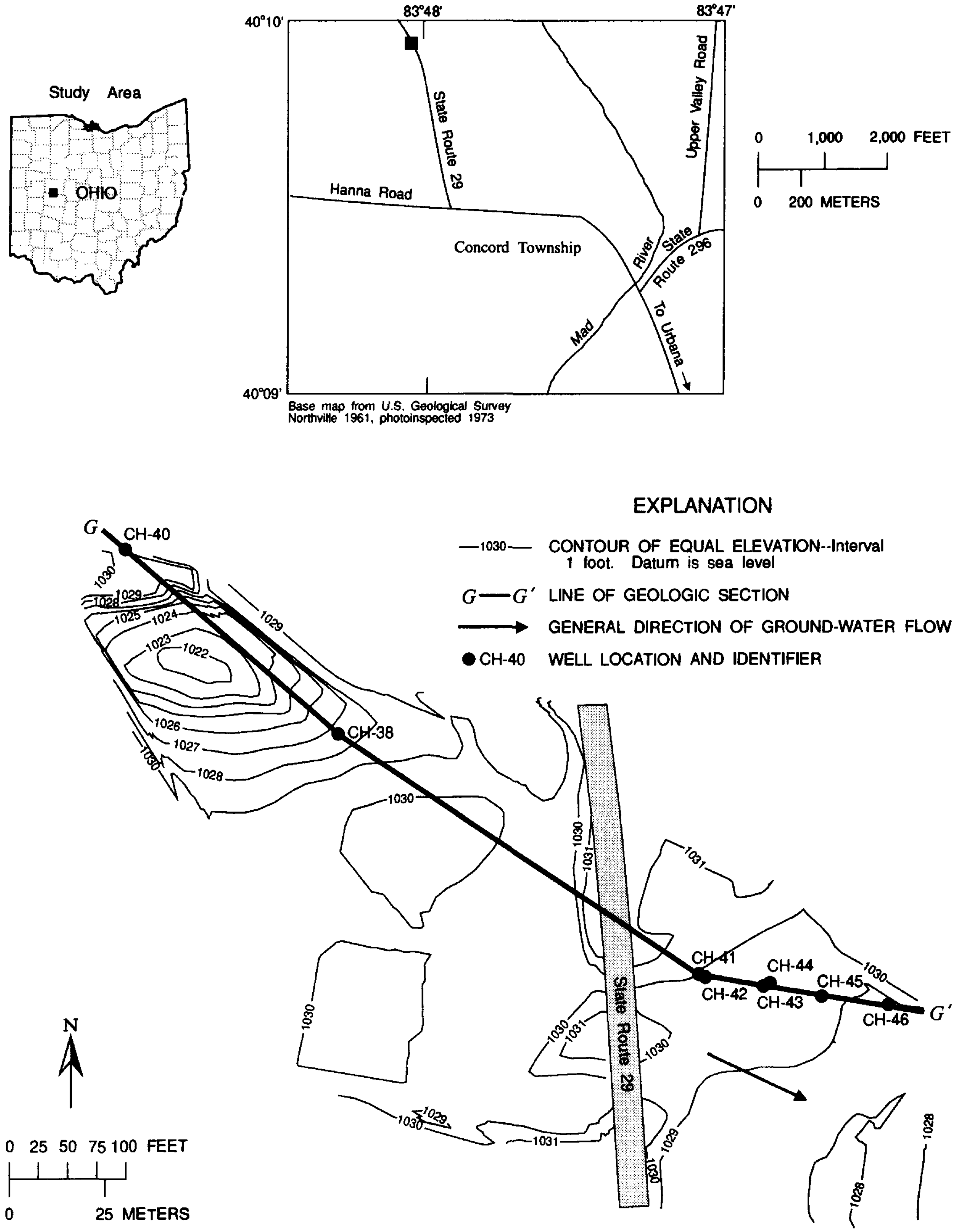


Figure 22. Topography, well locations, and ground-water flow direction at Champaign County study site.

loam farther downgradient (U.S. Department of Agriculture, 1971). Both are fairly poorly drained soils. Individual well logs were constructed for each of the wells. A geologic cross-section of the site was constructed on the basis of these logs (fig. 23).

The 12-winter (1981–93) average annual use of deicing-chemicals in Champaign County as a whole was 2,011 tons (table 3). The maximum for this 12-winter period was 2,858 tons in 1990–91, and the minimum for this period was 700 tons in 1982–83. The 3-winter (1990–93) average annual use of deicing-chemicals during the interim reporting period for this county as a whole was 2,186 tons. The maximum for this 3-winter period was 2,858 tons in 1990–91 and the minimum for this period was 1,723 tons in 1991–92. For all of Ohio, the 3-winter average annual use of deicing-chemicals was 8.0 ton/2-ln mi (16,000 lb/2-ln mi) (Ohio Department of Transportation, written commun., 1994). Data collected at this site indicate the 3-winter average annual use of deicing-chemicals was 2.54 ton/2-ln mi. (5,076 lb/2-ln mi.), which is 68 percent less than the State average. During the interim reporting period, a small amount of liquid calcium chloride ($CaCl_2$) also was applied to the highway in only one case in addition to sodium chloride and abrasives.

Climate

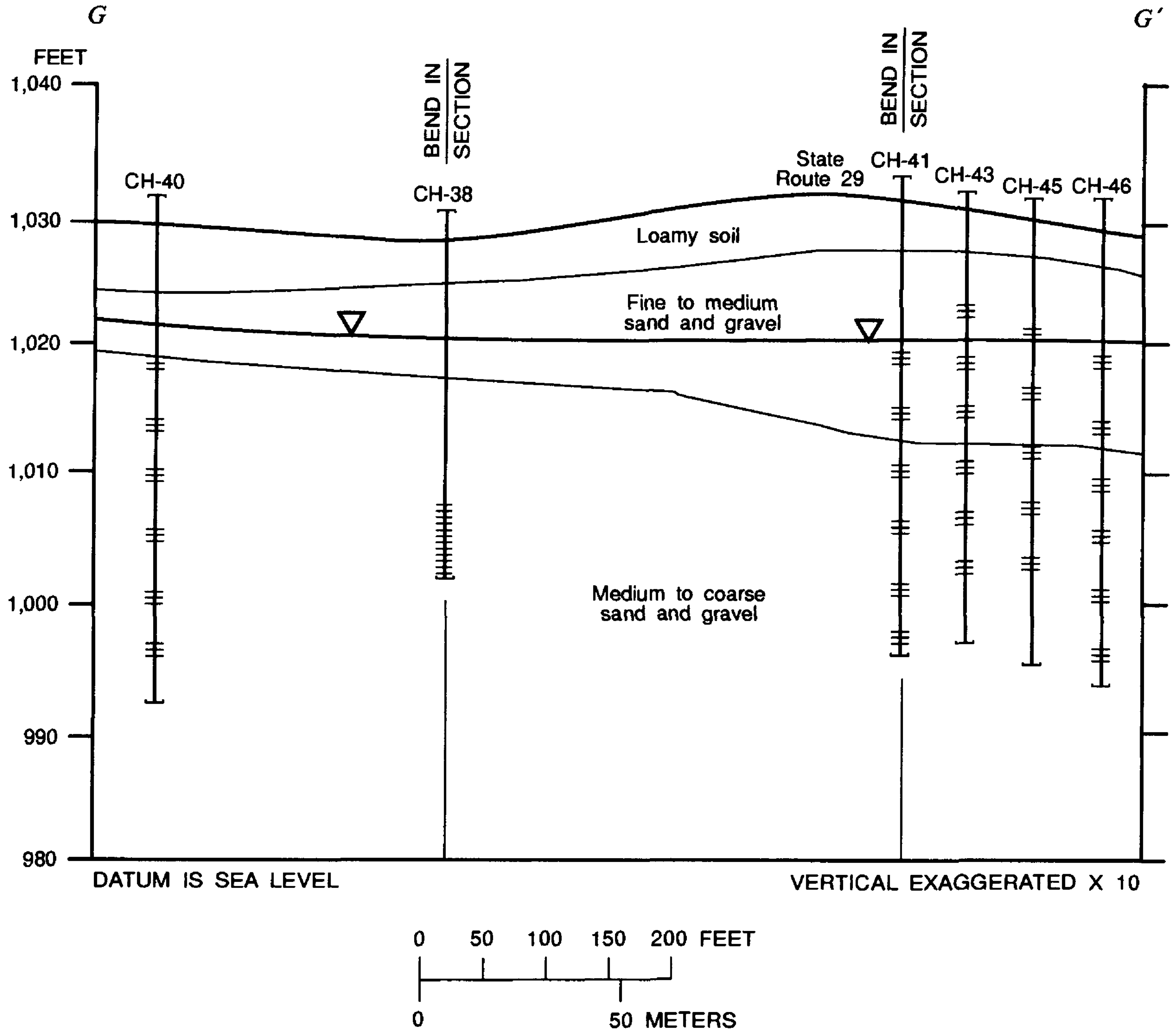
The average annual precipitation for the area is 37.3 in. The average annual temperature for the area is 9.9°C (49.9°F), with the monthly normal high of 29.2°C (84.5°F) in July and the monthly normal low of -9.1°C (15.7°F) in January (National Oceanic and Atmospheric Administration, 1982). During the interim reporting period, annual precipitation data collected from the site averaged 29.0 in. The average annual normal snowfall is 20–25 in. for nearby reporting areas (Miller and Weaver, 1971).

Hydrogeology

The ground-water level is 6–11 ft below land surface throughout the year at this site. During the interim reporting period, the direction of flow varied from approximately 52° to 90° to the alignment of the highway, as determined by the triangulation method using available wells; average water-table slope is about 0.001.

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 0.001 and an effective porosity of 35 percent, the ground-water velocity was computed to be 0.14 ft/d. At this site the ground-water level responds to precipitation within 1 day, owing to the porous aquifer materials at the surface.

The electrical conductivity of the subsurface materials was measured at the Champaign County site on two occasions by use of the Geonics EM-34-3 at the 10-m spacing. The composition of the aquifer materials was inferred from these measurements and well logs from the site. Surveys were completed in March 1992 and April 1993. Measurements upgradient from the highway ranged from 7 to 9 mS/m uniformly, whereas downgradient measurements ranged from 8 to 12 mS/m, indicating fine to coarse sands and gravel throughout the site. Variations in electrical conductivity measurements between EM surveys define changes in the ground conductivity, that would be attributable only to changes in water quality. Measurements at this site did not show much variability. Only a slight increase could be seen in the downgradient measurements, and they could not be identified as a distinct plume. Application of deicing chemicals was rare at this site because air temperature was rarely below freezing and snowstorms were infrequent.



EXPLANATION

CH-38 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

WELL SCREEN

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

Figure 23. Geologic section *G-G′*, Champaign County study site, Ohio. (Section trace shown on fig. 22.)

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 plots of these characteristics can be used to help compare events that resulted in increased specific conductance with ambient site conditions and deicer applications. The movement of chloride and other deicing-related constituents from the highway with time are indicated by boxplots of laboratory-determined data (fig. 25).

Field-monitored characteristics

Specific conductance. Specific conductance of ground water varied only slightly during the interim reporting period. A maximum of 918 µS/cm was recorded in April 1993, and a minimum of 725 µS/cm was recorded in July 1991 (range, 193 µS/cm). Annual extremes (based on water year) ranged from 852 µS/cm in March 1991 to 725 µS/cm in July 1991 (data incomplete), from 846 µS/cm in August 1992 to 759 µS/cm in March 1992, and from 918 µS/cm in April 1993 to 780 µS/cm in October 1992. For comparison, the mean specific conductance at the upgradient well for the interim reporting period was 699 µS/cm. The specific conductance of the ground water at this site varied little during the interim reporting period, as is evident from the absence of large spikes in the record. This constancy may be due, in part, to the fact that relatively small amounts of deicing chemicals were applied at this site. Background specific conductance may be higher than average at this site because the area is part of the Mad River outwash plain, a regional discharge area. As it discharges, ground water may be forced up through the underlying limestone formation and may become more highly mineralized. The ground water in general is in a limestone-dominated environment, one that may contribute to the somewhat high but steady specific conductance.

Air and soil temperature. During the interim reporting period the air temperature at this site varied from 37.0°C in August 1991 to a minimum of -22.2°C in February 1993. The annual maximum for 1991 was 37.0°C in August, but the minimum for 1991 could not be accurately determined because measurements were not made until February 1991. Annual extremes (based on water year) for the remainder of the interim reporting period ranged from a maximum of 30.7°C in July 1992 to a minimum of -14.8°C in December 1991 and from a maximum of 35.0°C in August 1993 to a minimum of -22.2°C in February 1993.

During the interim reporting period the soil temperature ranged from a maximum of 30.5°C in August 1991 to a minimum of 0.3°C in December 1992 and January through March 1993. The annual maximum for 1991 was 30.5°C in August, but the minimum for 1991 could not be accurately determined because measurements were not made until February 1991. Annual extremes (based on water year) for the remainder of the interim reporting period ranged from a maximum of 24.3°C in July 1992 to a minimum of 0.7°C in January and February 1992 and from a maximum of 24.8°C in August 1993 to a minimum of 0.3°C in December 1992 and January through March 1993. No soil temperature of 0°C or less was recorded on any day during that period; thus, frozen soil would not have inhibited infiltration of runoff water into the aquifer.

Laboratory-determined characteristics

At the Champaign County site, deicing chemicals were applied in small amounts. Temperatures were often above freezing throughout the winters and, in some cases, sampling was discontinued temporarily when little or no deicing chemicals were applied. Cold temperatures

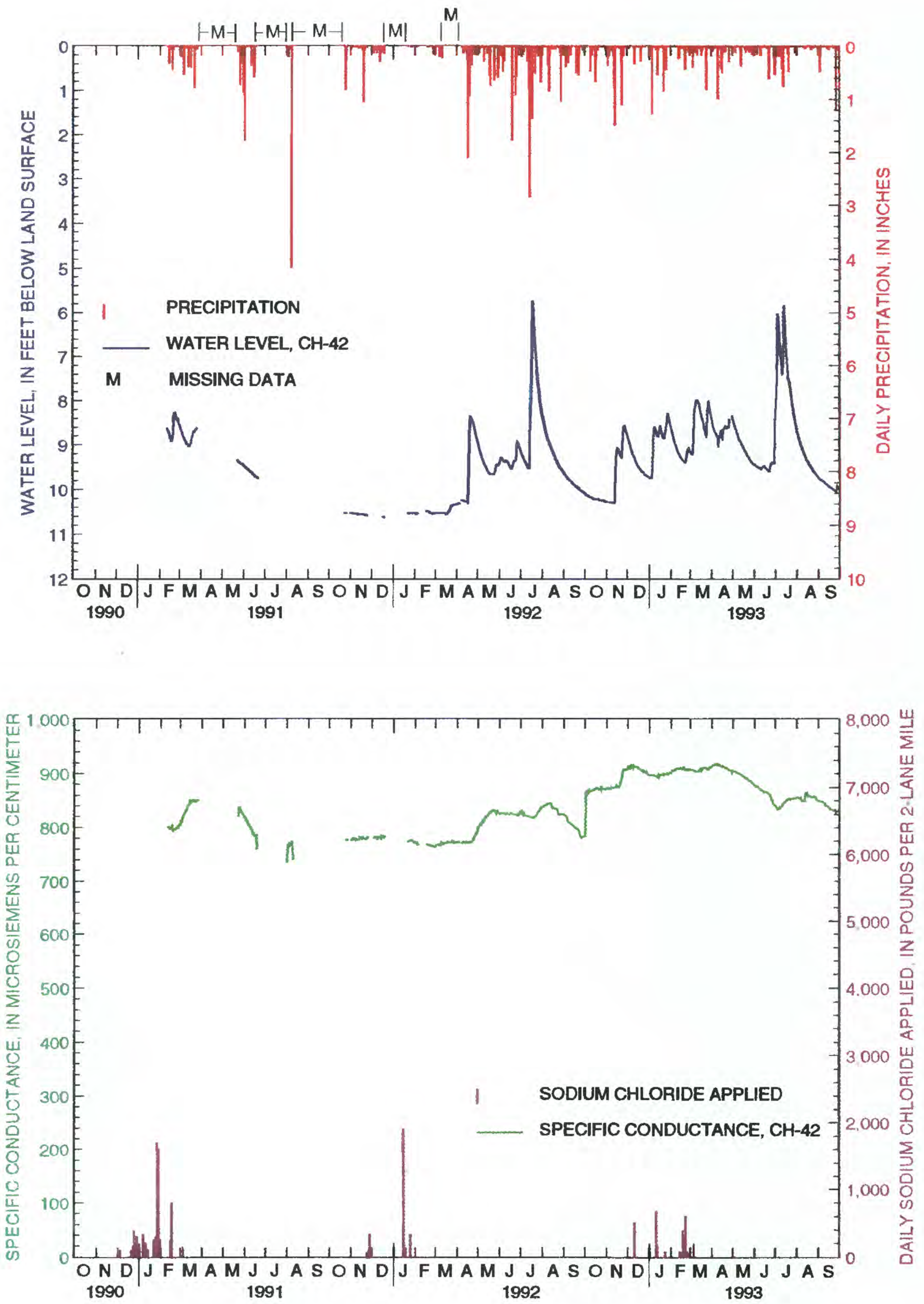


Figure 24. Ground-water levels, specific conductance of ground water, precipitation, and sodium chloride applied at the Champaign County study site, Ohio.

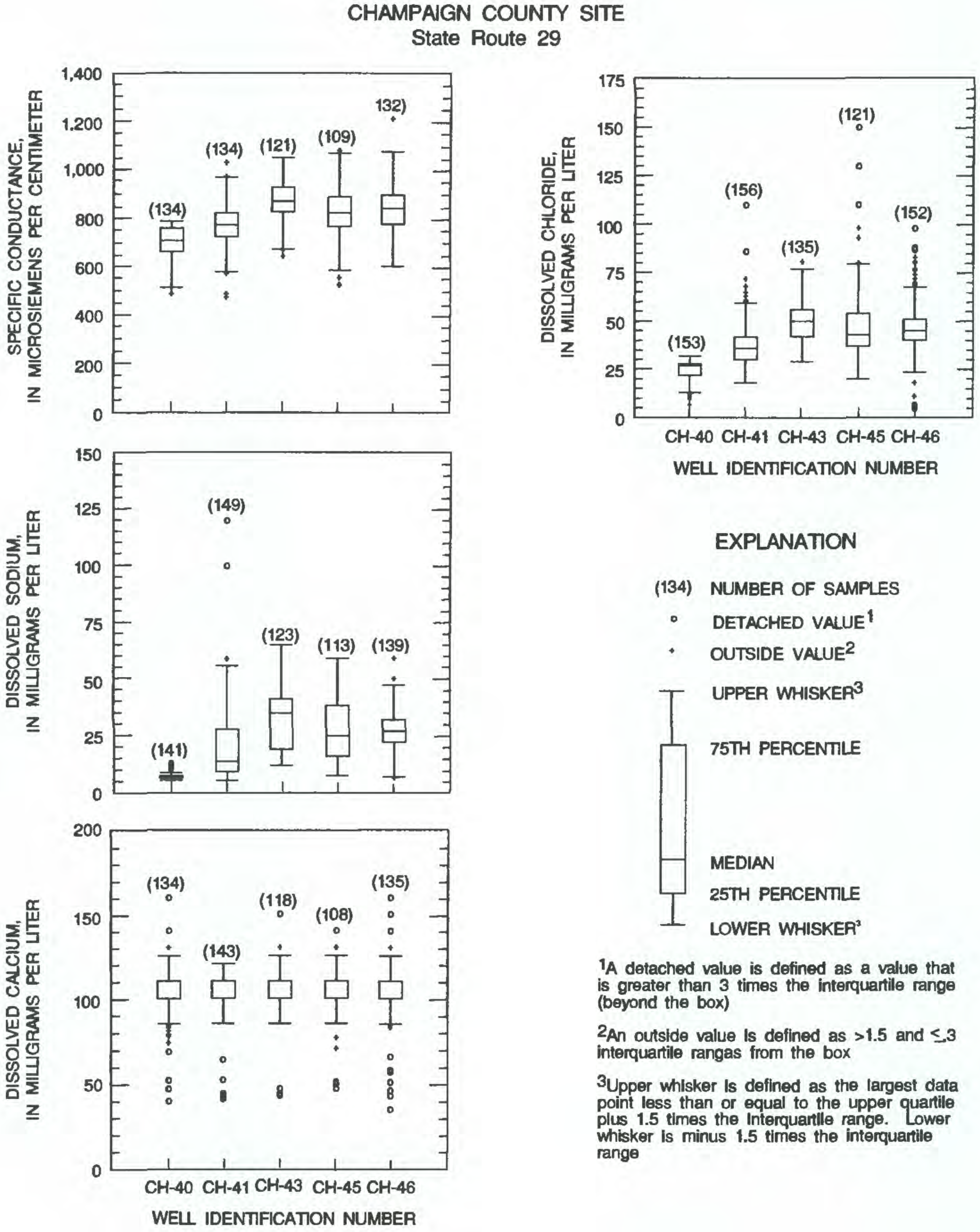


Figure 25. The distribution of specific conductance and concentrations of dissolved sodium, calcium, and chloride in ground water sampled at the Champaign County study site, Ohio, January 1991-September 1993. (Plots are shown in downgradient order from left to right. Far left plot is upgradient from highway; others are downgradient.)

Table 9. Water-quality data for multilevel wells at the Champaign County site, Ohio, January 1991 through August 1993

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

Well Name	Position	Statistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)	Bromide, dissolved (mg/L)
CH-40	UG	Maximum	790	160	13	32	0.08
		Minimum	490	40	6	7	<0.01
		Mean	699	105	7	25	0.03
		Median	709	110	7	27	0.03
		N	134	134	141	153	151
CH-41	1st DG	Maximum	1,030	120	120	110	0.06
		Minimum	474	41	6	18	<0.01
		Mean	773	103	20	38	0.03
		Median	772	110	14	36	0.03
		N	134	143	149	156	155
CH-43	2nd DG	Maximum	1,050	150	65	81	0.0.7
		Minimum	644	43	12	29	<0.01
		Mean	876	108	32	50	0.03
		Median	870	110	35	50	0.03
		N	121	118	123	135	134
CH-45	3rd DG	Maximum	1,080	140	59	150	0.05
		Minimum	524	47	8	20	<0.01
		Mean	825	108	27	48	0.03
		Median	823	110	25	43	0.03
		N	109	108	113	121	120
CH-46	4th DG	Maximum	1,210	160	59	98	0.09
		Minimum	602	35	7	5	<0.01
		Mean	835	107	27	48	0.03
		Median	841	110	27	45	0.03
		N	132	135	139	152	149

sometimes created icy conditions, but large snowfalls were uncommon. Summary statistics of the water-quality data collected in upgradient and downgradient wells are listed in table 9. 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 are shown in figure 25. Data shown are for the sampling period January 1991 through September 1993. Patterns that emerge from those data and require further discussion are noted below.

Chloride concentration. At the upgradient well, CH-40, the mean concentration was of chloride 25 mg/L and the maximum was 32 mg/L. Mean concentrations were 1.5 to 2 times greater at the downgradient wells (38–50 mg/L). Maximum concentrations at the four downgradient wells ranged from 81–150 mg/L. Thus, 150 ft downgradient from the highway, the mean concentration at the fourth downgradient well (48 mg/L) was about twice the upgradient or background concentration.

Soil samples were collected at this site in August 1993. The extract from the soil-sample preparation method was analyzed at the NWQL for dissolved chloride concentration. The chloride concentration of the samples collected within 15 ft of the highway was 5–37 mg/L and decreased to 7 mg/L by 80 ft downgradient from the highway.

Sodium concentration. At the upgradient well, CH-40, the mean concentration of sodium was 7 mg/L and the maximum was 13 mg/L. 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 both 27 mg/L and the maximum concentrations were 59 mg/L. Thus, 150 ft downgradient from the highway, the mean concentration at the fourth downgradient well was about four times the upgradient or background concentration.

Specific conductance. At the upgradient well, CH-40, the mean specific conductance was 699 μS/cm and the maximum was 790 μS/cm. Of the downgradient wells, mean values were lowest at the first downgradient well (773 μS/cm), increased slightly at the second downgradient well (876 μS/cm), and were slightly lower than the second downgradient well at the third (825 μS/cm) and the fourth (835 μS/cm) downgradient wells. However, 150 ft downgradient from the highway, the mean specific conductance at the fourth downgradient well was about 1.2 times the upgradient or background concentration.

Clark County Site

Site Characteristics

The Clark County site (fig. 26) 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 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 minimal, 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.

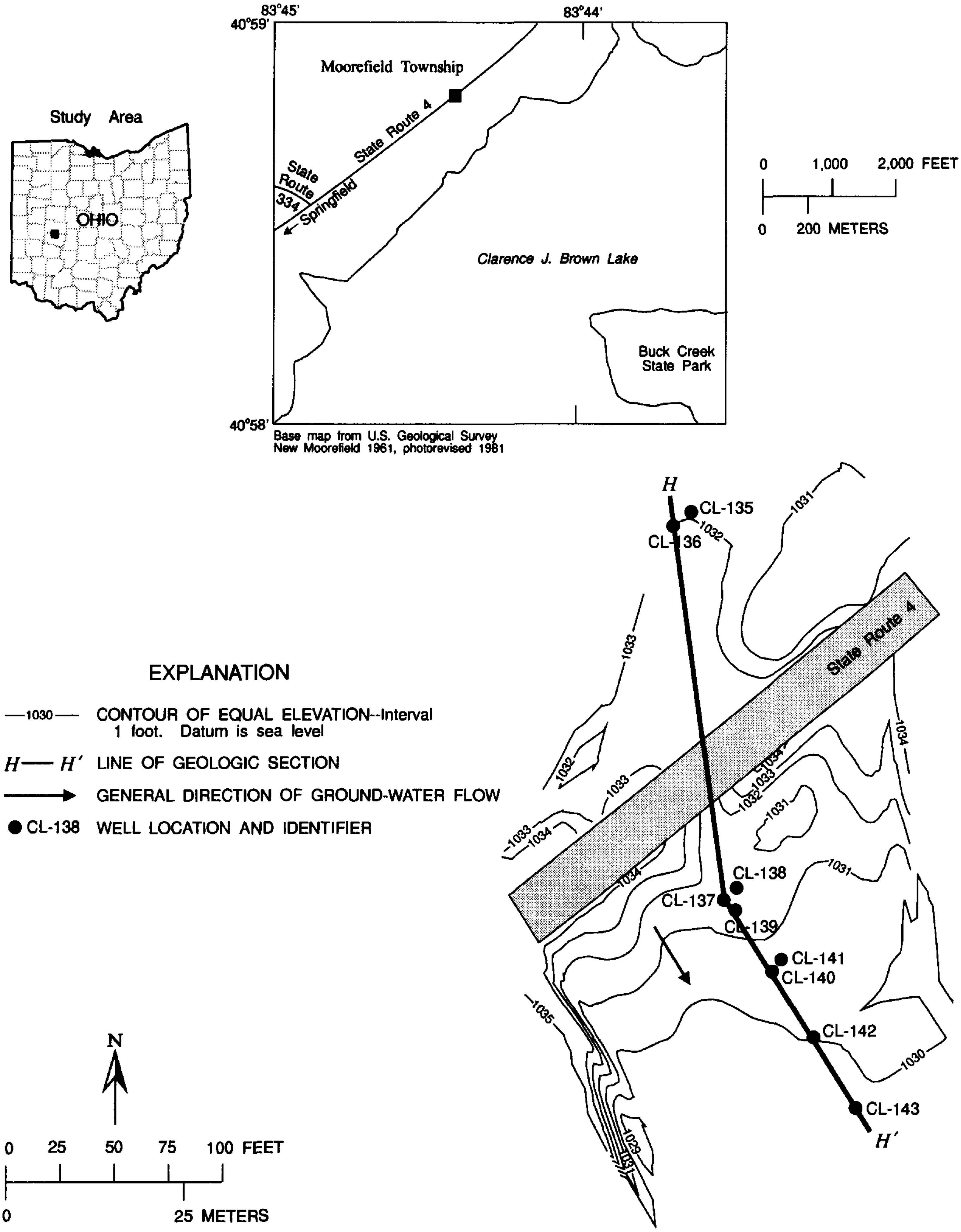


Figure 26. Topography, well locations, and ground-water flow direction at Clark County study site.

The surficial material at this site is a brown silty loam about 3 ft deep. This is underlain by 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. The soil type is the poorly drained Sloan silt loam upgradient and the well-drained Fox silt loam downgradient (U.S. Department of Agriculture, 1958). Individual well logs were constructed for each of the wells. A geologic cross-section of the site was constructed on the basis of these logs (fig. 27).

The 12-winter (1981–93) average annual use of deicing-chemicals in Clark County as a whole was 3,070 tons (table 3). The maximum for this 12-winter period was 4,161 tons in 1988–89, and the minimum for this period was 1,275 tons in 1982–83. The 3-winter (1990–93) average annual use of deicing-chemicals during the interim reporting period for this county as a whole was 3,410 tons. The maximum for this 3-winter period was 4,087 tons in 1990–91, and the minimum for this period was 2,672 tons in 1991–92. For all of Ohio, the 3-winter average annual use of deicing-chemicals was 8.0 ton/2-ln mi (16,000 lb/2-ln mi) (Ohio Department of Transportation, written commun., 1994). Data collected at this site indicate the 3-winter average annual use of deicing-chemicals was 3.05 ton/2-ln mi. (6,105 lb/2-ln mi.), which is 62 percent less than the State average. During the interim reporting period at this site, no calcium chloride ($CaCl_2$) was applied to the highway.

Climate

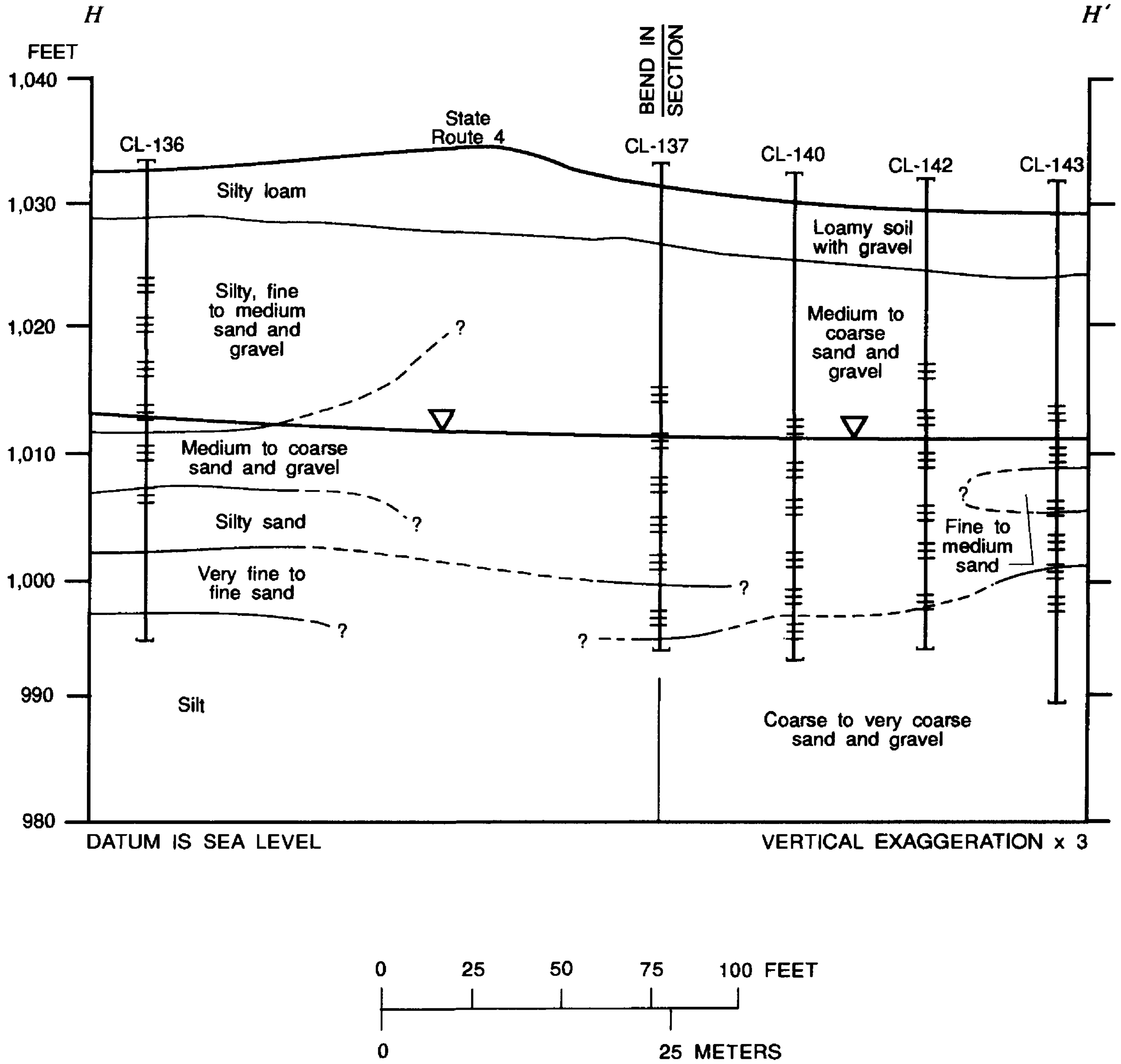
The average annual precipitation for the area is 38.7 in. The average annual temperature for the area is 9.9°C (49.9°F), with the monthly normal high of 29.2°C (84.5°F) in July and the monthly normal low of -9.1°C (15.7°F) in January (National Oceanic and Atmospheric Administration, 1982). During the interim reporting period, precipitation data collected at the site were incomplete and therefore insufficient for computing an annual average. The average annual snowfall is 25–30 in. for nearby reporting areas (Miller and Weaver, 1971).

Hydrogeology

The ground-water level is 19–23 ft below land surface throughout the year at this site. During the interim reporting period, the direction of flow was relatively constant, varying from 82° to 88° to the alignment of the highway, as determined by the triangulation method using available wells; average water-table slope is about 0.011. At this site the ground-water level responds to precipitation within 1 day, owing to the porous aquifer materials at the surface.

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 0.011 and an effective porosity of 35 percent, the ground-water velocity was computed to be 1.13 ft/d.

The electrical conductivity of the subsurface materials was measured at the Clark County site on two occasions by use of the Geonics EM-34-3 at the 10-m spacing. The composition of the aquifer materials was inferred from these measurements and well logs from the site. Surveys were completed at this site in March 1992 and April 1993. Measurements on both sides of the highway ranged from 4 to 12 mS/m, but were most often in the 8–10 mS/m range, indicating fine to coarse sands and gravel throughout the site. Upgradient from the highway, measurements were often slightly higher, most likely from the presence of some silt and silty sand that was not evident downgradient from the highway. Variations in electrical conductivity measurements between EM surveys define changes in the ground conductivity that would be attributable only to changes in water quality. Measurements at this site did not show much variability. This constancy of water quality was later confirmed by ground-water samples collected on a regular basis. Application of deicing chemicals was very rare at this site, owing to above-freezing temperatures and only occasional snowstorms.



EXPLANATION

CL-136 WELL LOCATION AND IDENTIFIER--Well logs on file with the U.D. 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

MEAN WATER LEVEL

Figure 27. Geologic section *H-H'*, Clark County study site, Ohio. (Section trace shown on fig. 26.)

Effects of highway deicing chemicals on water quality

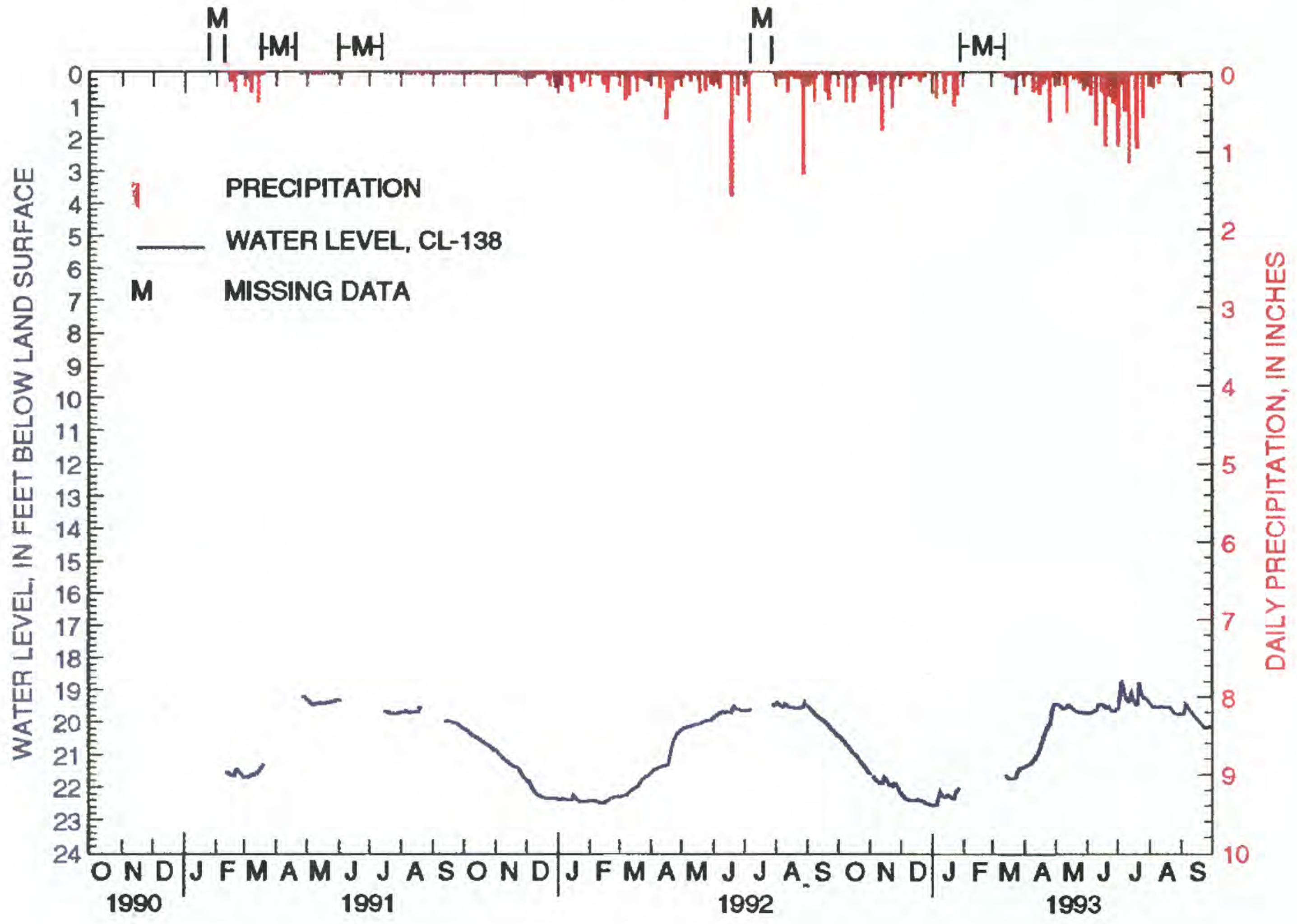
Field-monitored characteristics (rainfall, specific conductance, and ground-water levels recorded from dedicated instrumentation at a well near the first downgradient sampling well) and the amount of sodium chloride applied to the highway are shown in figure 28. The plots of these characteristics can be used to help compare the events that resulted in increased specific conductance with ambient site conditions and deicer applications. The movement of chloride and other deicing-related constituents from the highway with time are indicated by boxplots of laboratory-determined data (fig. 29).

Field-monitored characteristics

Specific conductance. Specific conductance of ground water varied only slightly during the interim reporting period. A maximum of 922 μS/cm was recorded in March 1993, and a minimum of 783 μS/cm was recorded in April 1992 (a range of 139 μS/cm, the smallest range of all eight sites). Annual extremes (based on water year) ranged from 879 μS/cm in March 1991 to 831 μS/cm in February 1991 (data incomplete), from 899 μS/cm in May 1992 to 835 μS/cm in September 1992, and from 922 μS/cm in March 1993 to 795 μS/cm in September 1993. For comparison, the mean specific conductance of the upgradient well for the interim reporting period was 642 μS/cm. 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.

Air and soil temperature. During the interim reporting period the air temperature at this site ranged from 37.5°C in July 1991 to a minimum of -21.2°C in January 1992. The annual maximum for 1991 was 37.5°C in July, but the minimum for 1991 could not be accurately determined because measurements were not made until February 1991. Annual extremes (based on water year) for the remainder of the interim reporting period ranged from a maximum of 33.3°C in August 1992 to a minimum of -21.2°C in January 1992 and from a maximum of 35.0°C in August 1993 to a minimum of -14.8°C in March 1993.

During the interim reporting period soil temperature ranged from a maximum of 39.5°C in July and August 1991 to a minimum of -2.7°C in December 1992. The annual maximum for 1991 was 39.5°C in July and August, but the minimum for 1991 could not be accurately determined because measurements were not made until February 1991. Annual extremes (based on water year) for the remainder of the interim reporting period ranged from a maximum of 29.9°C in July 1992 to a minimum of 9.4°C in September 1992 and from a maximum of 26.9°C in June 1993 to a minimum of -2.7°C in December 1992. No soil temperature of 0°C or less was recorded on any day during the winters of 1990–91 or 1991–92; however, soil temperature did reach the freezing point at several times during the winter of 1992–93. In December 1992, the soil temperature was below freezing for a 7-day period and a 6-day period. In January 1993, the temperature reached freezing for a 9-day period. In March 1993, the temperature reached freezing for a 4-day and an additional 3-day period. Data were not recorded during February 1993, but the period before and after February contained several freezing periods; therefore several opportunities existed for the infiltration of highway runoff to be occasionally delayed or rerouted because of frozen soil during this winter period.



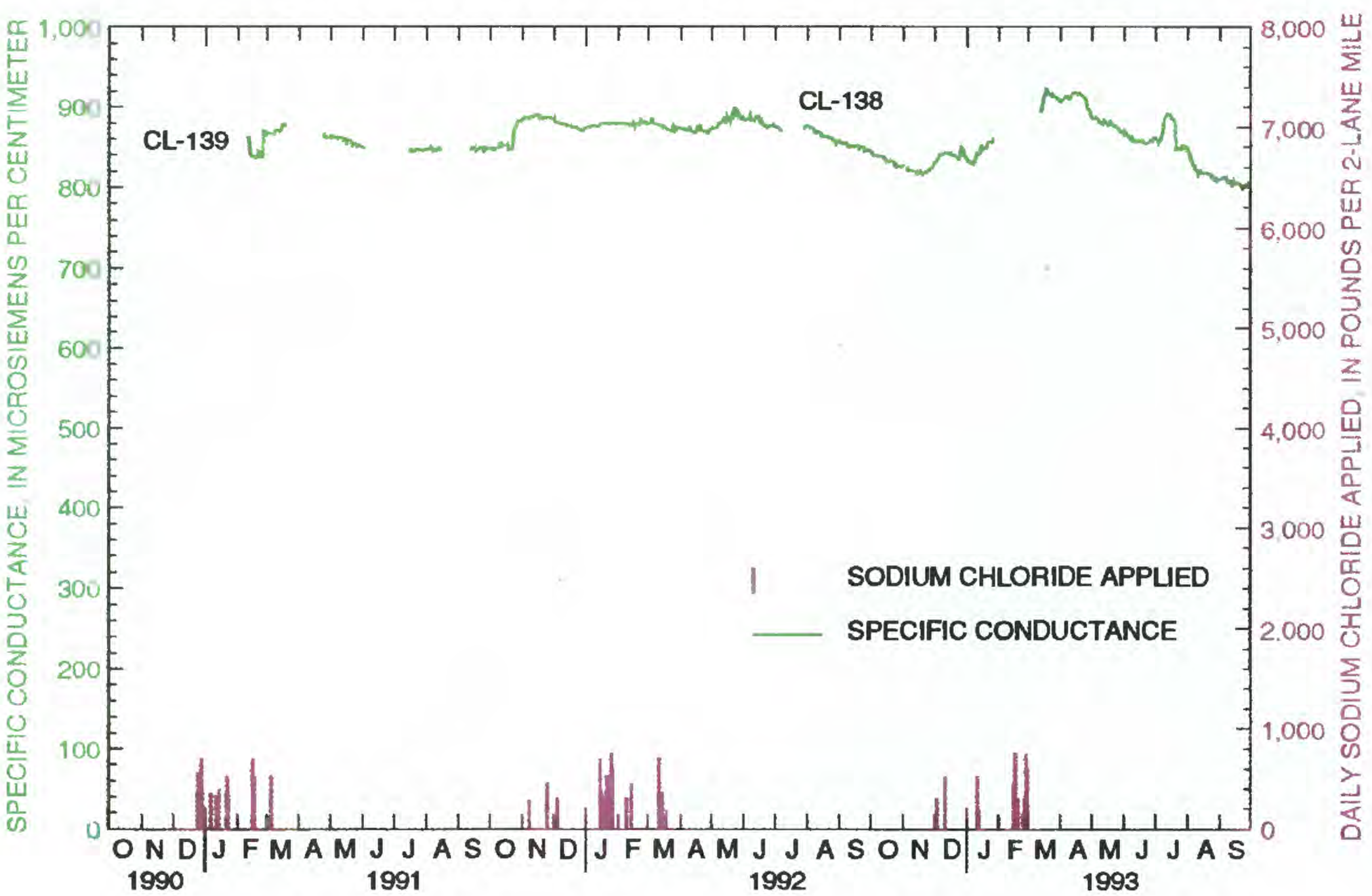


Figure 28. Ground-water levels, specific conductance of ground water, precipitation, and sodium chloride applied at the Clark County study site, Ohio.

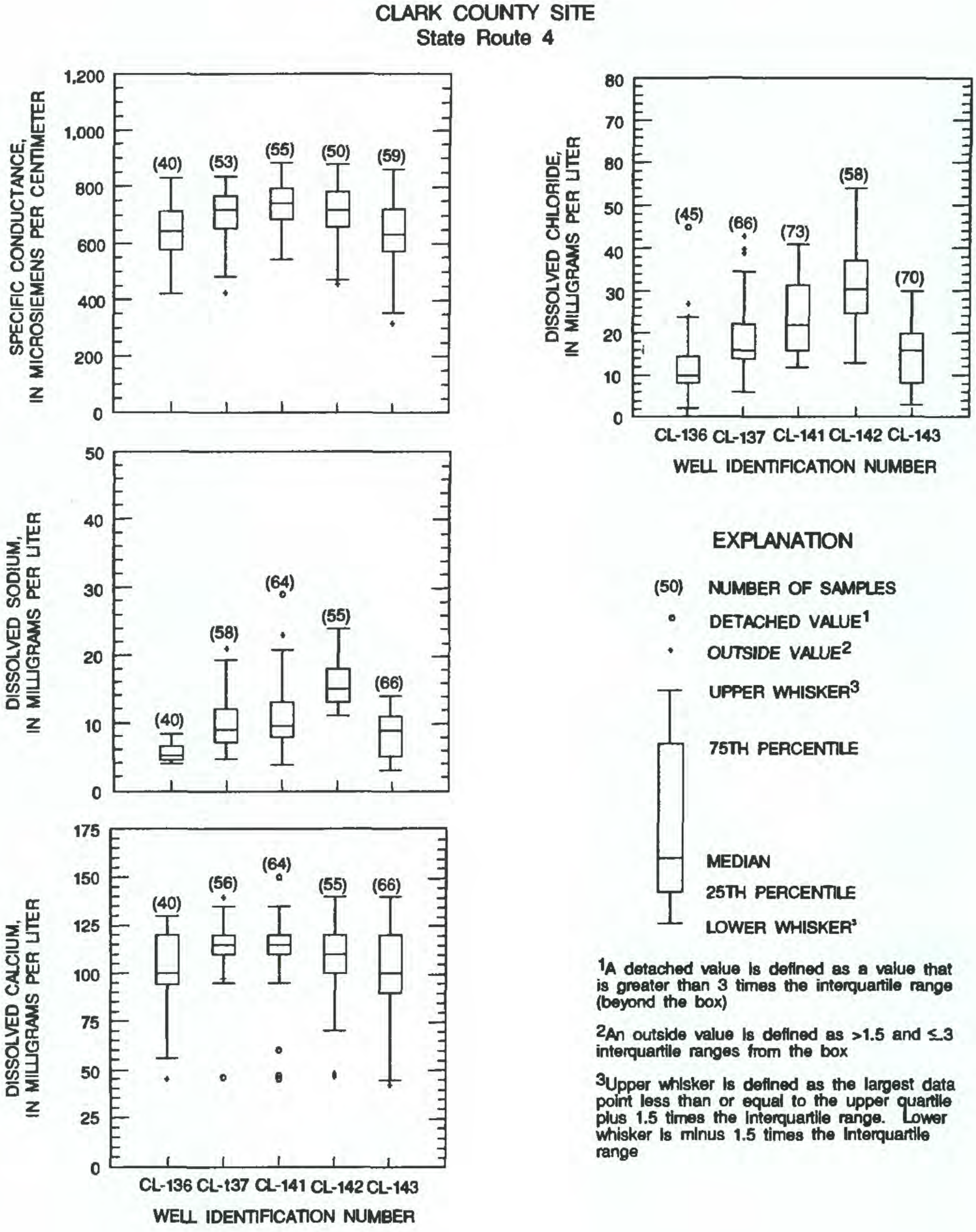


Figure 29. The distribution of specific conductance and concentrations of dissolved sodium, calcium, and chloride in ground water sampled at the Clark County study site, Ohio, January 1991-September 1993. (Plots are shown in downgradient order from left to right. Far left plot is upgradient from highway; others are downgradient.)

Laboratory-determined characteristics

At the Clark County site a significant amount of deicing-chemicals was applied to SR 4 only rarely. 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 in upgradient and downgradient wells are shown in table 10. 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 are shown in figure 29. Data shown are for the sampling period January 1991 through September 1993. Patterns that emerge from those data and require further discussion are noted below.

Chloride concentration. At the upgradient well, CL-136, the mean concentration was of chloride 12 mg/L and the maximum was 45 mg/L. Concentrations were slightly higher at all four downgradient wells than at the upgradient well (mean, 15–31 mg/L; maximum, 30–54 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 15 mg/L; maximum 30 mg/L). Thus, 150 ft downgradient from the highway, the mean concentration was about the same as the upgradient or background concentration.

Soil samples were collected at this site in August 1993. The extract from the soil sample preparation method was analyzed at the NWQL for dissolved chloride concentration. The chloride concentration of the samples collected within 10 ft of the highway was 15–18 mg/L and decreased to 4 mg/L by 80 ft downgradient from the highway.

Sodium concentration. At the upgradient well, CL-136, the mean concentration of sodium was 6 mg/L, and the maximum was 8mg/L. Concentrations were slightly higher at all the downgradient wells (mean, 8–16 mg/L; maximum, 14–29 mg/L). Concentrations remained fairly constant downgradient along the flowpath to the third downgradient well. Median 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 14 mg/L). Thus, 150 ft downgradient from the highway, the mean concentration at the fourth downgradient well was about the same as the upgradient or background concentration.

Specific conductance. At the upgradient well, CL-136, the mean specific conductance was 642 μS/cm, and the maximum was 832 μS/cm. Values were slightly increasing, but generally constant, throughout the four downgradient wells (mean, 637–738 μS/cm; maximum 4836–885 μS/cm). Thus, 150 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 significant change in the specific conductance.

Table 10. Water-quality data for multilevel wells at the Clark County site, Ohio, January 1991 through August 1993
[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples; UG, upgradient; DG, downgradient.]

Well Name	Position	Statistic	Property or constituent				
			Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)	Bromide, dissolved (mg/L)
CL-136	UG	Maximum	832	130	8	45	0.06
		Minimum	422	45	4	2	<0.01
		Mean	642	104	6	12	0.03
		Median	644	100	5	10	0.03
		N	40	40	40	45	45
CL-137	1st DG	Maximum	836	140	21	43	0.05
		Minimum	426	46	5	6	0.01
		Mean	700	114	10	18	0.03
		Median	720	115	9	16	0.03
		N	53	56	56	66	66
CL-141	2nd DG	Maximum	885	150	29	41	0.05
		Minimum	545	45	4	12	<0.01
		Mean	738	113	11	24	0.03
		Median	742	115	10	22	0.03
		N	55	64	64	73	73
CL-142	3rd DG	Maximum	880	140	24	54	0.06
		Minimum	457	46	11	13	0.02
		Mean	713	107	16	31	0.03
		Median	718	110	15	30	0.03
		N	50	55	55	58	58
CL-143	4th DG	Maximum	862	140	14	30	0.05
		Minimum	317	42	3	3	0.01
		Mean	637	101	8	15	0.03
		Median	633	100	9	16	0.03
		N	59	66	66	70	71

Lucas County Site

Site Characteristics

The Lucas County site (fig. 30) 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 minimal, 0.5 ft over 450 ft or 0.001. Highway runoff infiltrates the aquifer quickly, usually along the road edges, due to the porous sandy soils and the flat terrain at the site. The site is owned and maintained by the Toledo Express Airport. Both sides of the highway are mowed fields. The downgradient side has restricted access because it is within the outer boundaries of the runway area.

SR 2 is a wide four-lane undivided highway with shallow open-ditch drainage and no center median. Two hundred 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 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 occurs at about 70 ft below land surface. 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). Both soils are poorly drained. Individual well logs were constructed for each of the wells. A geologic cross-section of the site was constructed on the basis of these logs (fig. 31).

The 12-winter (1981–93) average annual use of deicing-chemicals in Lucas County as a whole was 5,277 tons (table 3). The maximum for this 12-winter period was 7,611 tons in 1983–84, and the minimum for this period was 2,056 tons in 1982–83. The 3-winter (1990–93) average annual use of deicing-chemicals during the interim reporting period for this county as a whole was 4,568 tons. The maximum for this 3-winter period was 4,892 tons in 1990–91, and the minimum for this period was 4,310 tons in 1991–92. For all of Ohio, the 3-winter average annual use of deicing-chemicals was 8.0 ton/2-ln mi (16,000 lb/2-ln mi) (Ohio Department of Transportation, written commun., 1994). Data collected at this site indicate the 3-winter average annual use of deicing-chemicals was 8.44 ton/2-ln mi (16,883 lb/2-ln mi.), which is 6 percent greater than the State average. During the interim reporting period, a small amount of liquid calcium chloride ($CaCl_2$) also was applied to the highway in about 40 percent of the cases, in addition to sodium chloride and abrasives.

Climate

The average annual precipitation for the area is 31.8 in. The average annual temperature for the area is 9.2°C (48.6°F), with the monthly normal high of 28.6°C (83.4°F) in July and the monthly normal low of -9.2°C (15.5°F) in January (National Oceanic and Atmospheric Administration, 1982). During the interim reporting period, annual precipitation based on data collected at the site averaged 28.2 in. The average annual snowfall is 30–40 in. for nearby reporting areas (Miller and Weaver, 1971).

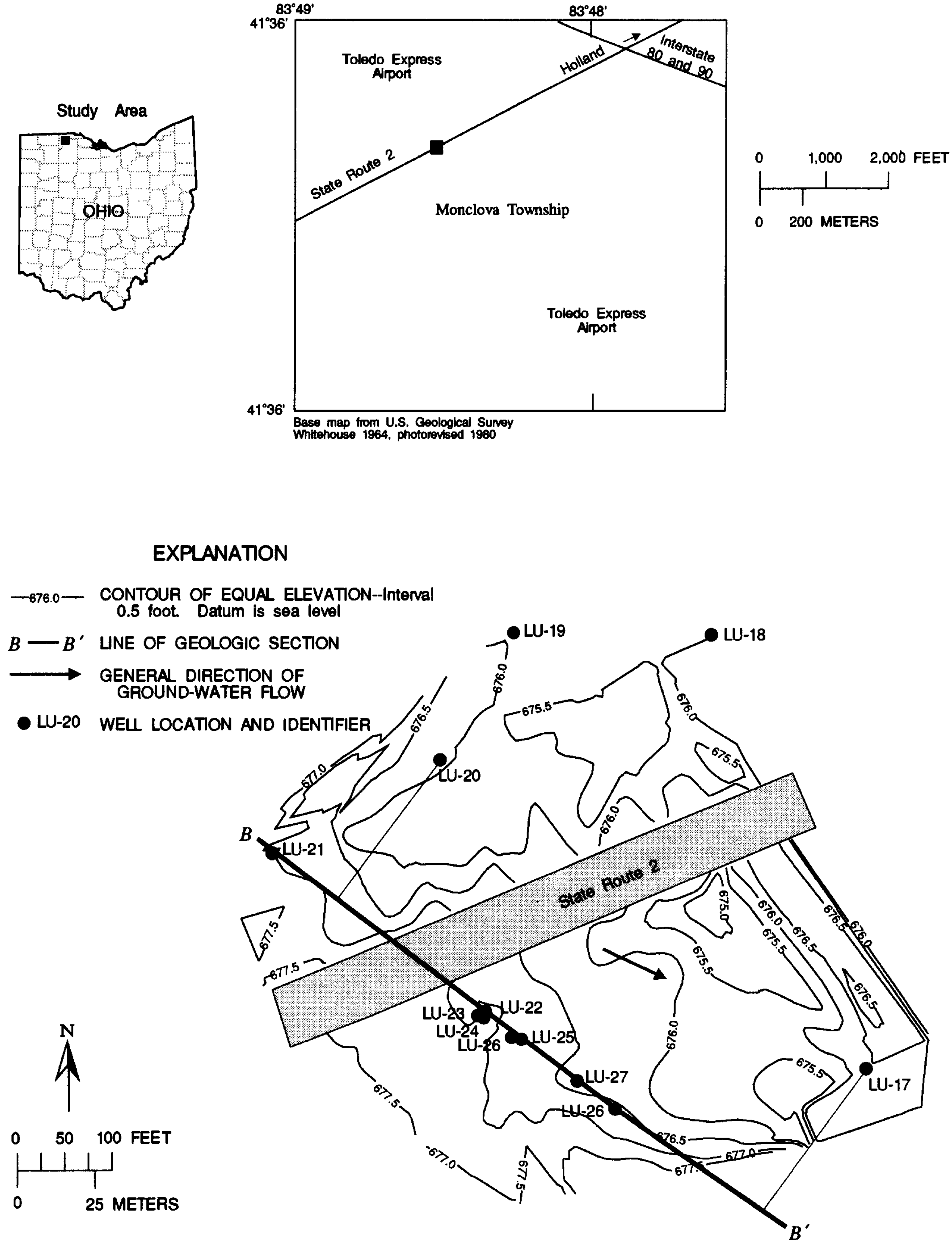


Figure 30. Topography, well locations, and ground-water flow direction at Lucas County study site.

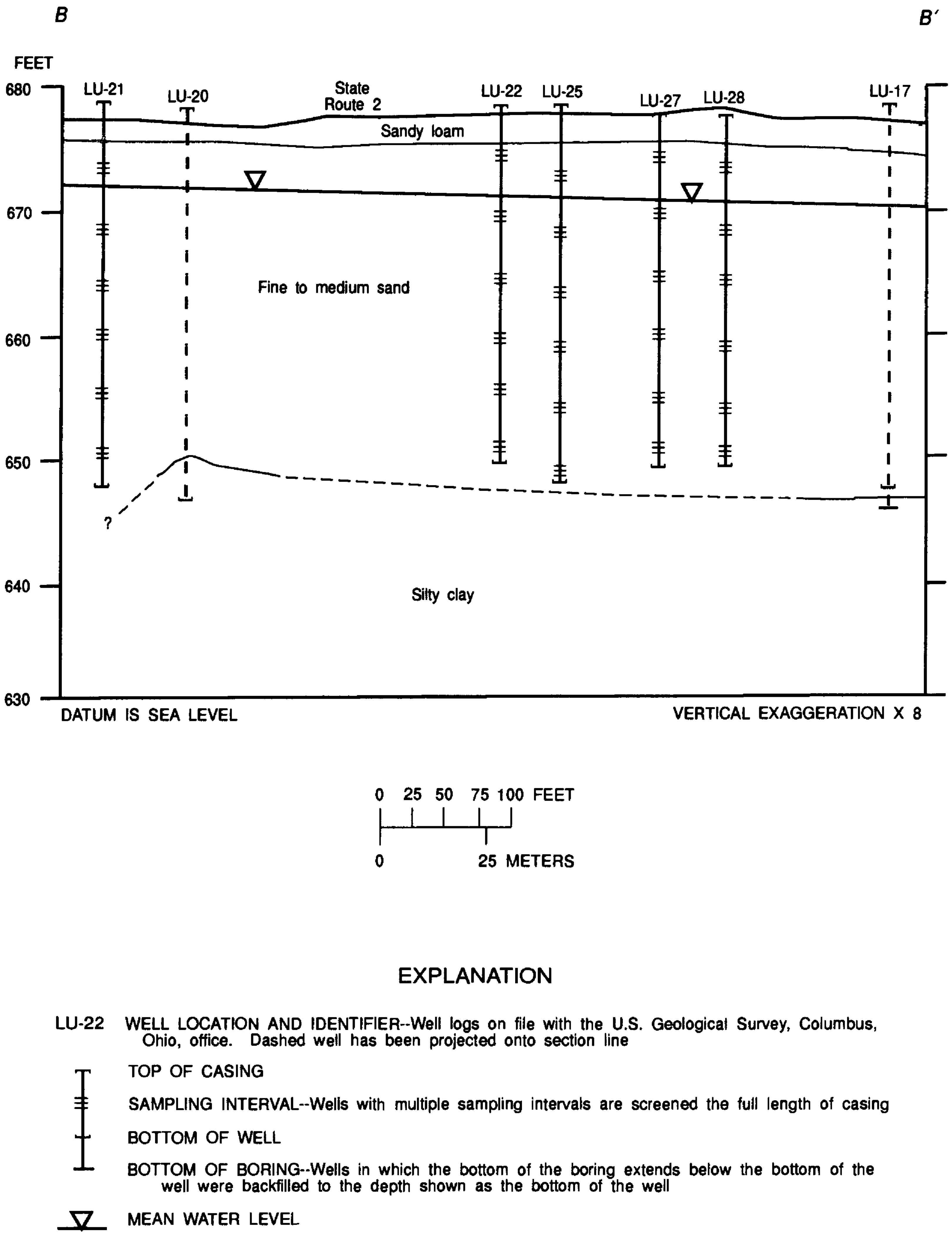


Figure 31. Geologic section *B-B′*, Lucas County study site, Ohio. (Section trace shown on fig. 30.)

Hydrogeology

The ground-water level is 4-8 ft below land surface throughout the year at this site. During the interim reporting period, the direction of flow varied from about 25°–65° and averaged about 45° to the alignment of the highway, as determined by the triangulation method using available wells; average water-table slope is about 0.004. At this site the ground-water level responds to precipitation within 1 day, owing to the porous aquifer materials at the surface and the shallow water table.

Results of single-well aquifer tests (slug tests) on the aquifer indicate that the hydraulic conductivity is 6.3 ft/d. Assuming an average gradient of 0.004 and an effective porosity of 43 percent, the ground-water velocity was computed to be 0.06 ft/d.

The electrical conductivity of the subsurface materials was measured at the Lucas County site on five occasions by use of the Geonics EM-34-3 at the 10-m spacing. The composition of the aquifer materials was inferred from these measurements and well logs from the site. Surveys were completed at this site in July 1991, June 1992, April 1993, June 1993, and August 1993. Measurements ranged from 1 to 7 mS/m upgradient (predominantly 1–5 mS/m) to 1 to 10 mS/m downgradient (predominantly 4–10 mS/m), indicating relatively coarse aquifer materials and low to mid-range values of specific conductance in the ground water. These indications were verified with local well logs and with later results of water-quality analyses. The aquifer materials are homogeneous across the site. Variations in electrical conductivity measurements between EM surveys define changes in the ground conductivity that would be attributable only to changes in water quality. Analysis of the regular ground-water samples verified that downgradient measurements were higher for the most part, because of increased conductivity of the ground water. Contour plots of a survey of both the upgradient and downgradient sides of the highway on April 8, 1993, are shown in figure 32. The plots show an overall view of the distribution of the combined ground conductivity of earth materials and ground water. The relatively low ground conductivity at this site can be generally attributed to the well-sorted medium sand aquifer that exists to a depth of more than 30 ft at this site. The small variability in ground conductivity from one survey to the next (generally in the range of 0–4 mS/m) is not at a scale that could be detected as a distinct saline-water plume, as there is considerable interference at a short distance downgradient from the highway from the adjacent airport.

Effects of highway deicing chemicals on water quality

Field-monitored characteristics (rainfall, specific conductance, and ground-water levels recorded from dedicated instrumentation at well near the first downgradient sampling well) and the amount of sodium chloride applied to the highway are shown in figure 33. The 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. The movement of chloride and other deicing-related constituents from the highway with time are indicated by boxplots of laboratory-determined data (fig. 34).

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); however, Lucas County is not located in the snowbelt area east of Lake Erie as are the other two sites. A maximum of 1,630 μS/cm was recorded in July 1991, and a minimum of 441 μS/cm was recorded in March 1992, a range

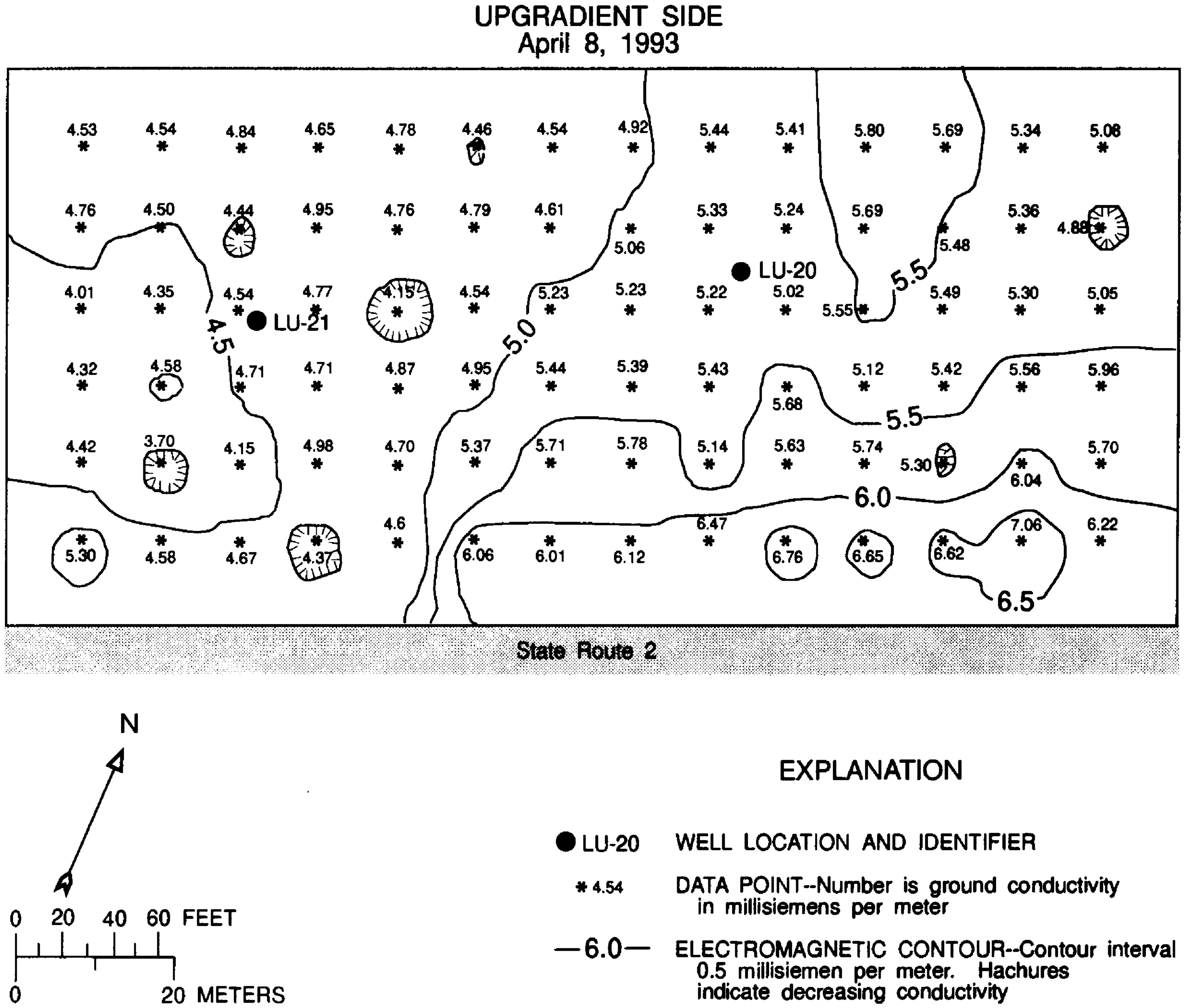


Figure 32. Contour plot of electromagnetic geophysical survey on upgradient and downgradient sides of Lucas County study site, Ohio, April 8,1993. (The horizontal coplanar arrangement was used with a 10-meter spacing.) *Continued on next page*

of 1,189 µS/cm. Annual extremes (based on water year) ranged from 1,630 µS/cm in July 1991 to 466 µS/cm in May 1991, from 898 µS/cm in December 1991 to 441 µS/cm in March 1992, and from 936 µS/cm in September 1993 to 447 µS/cm in January 1993. For comparison, the mean specific conductance of the upgradient well for the interim reporting period was 326 µS/cm.

Air and soil temperature. During the interim reporting period the air temperature at this site ranged from 35.5°C in August 1993 to a minimum of -19.8°C in January 1992. The annual maximum for 1991 was 34.5°C in July and August, but the minimum for 1991 could not be accurately determined because measurements were not made until February 1991. Annual extremes (based on water year) for the remainder of the interim reporting period ranged from a maximum of 33.6°C in August 1992 to a minimum of -19.8°C in January 1992 and from a maximum of 35.5°C in August 1993 to a minimum of -19.7°C in February 1993.

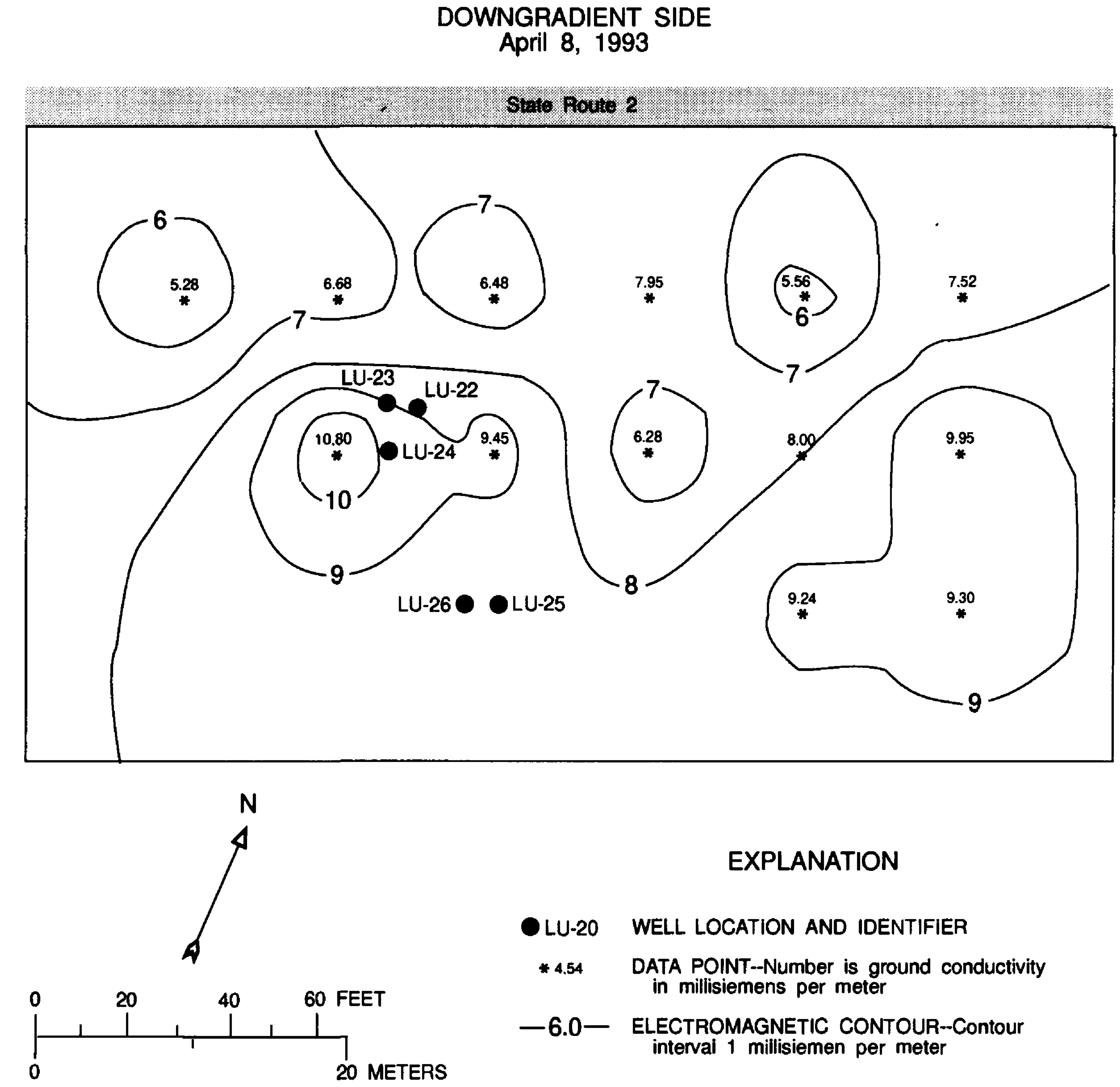
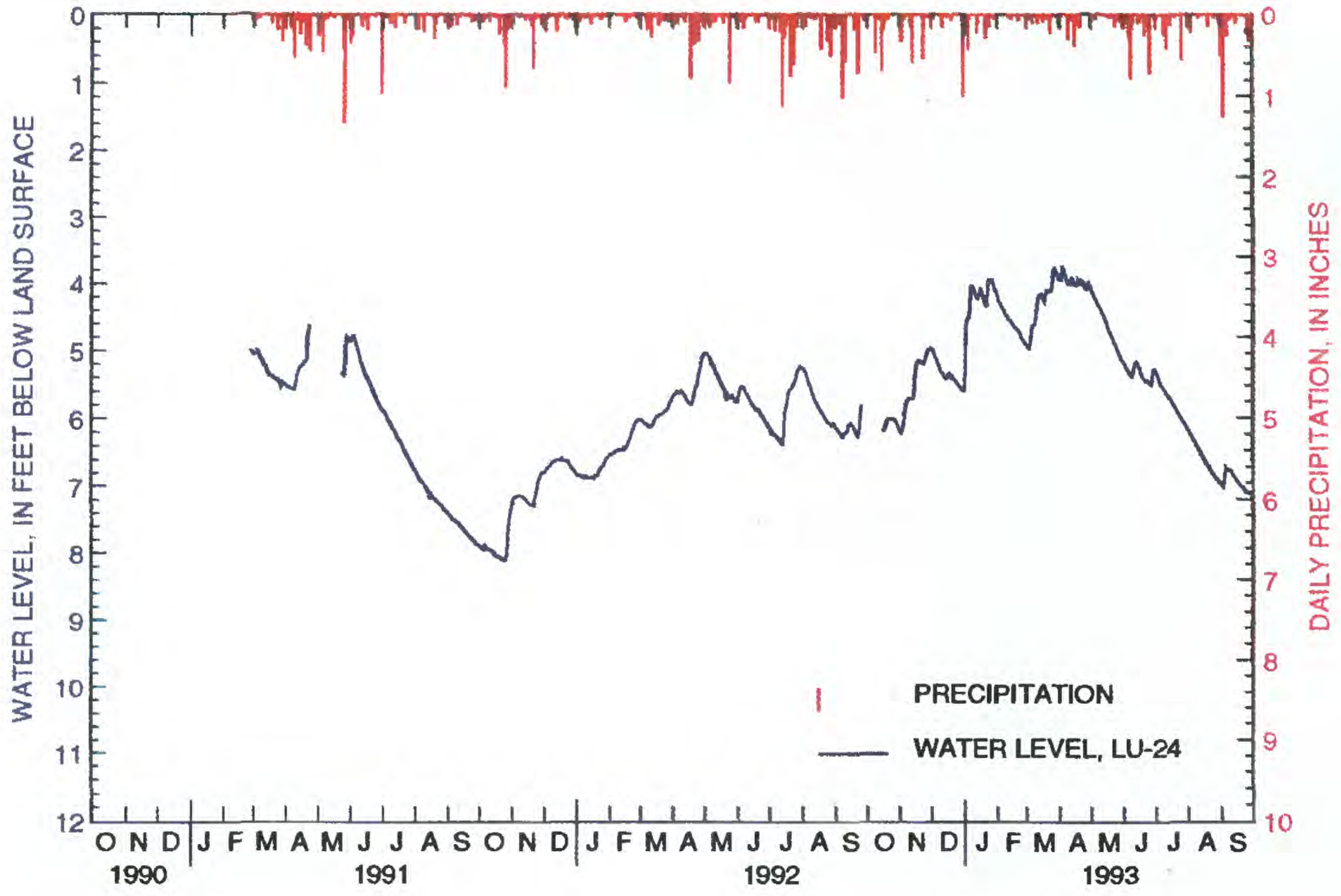


Figure 32. Contour plot of electromagnetic geophysical survey on upgradient and downgradient sides of Lucas County study site, Ohio, April 8,1993--Continued.

During the interim reporting period the soil temperature ranged from a maximum of 30.0°C in July 1991 to a minimum of 0.0°C in March 1993. The annual maximum for 1991 was 30.0°C in July 1991, but the minimum for 1991 could not be accurately determined because measurements were not made until February 1991. Annual extremes (based on water year) for the remainder of the interim reporting period ranged from a maximum of 26.7°C in August 1992 to a minimum of 0.4°C in February 1992 and from a maximum of 28.9°C in August 1992 to a minimum of 0.0°C in March 1993. Soil temperatures reached the freezing point of 0°C only once during the interim reporting period (1993), thus, frozen soil would not have inhibited infiltration of runoff water into the aquifer.



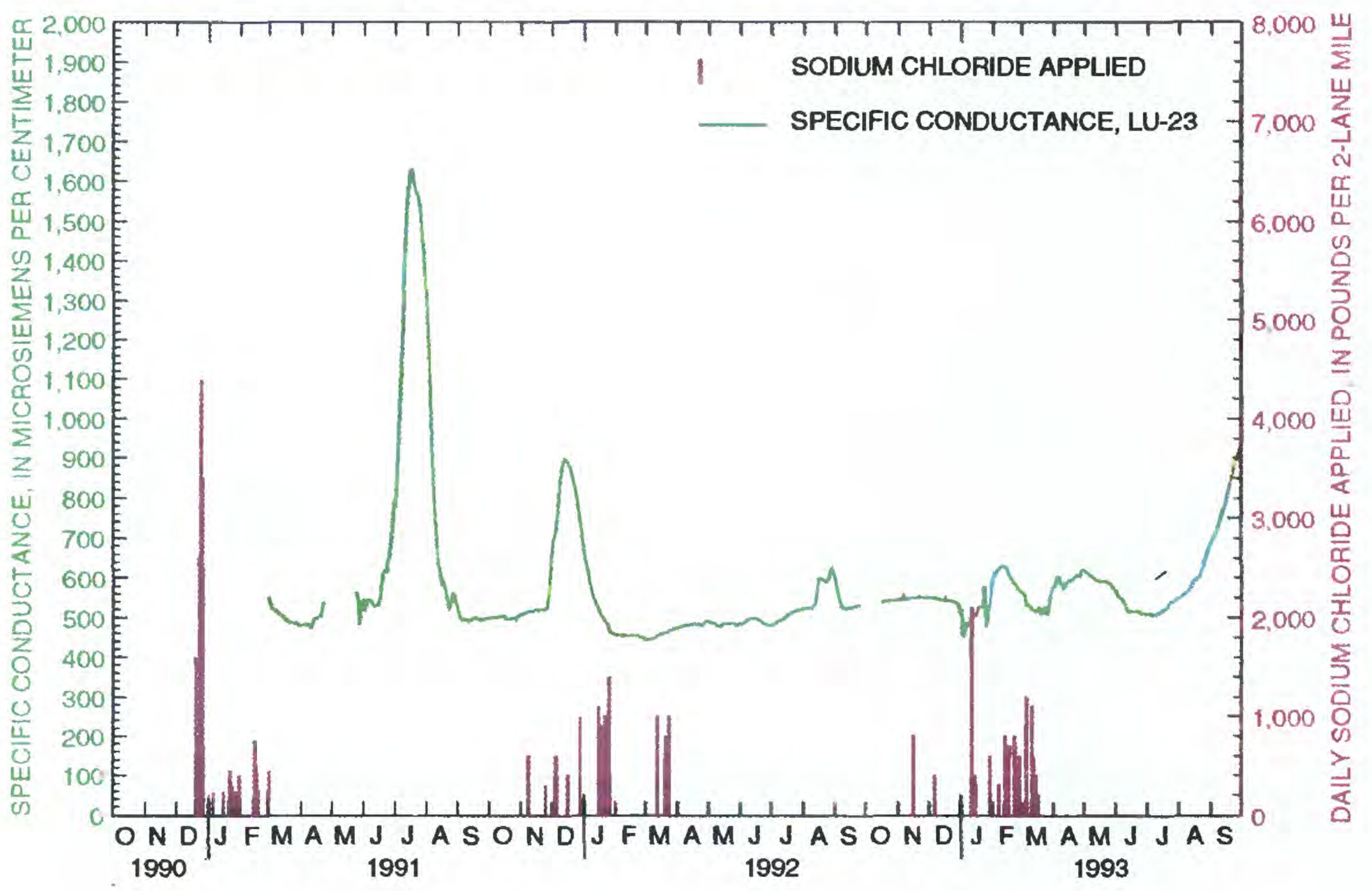


Figure 33. Ground-water levels, specific conductance of ground water, precipitation, and sodium chloride applied at the Lucas County study site, Ohio.

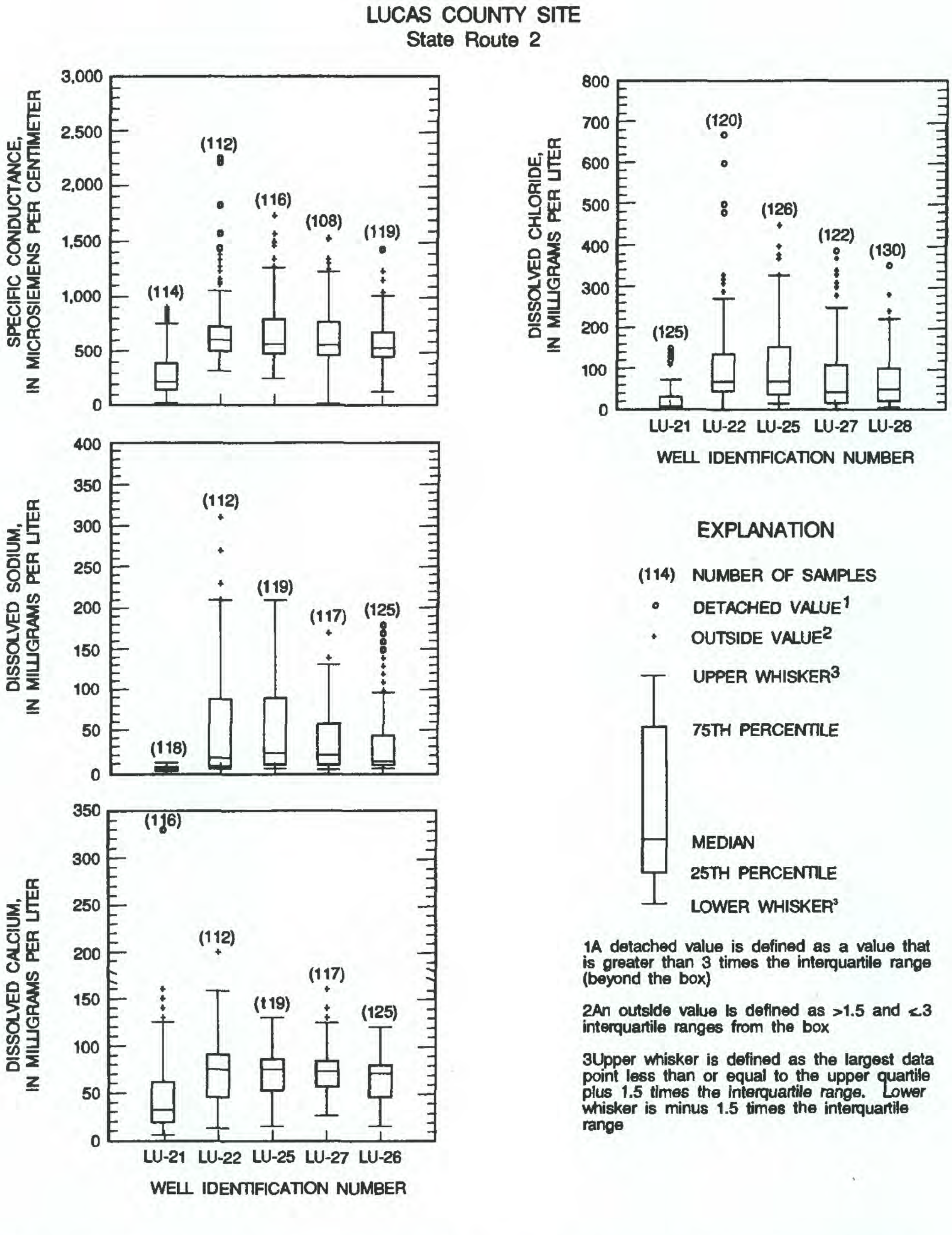


Figure 34. The distribution of specific conductance and concentrations of dissolved sodium, calcium, and chloride in ground water sampled at the Lucas County study site, Ohio, January 1991-September 1993. (Plots are shown in downgradient order from left to right. Far left plot is upgradient from highway; others are downgradient.)

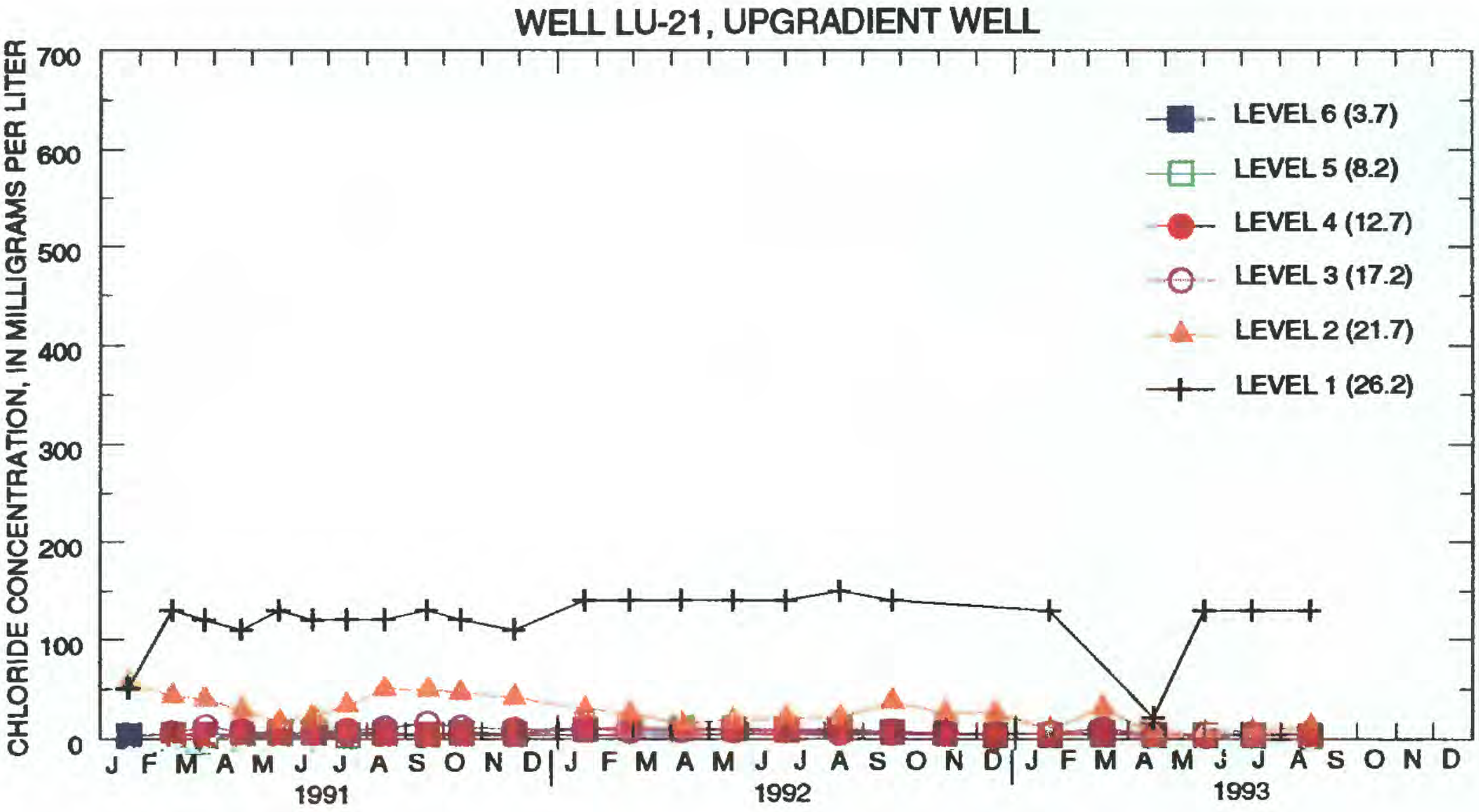
Laboratory-determined characteristics

The Lucas County site received steady applications of deicing chemicals, although they usually were not applied in large quantities. Temperatures were often below freezing creating icy conditions that needed attention, but average annual snowfall was 20–30 in. less than the sites in the snowbelt area. Summary statistics of the water-quality data collected in upgradient and downgradient wells are listed in table 11. 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 are shown in figure 34. Data shown are for the sampling period January 1991 through September 1993. Patterns that emerge from those data and require further discussion are noted below.

Chloride concentration. At the upgradient well, LU-21, the mean concentration of chloride was 32 mg/L and the maximum was 150 mg/L. The lowest level (level 1) in the upgradient well was uncharacteristically high 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, 111 mg/L; maximum, 670 mg/L) and the second downgradient well, LU-25 (mean, 111 mg/L; maximum 450 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 77 mg/L, and the maximum was 390 mg/L. At the fourth downgradient well, the mean concentration was similar to that at the third downgradient well (70 mg/L; maximum 350 mg/L). Thus, 150 ft downgradient from the highway, the median concentration at the fourth downgradient well was about six 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 each of six sampling levels in each well at the site are shown in figure 35. Sampling from several levels in one well allows a vertical distribution of chloride to be determined. A vertical distribution of chloride concentrations is evident throughout the year, especially at the first downgradient well, LU-22, and the fourth downgradient well, LU-28. Vertical distribution of chloride concentration is somewhat less pronounced in the second and third downgradient wells. For example, at LU-22, the chloride concentration in August 1992 at level 4 reached 670 mg/L, but was only 76 mg/L in level 5. A water sample from the entire screened interval may have produced a sample with an average concentration somewhere between these two values. Preferential flowpaths can be monitored in this way, especially at sites where aquifer materials are mixed, or, as in the case at this site, where low velocity and frequency of deicing-chemical input to the aquifer may be the determining factors of the flowpath of chloride-laden water. The first plot in figure 35 shows the chloride concentration in water from all levels of the upgradient well (LU-21). The average concentration at levels 3 through 6 is less than 10 mg/L, although concentrations at levels 1 and 2 often ranged from 30 to 150 mg/L. At level 1 chloride concentrations were often higher than at the other levels in that well, a pattern that may be a remnant of (1) deicing-chemical input from the turnpike far upgradient of SR 2 or (2) possibly a "backflush" of deicing-chemical runoff from SR 2 which may move short distances upgradient and downgradient along the bottom of the aquifer because of the very low groundwater velocity and gradient at this site. The chemical-laden ground water may slowly spread out along the bottom of the aquifer before eventually being transported downgradient. The effect of this anomaly is negligible at the downgradient wells. Spikes of chloride concentrations as high as 700 mg/L can be seen at the first downgradient well (closest to the highway); similar but subdued patterns can be seen in data from the other wells. At 150 ft downgradient from the highway,

Table 11. Water-quality data for multilevel wells at the Lucas County site, Ohio, January 1991 through August 1993
[μS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples; UG, upgradient; DG, downgradient]

Well Name	Position	Statistic	Specific conductance (μS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)	Bromide, dissolved (mg/L)
LU-21	UG	Maximum	903	330	12	150	0.10
		Minimum	31	6	2	2	<0.01
		Mean	326	53	5	32	0.02
		Median	223	32	4	8	<0.01
		N	114	116	116	125	121
LU-22	1st DG	Maximum	2,250	200	310	670	0.13
		Minimum	323	13	5	2	<0.01
		Mean	697	70	53	111	0.03
		Median	606	75	18	70	0.03
		N	112	112	112	120	116
LU-25	2nd DG	Maximum	1,730	130	210	450	0.08
		Minimum	252	15	5	16	<0.01
		Mean	679	69	50	111	0.03
		Median	569	75	23	70	0.03
		N	116	119	119	126	122
LU-27	3rd DG	Maximum	1,530	160	170	390	0.21
		Minimum	23	26	4	0.9	<0.01
		Mean	642	74	37	77	0.03
		Median	560	73	21	44	0.03
		N	108	117	117	122	115
LU-28	4th DG	Maximum	1,430	120	180	350	0.14
		Minimum	134	15	6	4	<0.01
		Mean	574	65	37	70	0.02
		Median	532	71	14	50	0.02
		N	119	125	125	130	121



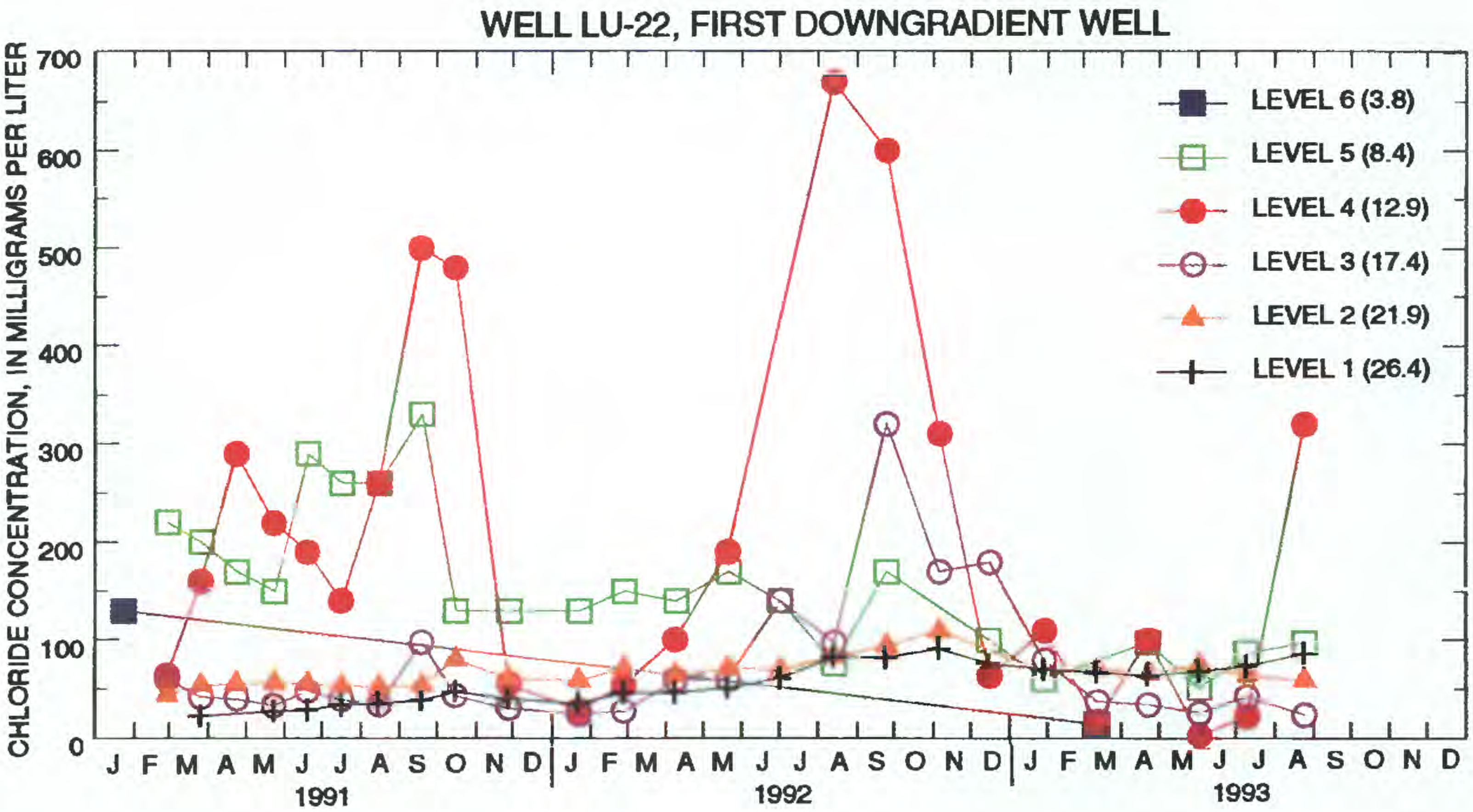
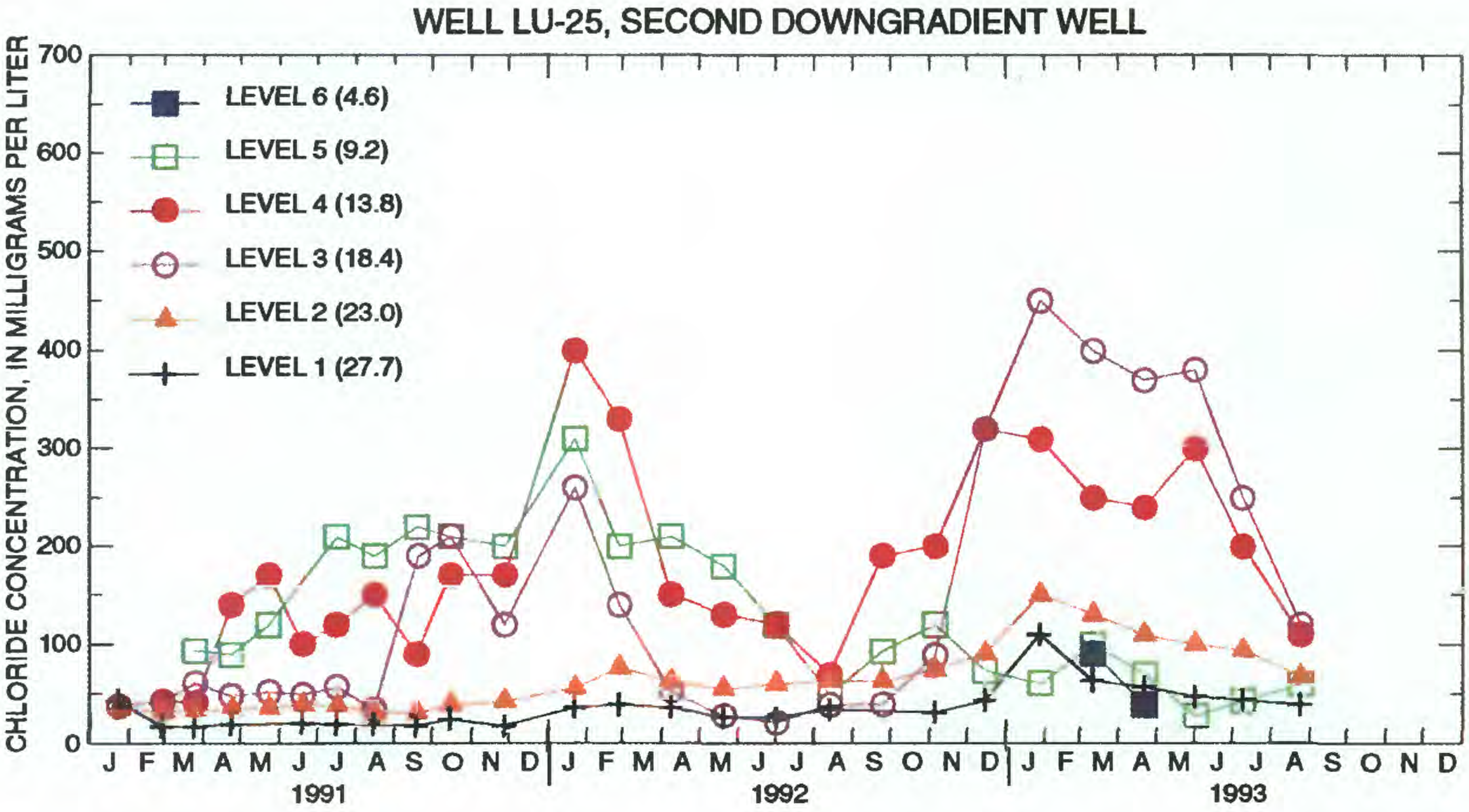


Figure 35. Dissolved chloride concentration, by level, for multilevel wells at the Lucas County study site, Ohio. (Number in parentheses is depth, in feet below land surface.)



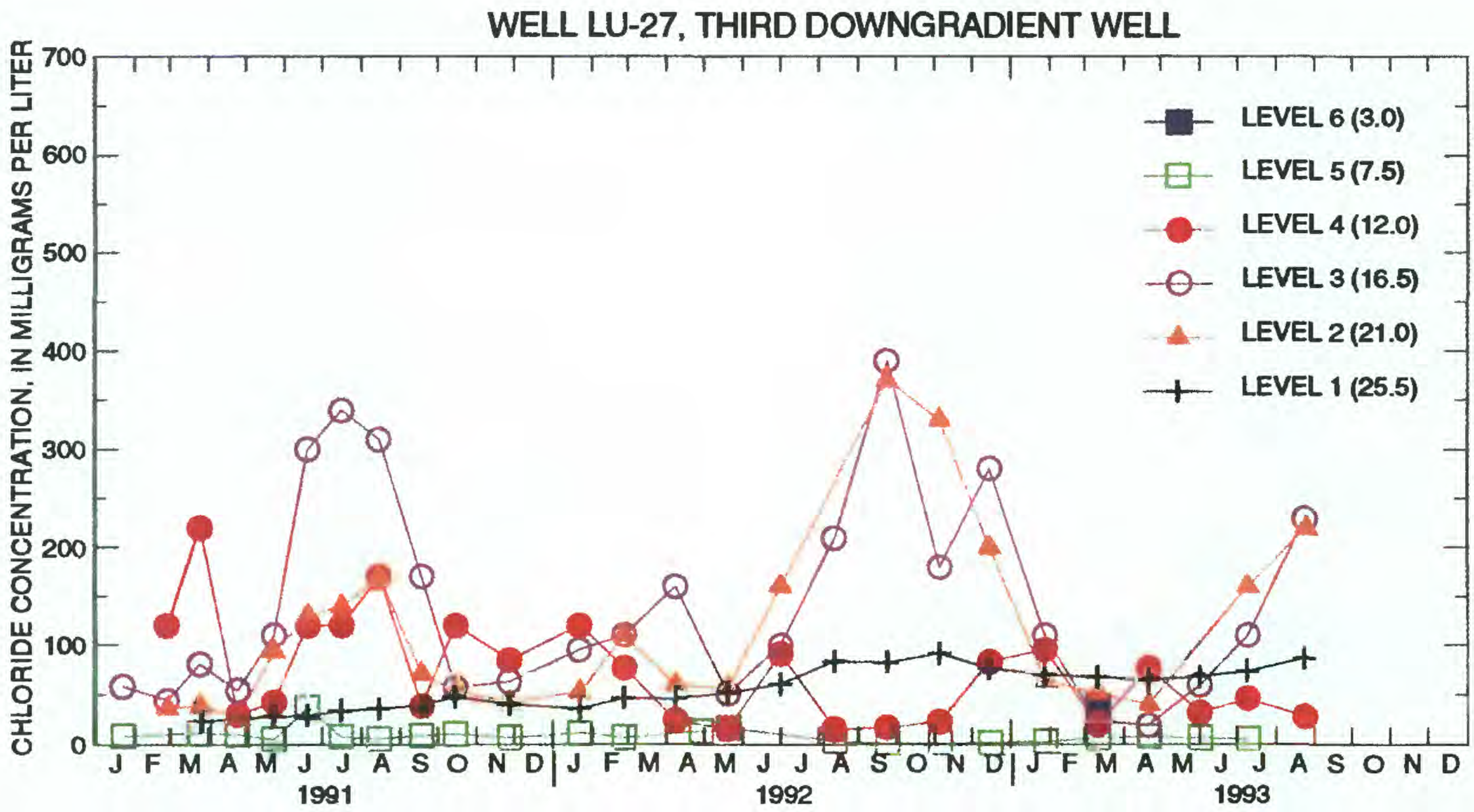


Figure 35. Dissolved chloride concentration, by level, for multilevel wells at the Lucas County study site, Ohio--Continued.

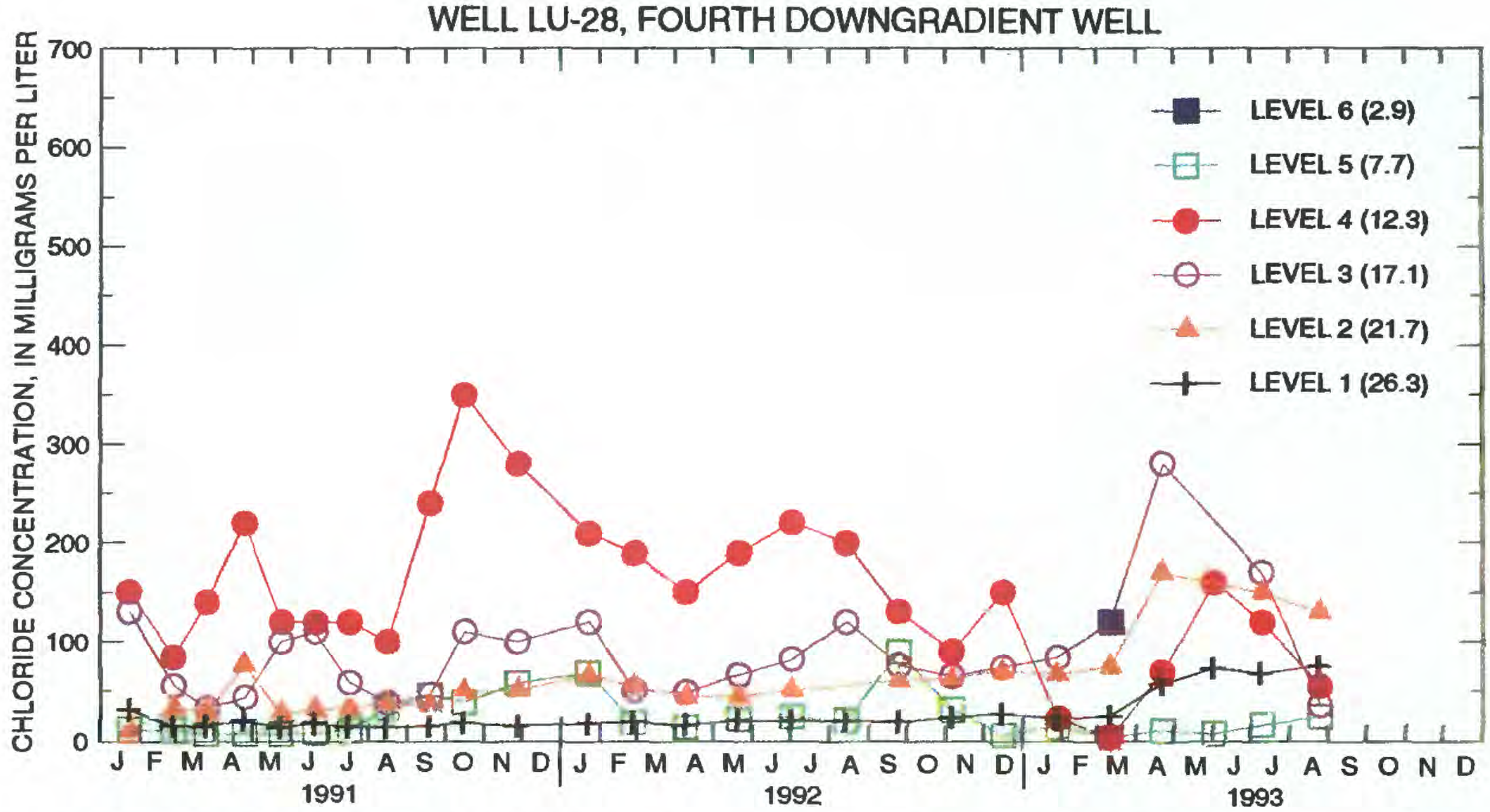


Figure 35. Dissolved chloride concentration, by level, for multilevel wells at the Lucas County study site, Ohio--*Continued.*

chloride concentrations are still as high as 350 mg/L. At this site, it cannot be determined at what distance downgradient from the highway background concentrations of chloride are reached.

Soil samples were collected at this site in August 1993. The extract from the soil-sample preparation method was analyzed at the NWQL for dissolved chloride concentration. The chloride concentration of the samples collected within 6 ft of the highway was 32 mg/L and decreased to 3 mg/L by 100 ft downgradient from the highway. The concentration upgradient from the highway was approximately 5 mg/L.

Sodium concentration. At the upgradient well, LU-21, the mean concentration of sodium was 5 mg/L and the maximum was 12 mg/L. Mean concentration at the fourth downgradient well was about 7 times higher downgradient from the highway, although the concentrations were fairly constant throughout the four downgradient wells (mean, 37–53 mg/L; maximum, 170–310 mg/L).

Specific conductance. At the upgradient well, LU-21, the mean specific conductance was 326 µS/cm and the maximum was 903 µS/cm. Values were generally highest at the first downgradient well, LU-22, (mean, 697 µS/cm; maximum, 2,250 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 642 µS/cm and the maximum was 1,530 µS/cm. At the fourth downgradient well, the mean concentration was 574 µS/cm and the maximum was 1,430 µS/cm. Thus, 150 ft downgradient from the highway, the mean specific conductance at the fourth downgradient well was 1.8 times the upgradient or background value although the mean value of the first, second, and third wells had not decreased significantly. This may be due to the extremely low ground-water velocity at this site. The median change was about 2.4 times the background value.

Pickaway County Site

Site Characteristics

The Pickaway County site (fig. 36) 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 very shallow, and the material of the soils and aquifer very porous, allowing for easy infiltration of runoff. The downgradient side of the highway is occasionally-used farmland and pasture. The upgradient side is a mowed lawn and rural 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 very straight at this site, but it slopes down slightly to the south where it crosses an intermittent stream.

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, D.L., 1993a, 1993b). 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 very well drained soils. Individual well logs were constructed for each of the wells. A geologic cross-section of the site was constructed on the basis of these logs (fig. 37).

The 12-winter (1981–93) average annual use of deicing-chemicals in Pickaway County as a whole was 1,346 tons (table 3). The maximum for this 12-winter period was 3,000 tons in 1984–85, and the minimum for this period was 450 tons in 1982–83. The three-winter (1990–93) average annual use of deicing-chemicals during the interim reporting period for this county as a whole was 950 tons. The maximum for this 3-winter period was 1,071 tons in 1992–93, and the minimum for this period was 782 tons in 1991–92. For all of Ohio, the 3-winter average annual use of deicing-chemicals was 8.0 ton/2-ln mi (16,000 lb/2-ln mi) (Ohio Department of Transportation, written commun., 1994). Data collected at this site indicate the 3-winter average annual use of deicing-chemicals was 2.52 ton/2-ln mi. (5,050 lb/2-ln mi.), which is 68 percent less than the State average. During the interim reporting period, in only one case, a small amount of liquid calcium chloride ($CaCl_2$) also was applied to the highway in addition to sodium chloride and abrasives.

Climate

The average annual precipitation for the area is 38.3 in. The average annual temperature for the area is 12.0°C (53.6°F), with the monthly normal high of 30.3°C (86.6°F) in July and the monthly normal low of -6.1°C (21.1°F) in January (National Oceanic and Atmospheric Administration, 1982). During the interim reporting period, annual precipitation data from the site averaged 29.9 in. The average annual snowfall is 20–30 in. for nearby reporting areas (Miller and Weaver, 1971).

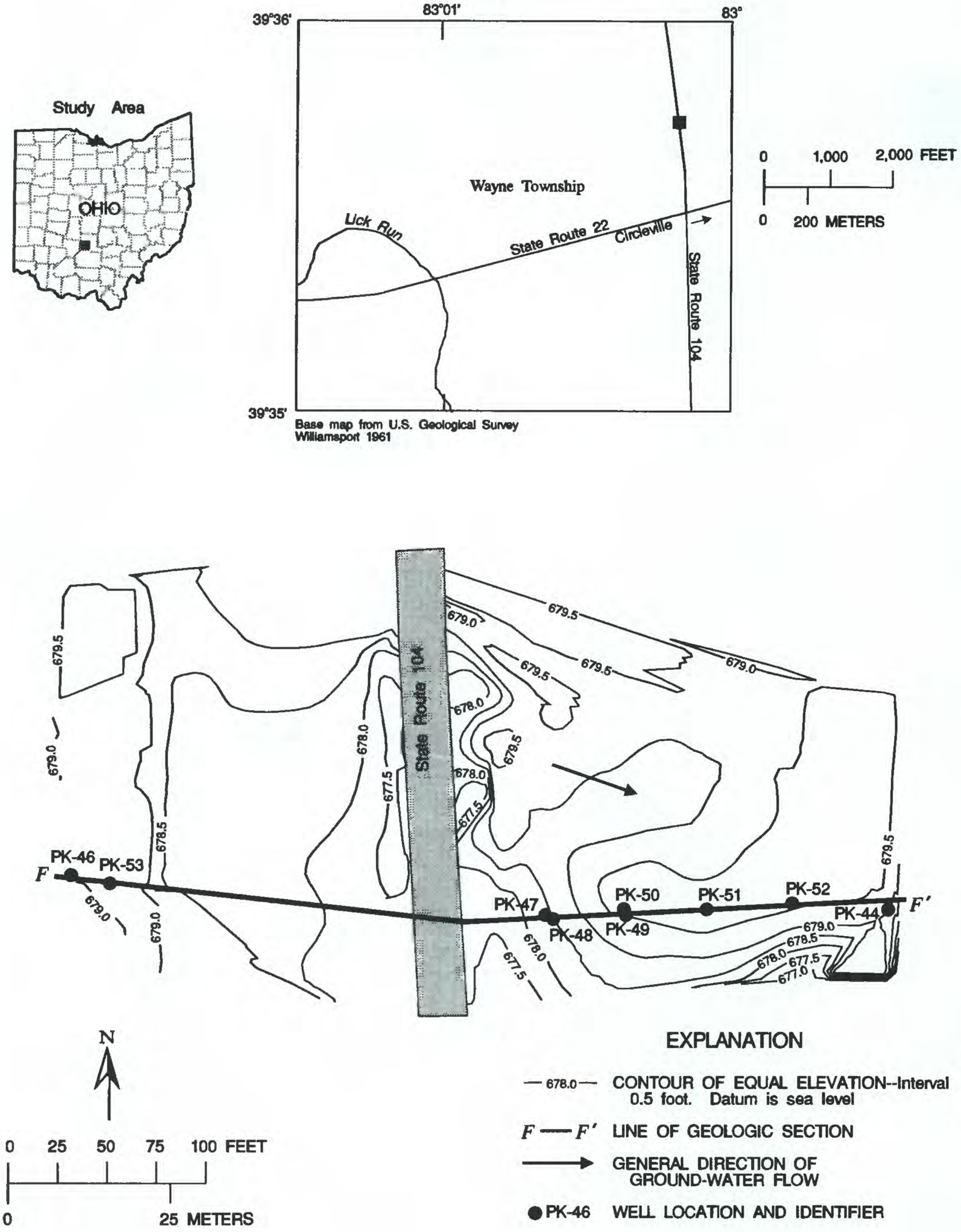
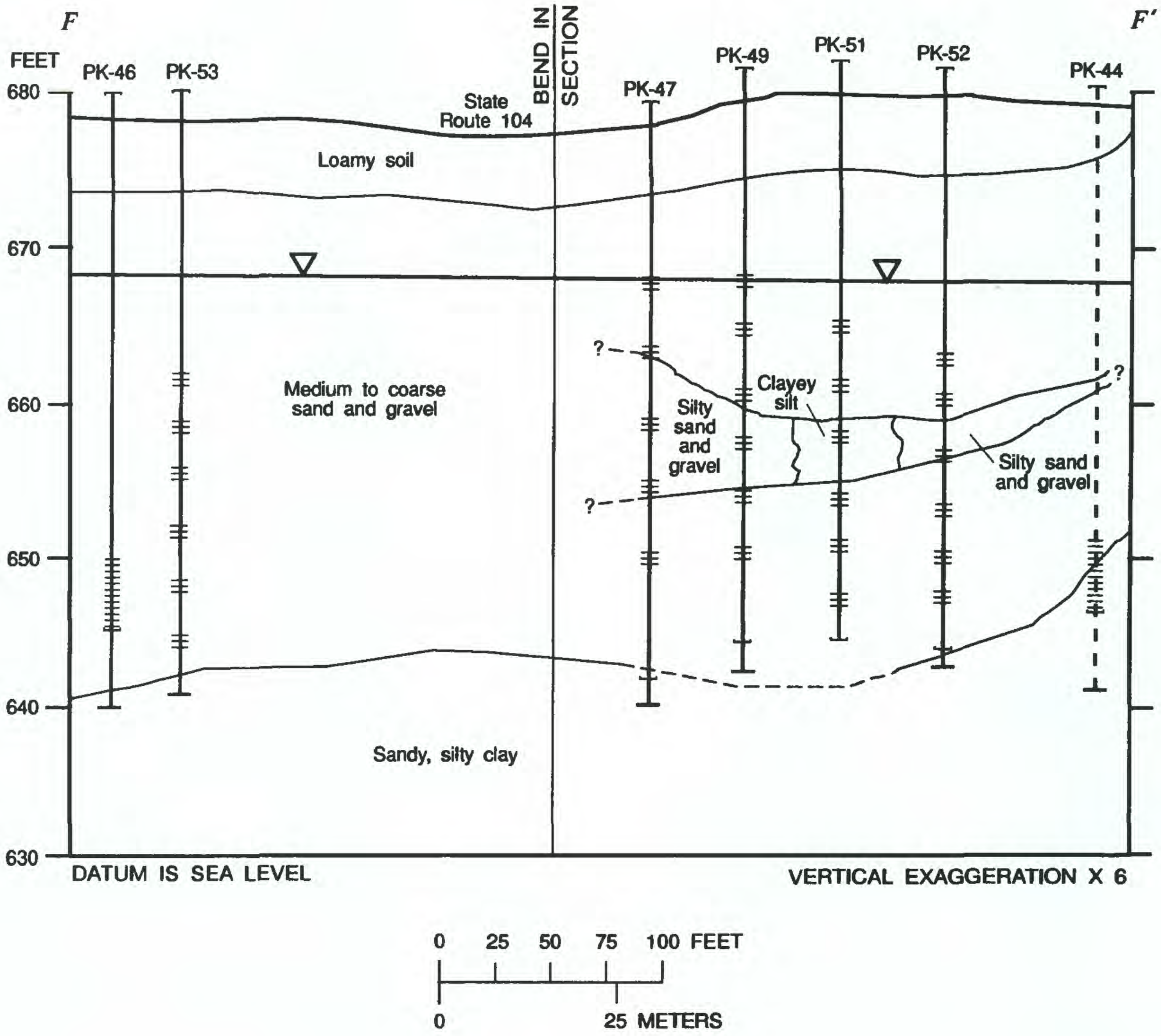


Figure 36. Topography, well locations, and ground-water flow direction at Pickaway County study site.



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

WELL SCREEN

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

Figure 37. Geologic section *F-F′*, Pickaway County study site, Ohio. (Section trace shown in fig. 36.)

Hydrogeology

The ground-water level is 7–13 ft below land surface throughout the year at this site. During the interim reporting period, the direction of flow varied from about 50° to 75° to the alignment of the highway, as determined by the triangulation method using available wells; average water-table slope is about 0.003. At this site the ground-water level responds to precipitation within 1 day, owing to the porous aquifer materials at the surface.

Results of single-well aquifer tests (slug tests) on the aquifer indicate that the hydraulic conductivity is 31.6 ft/d. Assuming an average gradient of 0.003 and an effective porosity of 40 percent, the ground-water velocity was computed to be 0.24 ft/d.

The electrical conductivity of the subsurface materials was measured at the Pickaway County site on one occasion by use of the Geonics EM-34-3 at the 10-m spacing. The composition of the aquifer materials was inferred from these measurements and well logs from the site. The survey was completed at this site in August 1991. The measurements which ranged from 7 to 10 mS/m downgradient from the highway and from 8 to 10 mS/m upgradient from the highway, indicate a very thick, medium to coarse sand and gravel with water of probable low specific conductance, except for two small areas of high measurements that were possibly caused by interference from buried objects. Above-freezing temperatures and very low deicing rates made repeated surveys unnecessary during this period.

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 38. The 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. The movement of chloride and other deicing-related constituents from the highway with time are indicated by boxplots of laboratory-determined data (fig. 39).

Field-monitored characteristics

Specific conductance. Specific conductance of ground water at this site varied only slightly during the interim reporting period. A maximum of 799 µS/cm was recorded in April 1993, whereas a minimum of 585 µS/cm was recorded in October 1991, (a range of 214 µS/cm). Annual extremes (based on water year) ranged from 717 µS/cm in March 1991 to 586 µS/cm in September 1991, 699 µS/cm in September 1992 to 585 µS/cm in October 1991, and 799 µS/cm in April 1993 to 593 µS/cm in August 1993. For comparison, the mean specific conductance of the upgradient well for the interim reporting period was 511 µS/cm. During periods of relatively higher ground-water levels, specific conductance rises and returns to average levels fairly quickly, usually in several weeks. This pattern indicates that the properties of the aquifer may allow quick movement of ground water during most times of the year, although only small amounts of deicing chemical were applied at this site.

Air and soil temperature. During the interim reporting period the air temperature at this site ranged from 37.0°C in June and August 1991 and August 1993 to a minimum of -19.8°C in January 1992. The annual maximum for 1991 was 37.0°C in June and August, but the minimum for 1991 could not be accurately determined because measurements were not made until February 1991. Annual extremes (based on water year) for the remainder of the interim reporting period ranged from a maximum of 33.0°C in July 1992 to a minimum of -19.8°C in January 1992 and from a maximum of 37.0°C in August 1993 to a minimum of -18.9°C in February 1993.

The annual maximum soil temperature for 1991 was 32.5°C in September, but the minimum for 1991 could not be accurately determined because measurements were not made until February 1991. Soil temperature records for 1992 are incomplete during the summer period, but the annual minimum was 8.9°C in December 1991. Annual extremes (based on water year) for 1993 ranged from a maximum of 24.6°C in August 1993 to a minimum of 0.3°C in February 1993. There were no recorded days of the soil temperature reaching 0°C or less, thus indicating no periods when frozen soil could inhibit infiltration of runoff water into the aquifer.

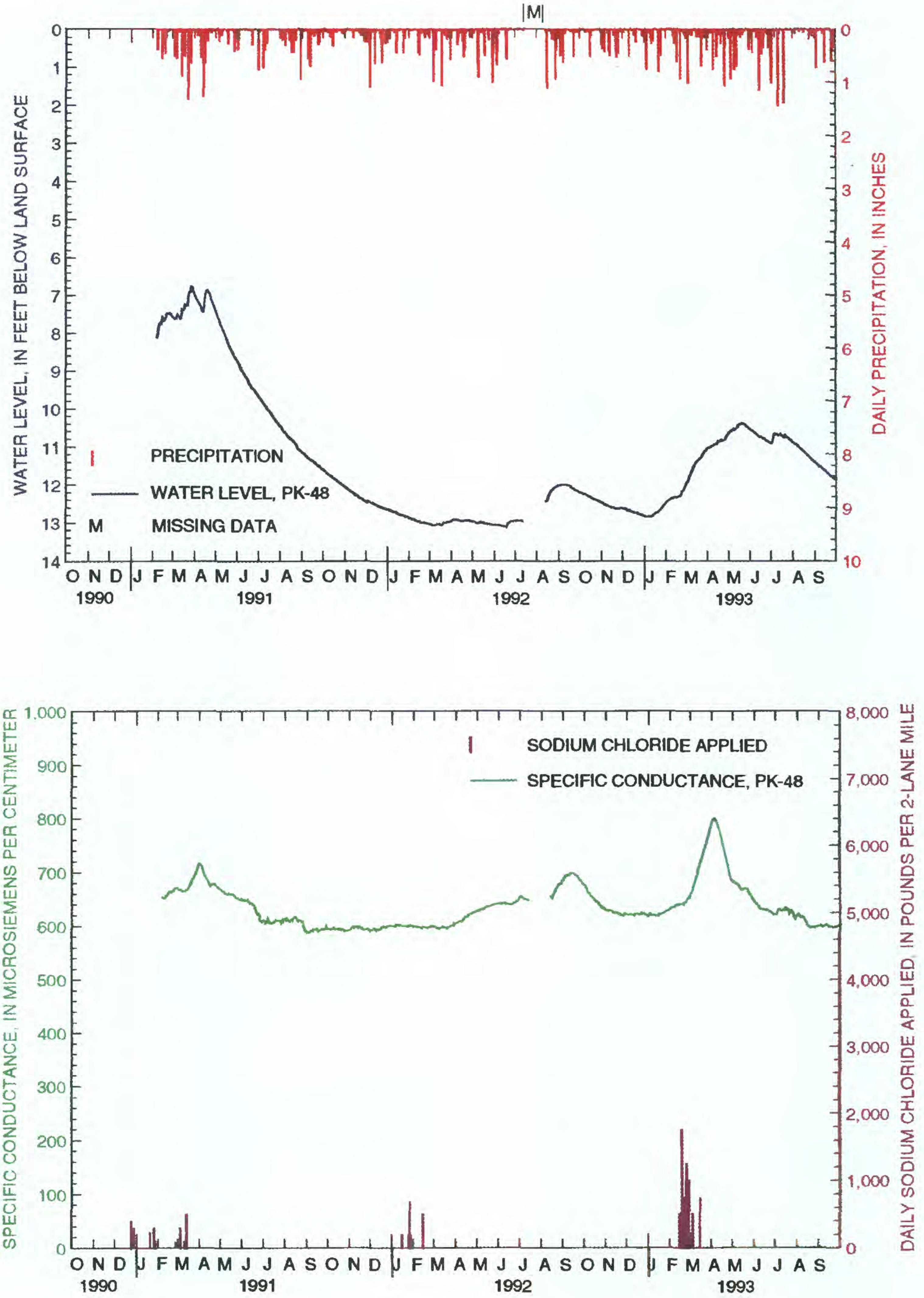


Figure 38. Ground-water levels, specific conductance of ground water, precipitation, and sodium chloride applied at the Pickaway County study site, Ohio.

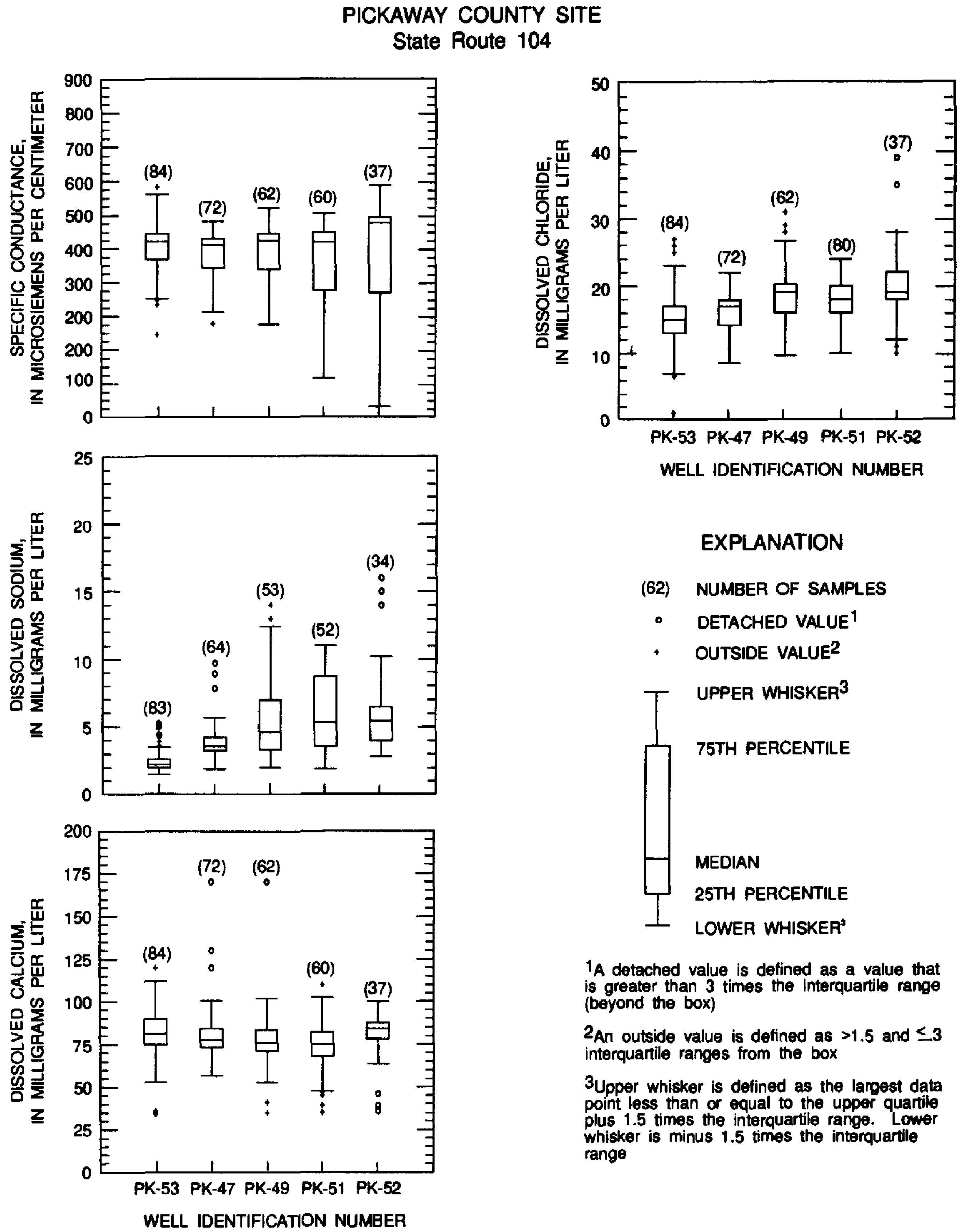


Figure 39. The distribution of specific conductance and concentrations of dissolved sodium, calcium, and chloride in ground water sampled at the Pickaway County study site, Ohio, January 1991-September 1993. (Plots are shown in downgradient order from left to right. Far left plot is upgradient from highway; others are downgradient.)

Table 12. Water-quality data for multilevel wells at the Pickaway County site, Ohio, January 1991 through August 1993

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

Well Name	Position	Statistic	Property or constituent				
			Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)	Bromide, dissolved (mg/L)
PK-53	UG	Maximum	684	120	5	27	0.06
		Minimum	245	34	2	1	0.01
		Mean	511	82	2	15	0.03
		Median	524	81	2	15	0.03
		N	74	83	83	83	84
PK-47	1st DG	Maximum	582	170	10	22	0.10
		Minimum	279	62	2	10	<0.01
		Mean	491	82	4	17	0.03
		Median	516	79	4	17	0.03
		N	65	64	64	71	70
PK-49	2nd DG	Maximum	621	170	14	31	0.06
		Minimum	328	35	2	10	0.02
		Mean	513	79	5	19	0.03
		Median	536	79	5	19	0.03
		N	54	53	53	61	61
PK-51	3rd DG	Maximum	606	110	11	24	0.13
		Minimum	348	35	2	11	0.03
		Mean	502	75	6	18	0.04
		Median	532	76	5	18	0.04
		N	52	52	52	59	59
PK-52	4th DG	Maximum	688	100	16	39	0.07
		Minimum	304	36	3	10	0.01
		Mean	544	81	6	20	0.03
		Median	582	85	5	20	0.03
		N	32	34	34	36	36

Laboratory-determined characteristics

At the Pickaway County site, significant amounts of deicing chemicals were rarely applied to the highway. Temperatures were often above freezing throughout the winters 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 in upgradient and downgradient wells are listed in table 12. Boxplots of specific conductance, dissolved calcium, dissolved sodium, and dissolved chloride for water-quality data from all levels of the upgradient well and the four downgradient sampling wells are shown in figure 39. Data shown are for the sampling period January 1991 through September 1993. Patterns that emerge from those data and require further discussion are noted below.

Chloride concentration. At the upgradient well, PK-53, the mean concentration of chloride was 15 mg/L and the maximum was 27 mg/L. Concentrations were slightly higher at the downgradient wells (mean, 17–20 mg/L; maximum, 22–39 mg/L). Concentrations remained fairly constant downgradient along the flowpath through the fourth downgradient well. Thus, 150 ft downgradient from the highway, the mean concentration at the fourth downgradient well was about 1.3 times the upgradient or background concentration. The pattern observed at most of the other sites was not observed here because of low chloride concentrations and a low deicing-chemical input into the aquifer.

Soil samples were collected at this site in August 1993. The extract from the soil- sample preparation method was analyzed at the NWQL for dissolved chloride concentration. The chloride concentration of the samples collected within 13 ft of the highway was 6–13 mg/L and decreased to 5 mg/L by 80 ft downgradient from the highway.

Sodium concentration. At the upgradient well, PK-53, the mean concentration of sodium was 2 mg/L and the maximum was 5 mg/L. Concentrations were slightly higher at the downgradient wells (mean, 4–6 mg/L; maximum, 10–16 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, 150 ft downgradient from the highway, the mean concentration at the fourth downgradient well was about three times the upgradient or background concentration; however, because concentrations in all wells were very low, this increase is insignificant 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.

Specific conductance. At the upgradient well, PK-53, the mean specific conductance was 511 μS/cm and the maximum was 684 μS/cm. Values were generally constant throughout the four downgradient wells (mean, 491–544 μS/cm; maximum 582–688 μS/cm), Thus, 150 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.

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 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

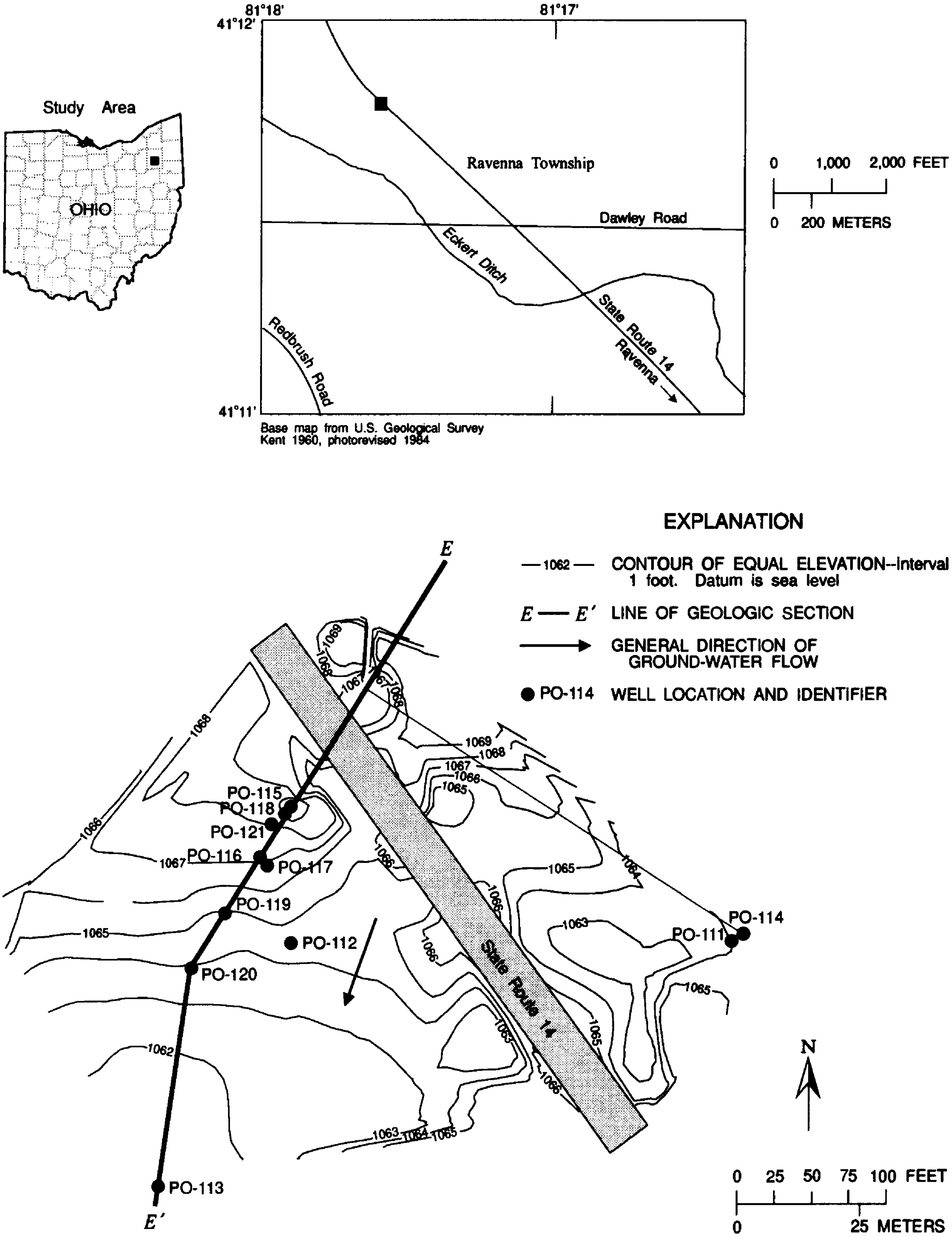


Figure 40. Topography, well locations, and ground-water flow direction at Portage County study site.

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 newly planted 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 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. 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). Individual well logs were constructed for each of the wells. A geologic cross-section of the site was constructed on the basis of these logs (fig. 41).

The 12-winter (1981–93) average annual use of deicing-chemicals in Portage County as a whole was 8,320 tons (table 3). The maximum for this 12-winter period was 13,800 tons in 1983–84, and the minimum for this period was 5,700 tons in 1982–83. The 3-winter (1990–93) average annual use of deicing-chemicals during the interim reporting period for this county as a whole was 6,667 tons. The maximum for this 3-winter period was 7,000 tons in 1990–91 and 1991–92, and the minimum for this period was 6,000 tons in 1992–93. For all of Ohio, the 3-winter average annual use of deicing-chemicals was 8.0 ton/2-ln mi (16,000 lb/2-ln mi) (Ohio Department of Transportation, written commun., 1994). Data collected at this site indicate the 3-winter average annual use of deicing-chemicals was 9.74 ton/2-ln mi. (19,490 lb/2-ln mi.), which is 22 percent greater than the State average. During the interim reporting period, a small amount of liquid calcium chloride ($CaCl_2$) also was applied to the highway in about 22 percent of the cases in addition to sodium chloride and abrasives.

Climate

The average annual precipitation for the area is 38.4 in. The average annual temperature for the area is 9.6°C (49.2°F), with the monthly normal high of 27.8°C (82.0°F) in July and the monthly normal low of -8.4°C (16.8°F) in January (National Oceanic and Atmospheric Administration, 1982). During the interim reporting period, annual precipitation data collected from the site averaged 28.5 in. The average annual snowfall is 50–60 in. for nearby reporting areas (Miller and Weaver, 1971).

Hydrogeology

The ground-water level is 5–9 ft below land surface throughout the year at this site. During the interim reporting period, the direction of flow varied from about 40° to 80° to the alignment of the highway, as determined by the triangulation method using available wells; average water-table slope is about 0.007. At this site the ground-water level responds to precipitation within 1 day, owing to the porous aquifer materials at the surface and the shallow water table.

Results of single-well aquifer tests (slug tests) on the aquifer indicate that the hydraulic conductivity is 30 ft/d. Assuming an average gradient of 0.007 and an effective porosity of 38 percent, the ground-water velocity was computed to be 0.55 ft/d.

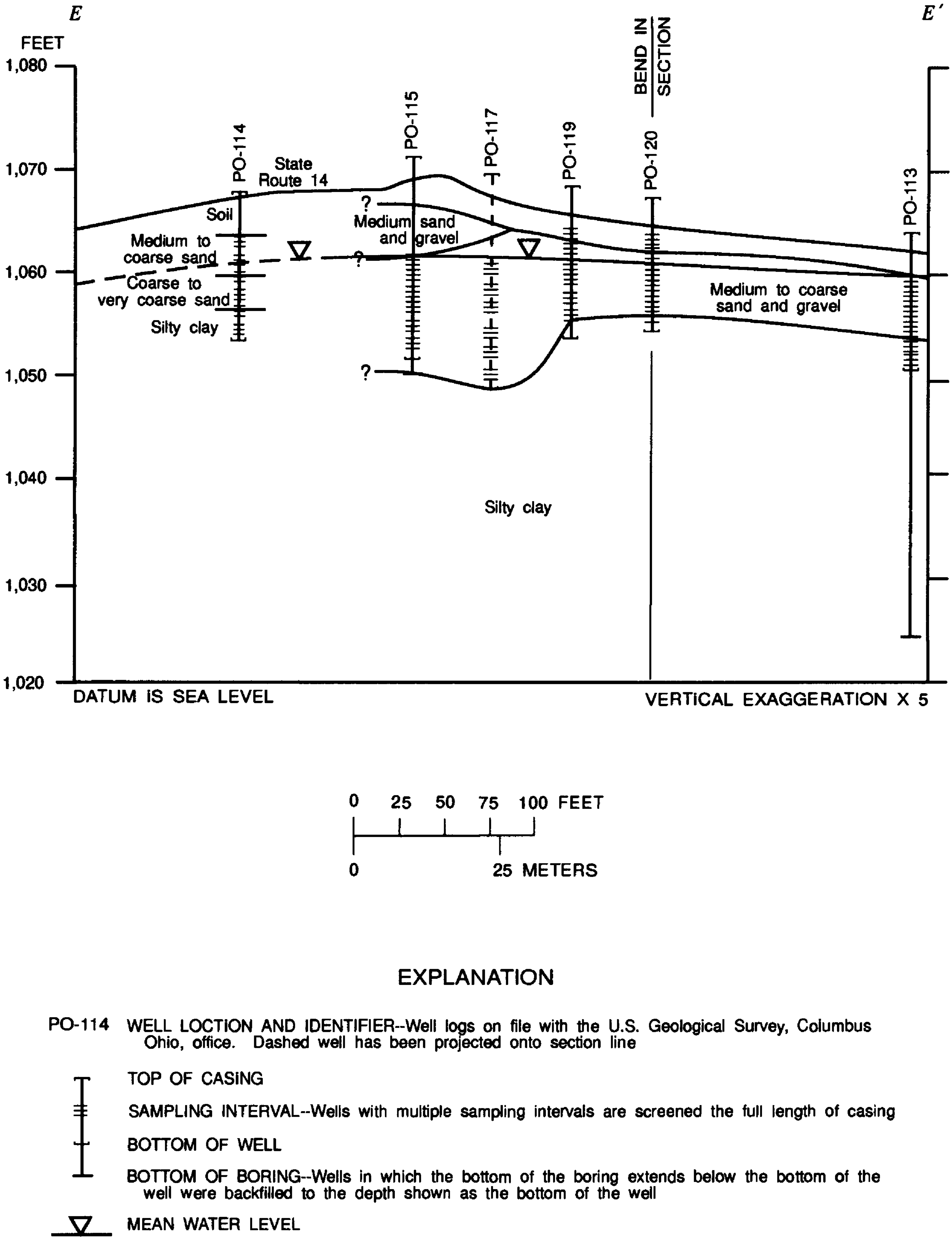


Figure 41. Geologic section *E-E′*, Portage County study site, Ohio. (Section trace shown in fig. 40.)

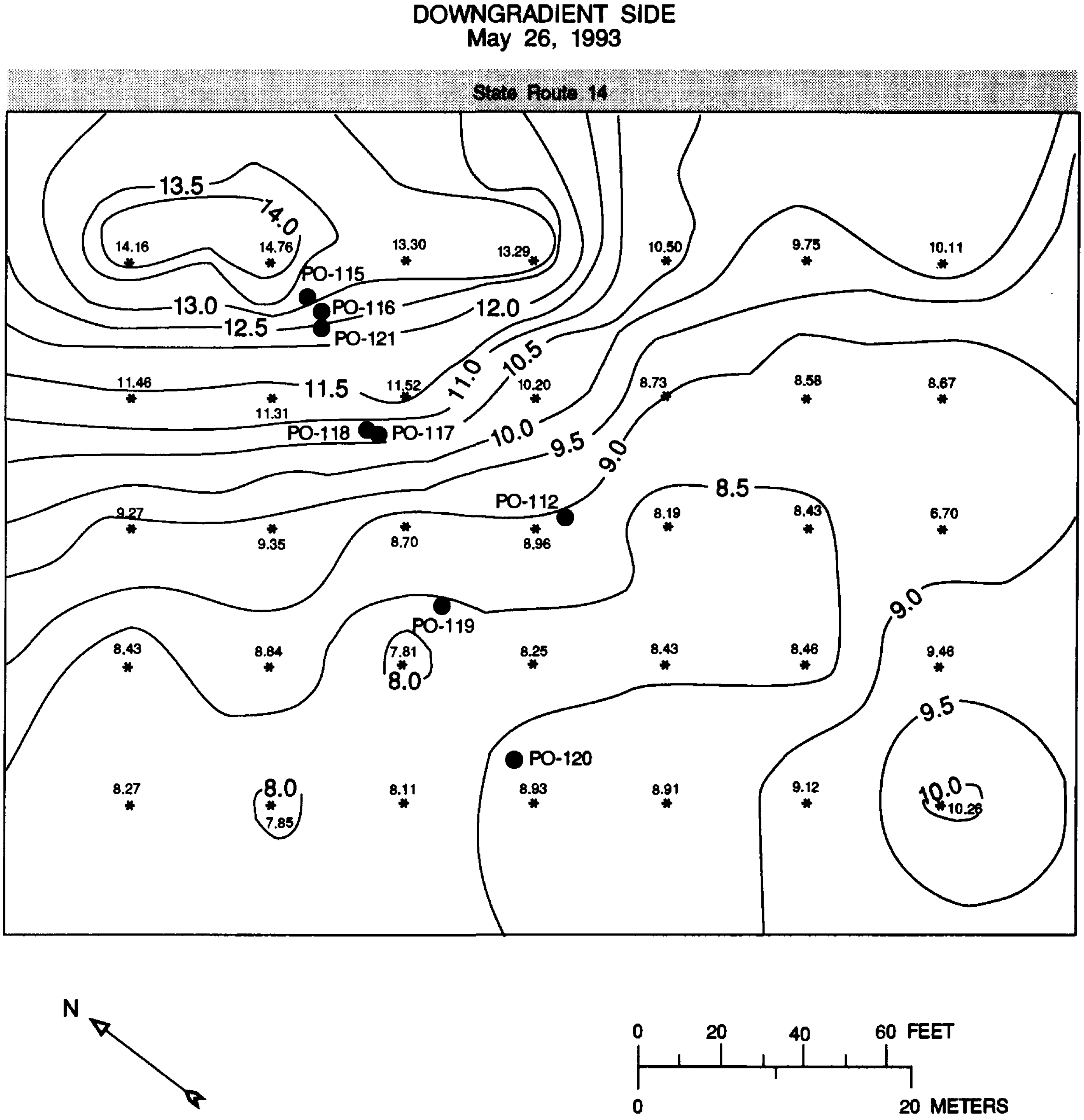
The electrical conductivity of the subsurface materials was measured at the Portage County site on four occasions by use of the Geonics EM-34-3 at the 10-m spacing. The composition of the aquifer materials was inferred from these measurements and well logs from the site. Surveys were completed at this site in July 1991, April 1993, May 1993, and August 1993. Measurements downgradient from the highway ranged from 3 mS/m at the well farthest from the highway to 15–20 mS/m within 100 ft of the highway. This range indicated medium to coarse sand and gravel, possibly including ground water with high specific conductance near the highway and also some fine sand or silt in some areas. Variations in electrical conductivity measurements between EM surveys define changes in the ground conductivity that would be attributable only to changes in water quality. Analysis of the regular ground-water samples verified that higher measurements downgradient from the highway are due, for the most part, to increased specific conductance of the ground water. Contour plots of two EM surveys of the downgradient side of the highway completed on May 26, 1993 and August 18, 1993, are shown in figure 42. The plots show an overall view of the distribution of the combined ground conductivity of earth materials and ground water. In general, the higher values are closer to the highway and the slight differences between the two plots are due to changes in the water quality of the aquifer. Measurements at this site did not show much variability in ground conductivity from one survey to the next (generally in the range of 0–5 mS/m), at least not at a scale that could be detected as a distinct plume. Chloride concentrations and specific conductance rarely return to their original upgradient values during a yearly cycle at this site.

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 sodium chloride applied to the highway are shown in figure 43. The plots of these characteristics can be used to compare events that resulted in increased specific conductance with ambient site conditions and deicer applications. The movement of chloride and other deicing-related constituents from the highway with time are indicated by boxplots of laboratory-determined data (fig. 44).

Field-monitored characteristics

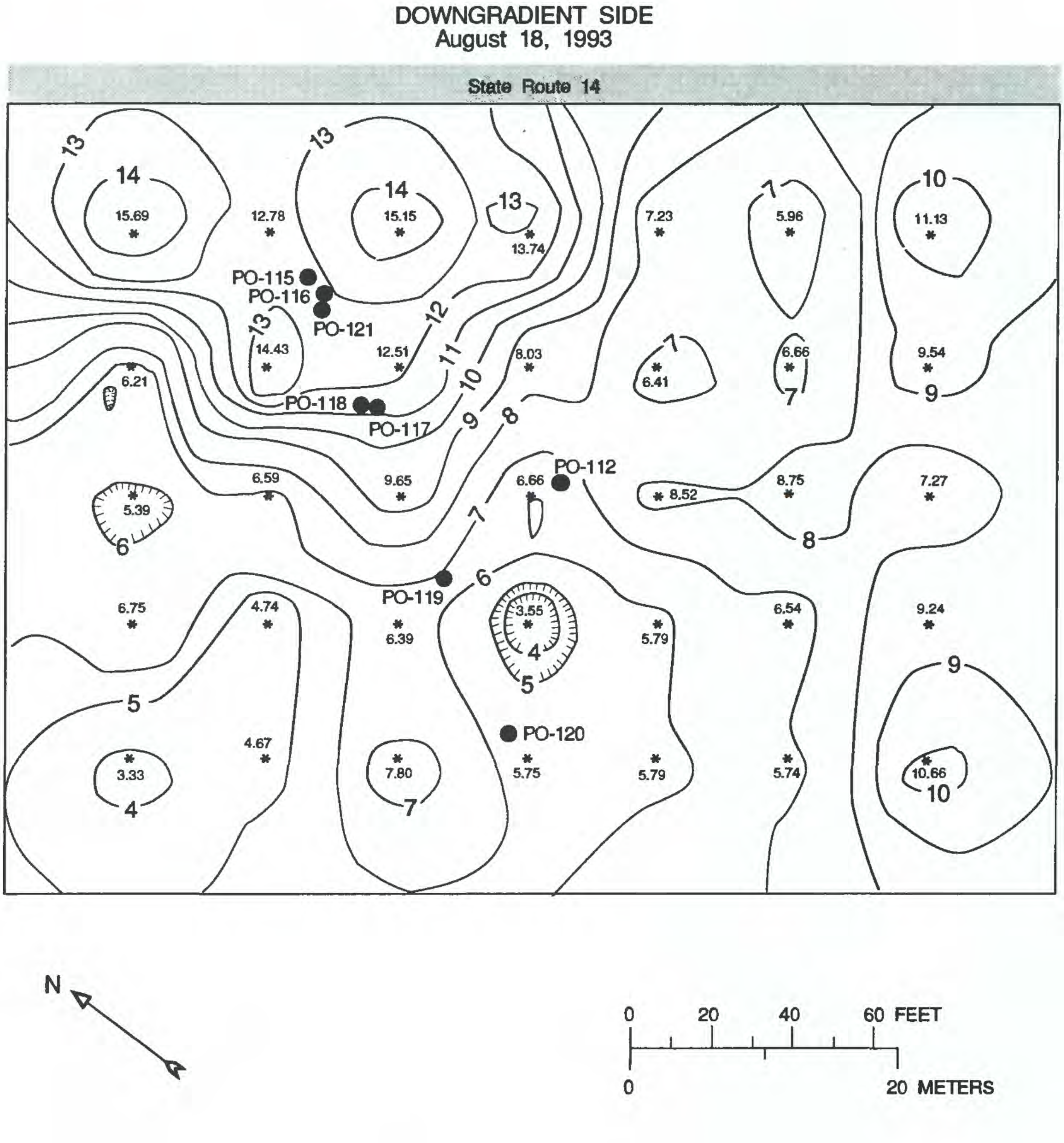
Specific conductance. Specific conductance of ground water varied considerably during the interim reporting period. A maximum of 2,540 μS/cm was recorded in December 1991, whereas a minimum of 125 μS/cm was recorded in January 1993. Annual extremes (based on water year) ranged from 2,080 μS/cm in September 1991 to 329 μS/cm in March 1991, 2,540 μS/cm in December 1991 to 136 μS/cm in August 1992, and 2,000 μS/cm in October 1992 to 125 μS/cm in January 1993. For comparison, the mean specific conductance at the upgradient well for the interim reporting period was 580 μS/cm. During periods of light and infrequent rainfall, specific conductance generally rose slowly to high levels, possibly as a result of ground water somewhat concentrated from water levels declining in the well. Deicing chemicals might also have been slowly entering the ground water from the base of the unsaturated zone; until the next significant precipitation probably washed the remaining chemicals held in the soils and unsaturated zone through to the water table, causing the specific conductance to immediately increase and then slowly decrease as the highest concentration of deicing chemicals flushed through the aquifer. During periods of high ground-water levels, specific conductance rose and returned to average levels more quickly, usually in a few days. This pattern indicates that the properties of the aquifer allow fairly rapid flow of ground water during most times of the year.



EXPLANATION

● PO-114	WELL LOCATION AND IDENTIFIER
* 10.26	DATA POINT--Number is ground conductivity, in millisiemens per meter
— 10 —	ELECTROMAGNETIC CONTOUR--Contour interval 0.5 millisiemen per meter

Figure 42. Contour plot of electromagnetic geophysical surveys on downgradient side of Portage County study site, Ohio, May 26, 1993, and August 18, 1993. (The horizontal coplanar arrangement was used with a 10-meter spacing.)



EXPLANATION

● PO-112	WELL LOCATION AND IDENTIFIER
* 10.68	DATA POINT--Number is ground conductivity, in millisiemens per meter
—10—	ELECTROMAGNETIC CONTOUR--Contour interval 1 millisiemen per meter. Hachures indicates depression

Figure 42. Contour plot of electromagnetic geophysical surveys on downgradient side of Portage County study site, Ohio, May 26, 1993, and August 18, 1993--Continued.

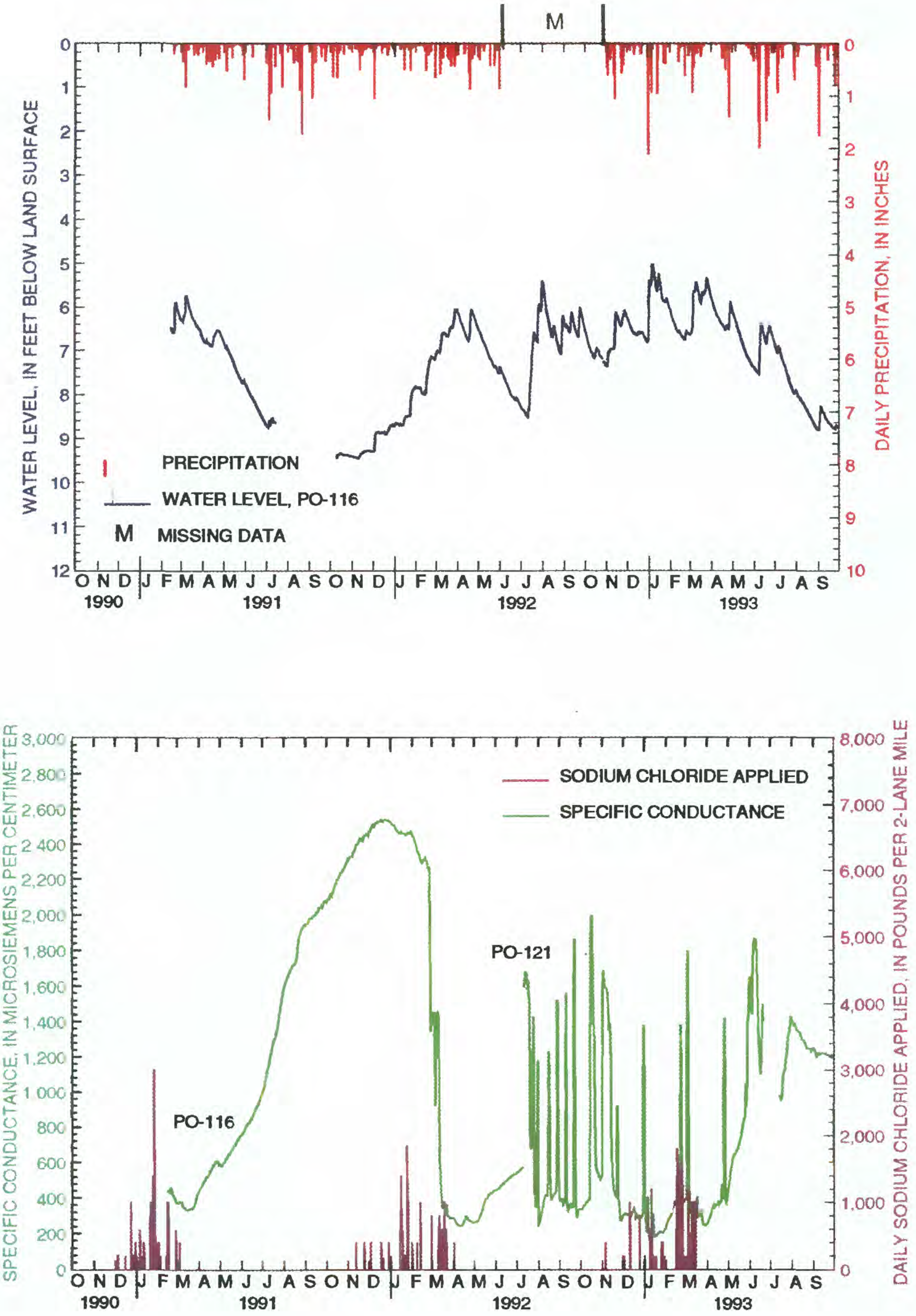


Figure 43. Ground-water levels, specific conductance of ground water, precipitation, and sodium chloride applied at the Portage County study site, Ohio.

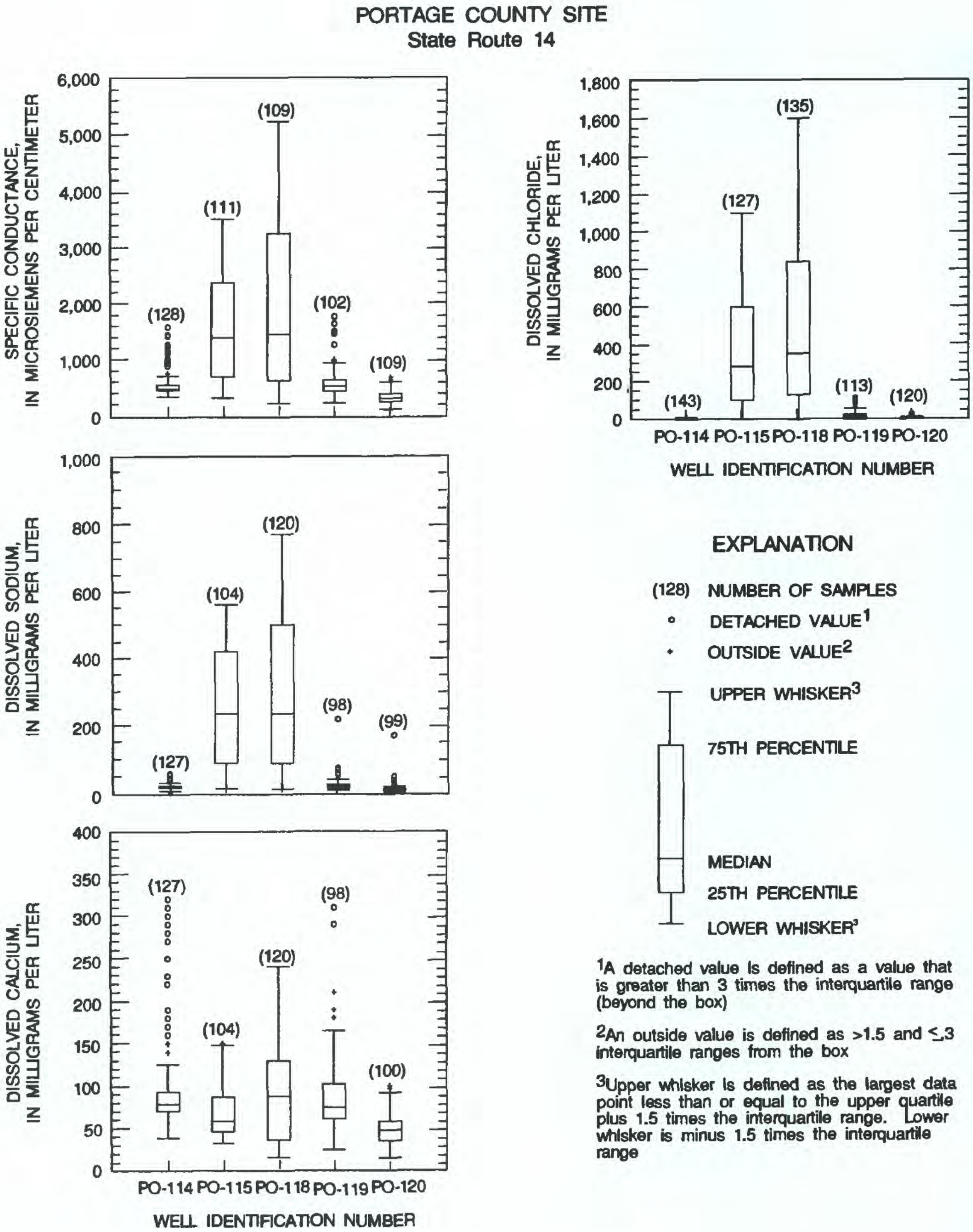


Figure 44. The distribution of specific conductance and concentrations of dissolved sodium, calcium, and chloride in ground water sampled at the Portage County study site, Ohio, January 1991-September 1993. (Plots are shown in downgradient order from left to right. Far left plot is upgradient from highway; others are downgradient.)

Air and soil temperature. During the interim reporting period the air temperature at this site ranged from 36.0°C in August 1991 to a minimum of -24.9°C in February 1993. The annual maximum for 1991 was 36.0°C in August, but the minimum for 1991 could not be accurately determined because measurements were not made until February 1991. Annual extremes (based on water year) for the remainder of the interim reporting period ranged from a maximum of 31.9°C in July 1992 to a minimum of -19.1°C in February 1992 and from a maximum of 35.9°C in August 1993 to a minimum of -24.9°C in February 1993.

Soil-temperature records were incomplete for 1991 and 1992; therefore, no extremes are reported. During 1993 the soil temperature ranged from a maximum of 26.2°C in July to a minimum of 0.4°C in February 1993. No soil temperature of 0°C or less was recorded on any day in 1993; thus, frozen soil would not have inhibited infiltration of runoff water into the aquifer.

Laboratory-determined characteristics

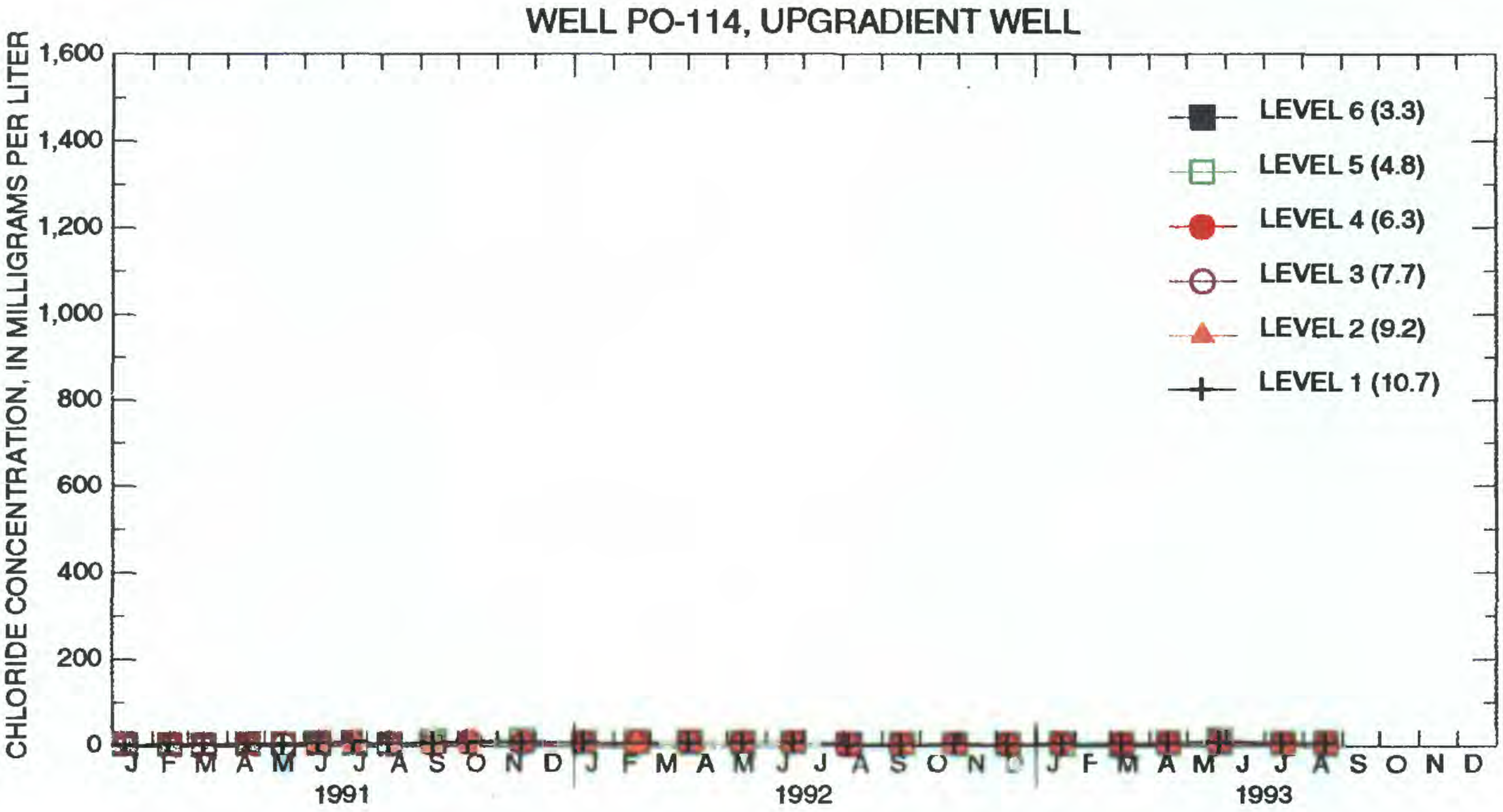
The amount of deicing chemicals applied to the highway at the Portage County site was fairly steady during the winter months. Cold temperatures often created icy conditions, and significant snowfalls were common. Summary statistics of the water-quality data collected at upgradient and downgradient wells are listed in table 13. Boxplots of specific conductance, dissolved calcium, dissolved sodium, and dissolved chloride for water-quality data from all levels of the upgradient well and the four downgradient sampling wells are shown in figure 44. Data shown are for the sampling period January 1991 through September 1993. Patterns that emerge from those data and require further discussion are noted below.

Chloride concentration. At the upgradient well, PO-114, the mean concentration of chloride was 6 mg/L and the maximum was 13 mg/L. Concentrations were much higher than background, however, at the first two downgradient wells. At the first downgradient well, the mean concentration was 369 mg/L and the maximum was 1,100 mg/L. At the second downgradient well, the mean concentration was 496 mg/L and the maximum was 1,600 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 5–19 mg/L; maximum 27–110 mg/L). These wells are completed just above a clay confining unit but are slightly shallower than the first two downgradient wells. 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. Dissolved chloride concentrations at each of six sampling levels in each well at the site are shown in figure 45. A vertical distribution of chloride concentrations is evident during most times of the year in the first downgradient well, and, to a lesser extent, in the second downgradient well. For example, in PO-115 in June 1992, the chloride concentration in levels 1 and 2 reached 890 mg/L but was only 210 mg/L in level 6, although samples from levels 1, 2, and 3 were often in a similar, elevated range. A water sample from the entire screened interval may have an average concentration somewhere between 210 and 890 mg/L. Preferential flowpaths can be monitored in this way, especially at sites with mixed aquifer materials. It is easy to see at this site that chemical-laden water is most highly concentrated in the bottom levels of the well, even at the first downgradient well. This vertical distribution appears to be lost as distance from the highway increases because elevated chloride concentrations were not seen in the two farthest downgradient wells, even though they were completed just above a clay confining unit. The configuration of the clay unit(s) is being investigated further.

Soil samples were collected at this site in August 1993. The extract from the soil-sample preparation method was analyzed at the NWQL for dissolved chloride concentration. The chloride concentration of the samples collected within 12 ft of the highway was 16–21 mg/L and decreased slightly to 12 mg/L by 80 ft downgradient from the highway.

Table 13. Water-quality data for multilevel wells at the Portage County site, Ohio, January 1991 through August 1993
[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples; UG, upgradient; DG, downgradient]

Well Name	Position	Statistic	Property or constituent				
			Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)	Bromide, dissolved (mg/L)
PO-114	UG	Maximum	1,590	320	57	13	0.06
		Minimum	340	39	1	0.5	<0.01
		Mean	580	102	19	6	0.01
		Median	477	79	19	5	0.01
		N	128	127	127	143	146
P0-115	1st DG	Maximum	3,510	150	560	1,100	0.16
		Minimum	310	33	13	1	<0.01
		Mean	1,569	68	255	369	0.06
		Median	1,390	58	235	280	0.05
		N	111	104	104	127	127
PO-118	2nd DG	Maximum	5,230	240	770	1,600	0.09
		Minimum	212	16	11	2	<0.01
		Mean	1,869	85	298	496	0.10
		Median	1,450	88	235	350	0.07
		N	119	120	120	135	137
PO-119	3rd DG	Maximum	1,770	310	220	110	0.14
		Minimum	218	25	7	1	<0.01
		Mean	582	89	23	19	<0.01
		Median	518	75	18	13	<0.01
		N	102	98	98	113	108
PO-120	4th DG	Maximum	671	100	170	27	0.09
		Minimum	107	15	2	0.2	<0.01
		Mean	316	48	12	5	<0.01
		Median	299	48	9	3	<0.01
		N	109	100	99	120	115



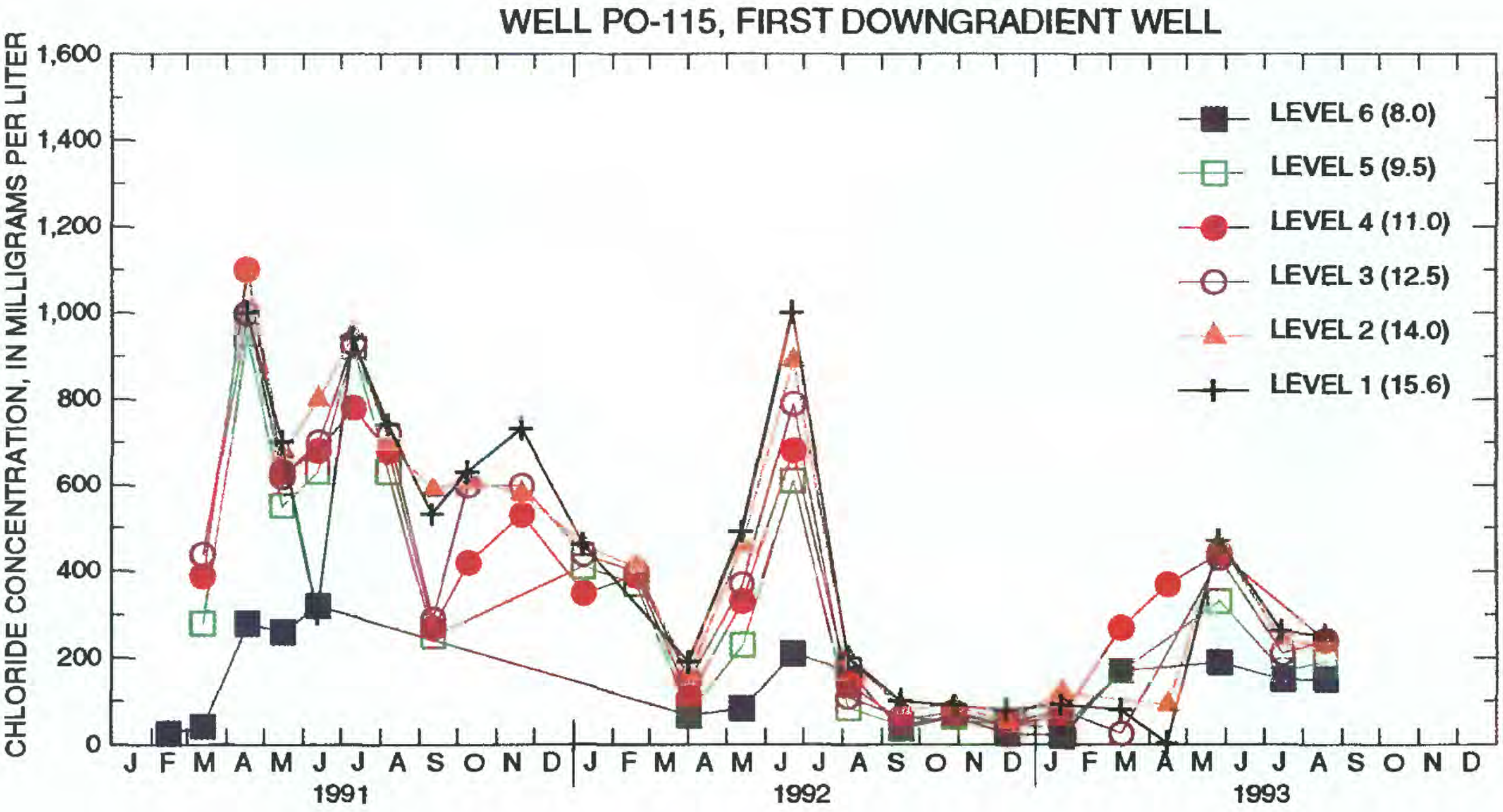
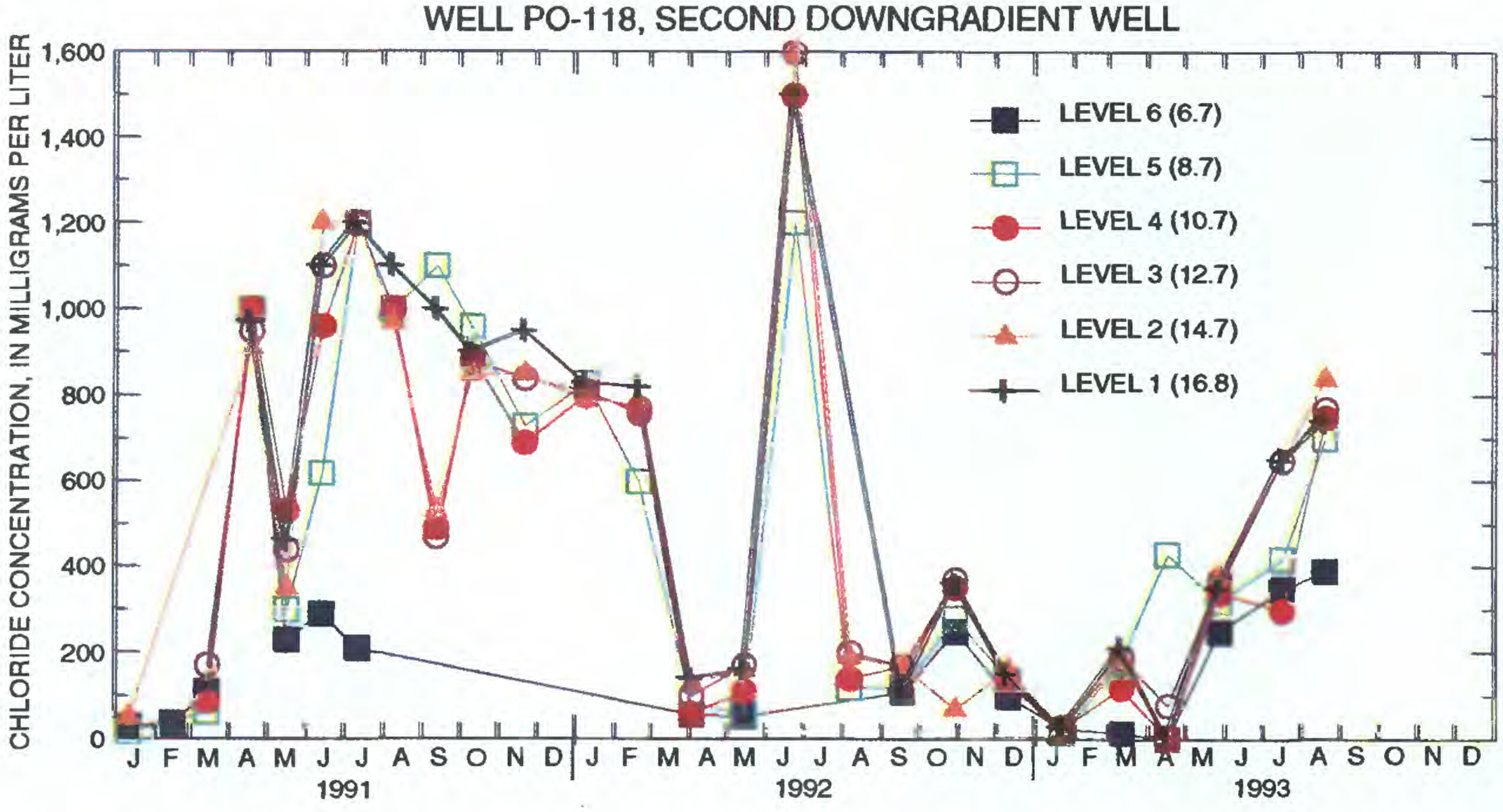


Figure 45. Dissolved chloride concentration, by level, for multilevel wells at the Portage County study site, Ohio. (Number in parentheses is depth, in feet below land surface.)



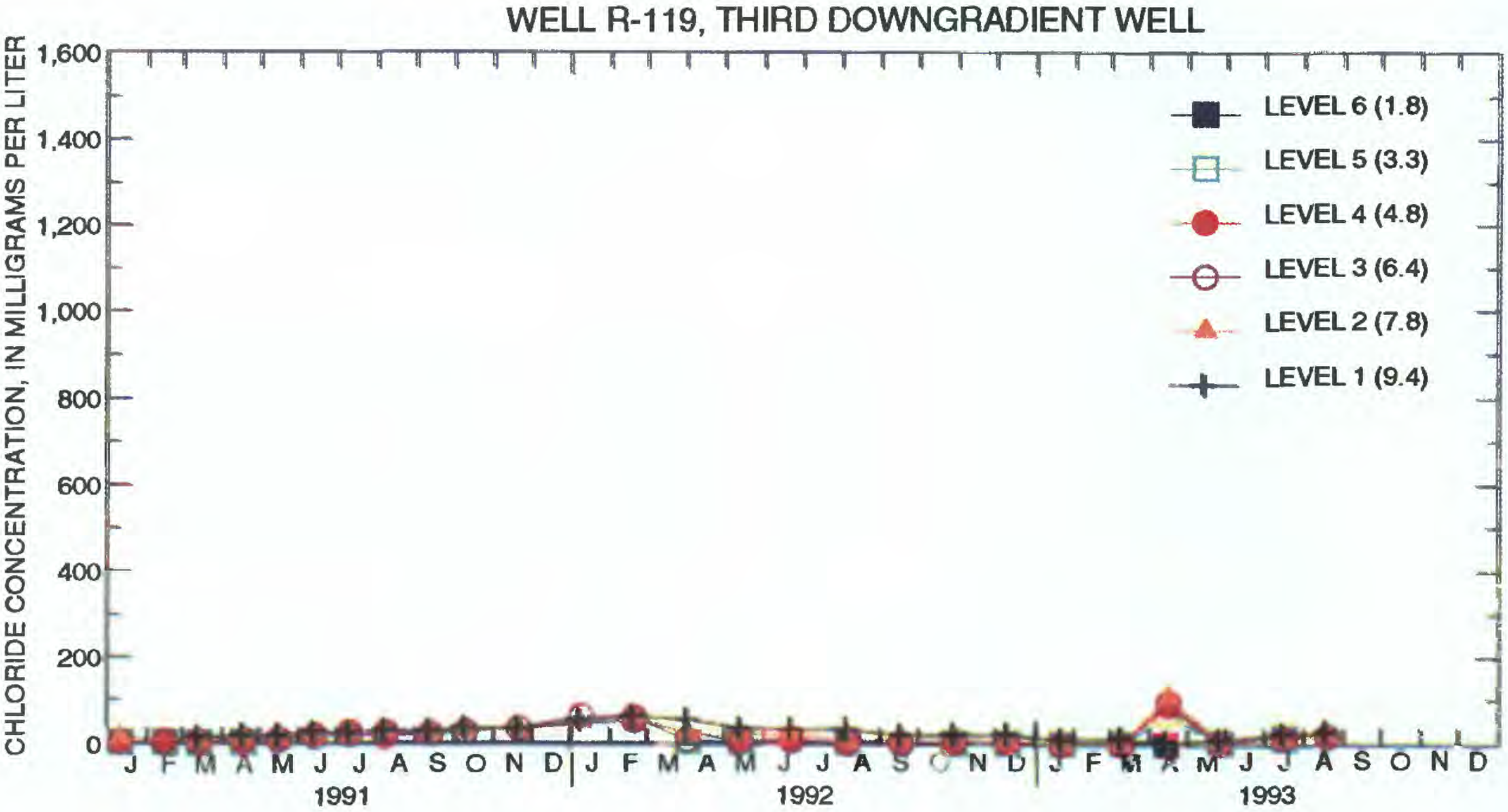


Figure 45. Dissolved chloride concentration, by level, for multilevel wells at the Portage County study site, Ohio--Continued.

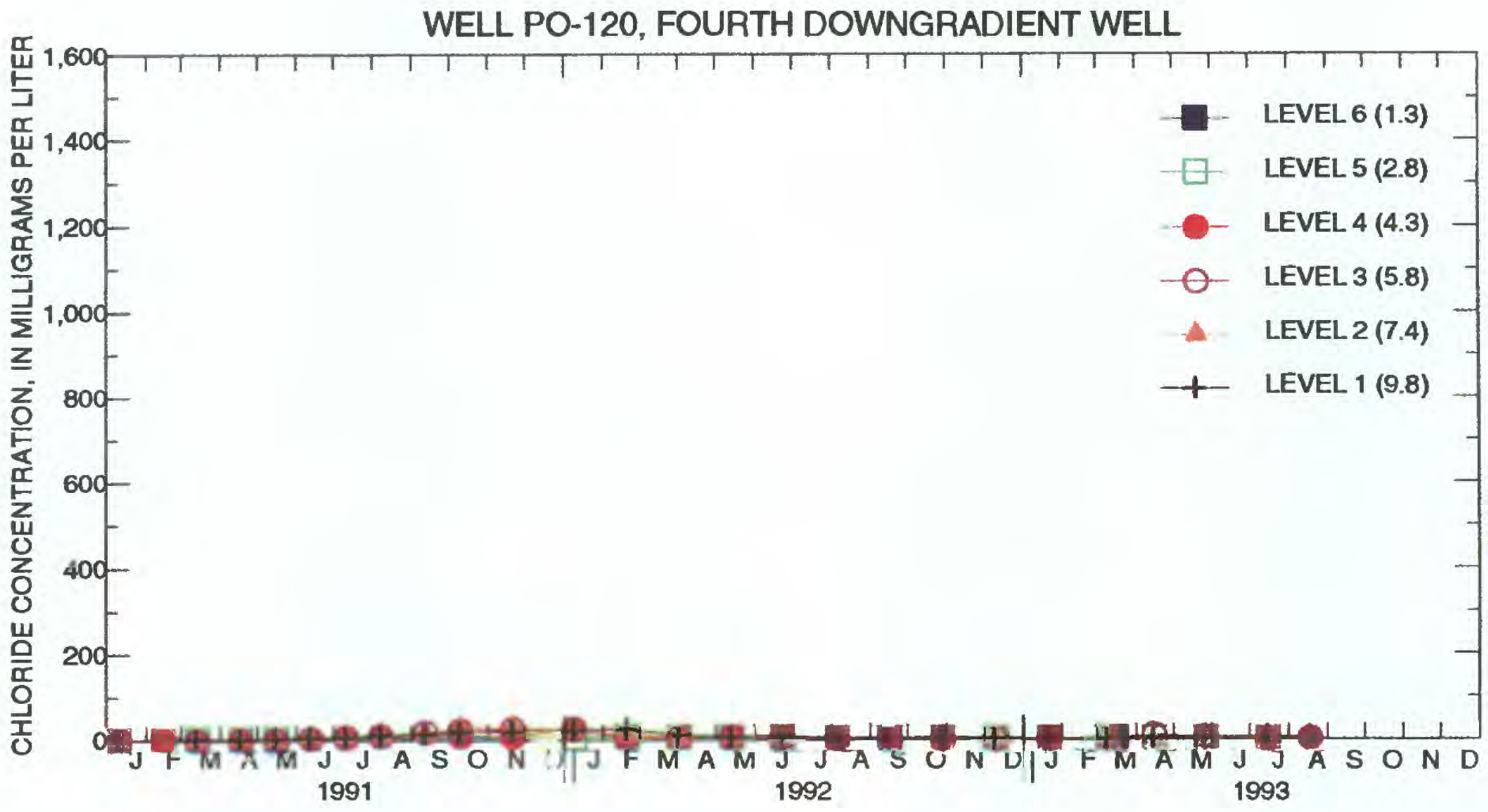


Figure 45. Dissolved chloride concentration, by level, for multilevel wells at the Portage County study site, Ohio--Continued.

Sodium concentration. At the upgradient well, PO-114, the mean concentration of sodium was 19 mg/L and the maximum was 57 mg/L. Concentrations were much higher at the first two downgradient wells. At the first downgradient well, the mean concentration was 255 mg/L and the maximum was 560 mg/L. At the second downgradient well, the mean concentration was 298 mg/L and the maximum was of 770 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 12 and 23 mg/L; maximum 170 and 220 mg/L) than those found at the first and second downgradient wells. The configuration of the clay units at this site may provide an explanation.

Specific conductance. At the upgradient well, PO-114, the mean specific conductance was 580 µS/cm and the maximum was 1,590 µS/cm. Values increased considerably at the first two downgradient wells. At the first downgradient well, the mean specific conductance was 1,569 µS/cm and the maximum was 3,510 µS/cm. At the second downgradient well, the mean value was 1,869 µS/cm and the maximum was 5,230 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 316– 582 mg/L; maximum 671–1,770 mg/L) than at the first and second downgradient wells. In fact, at the fourth downgradient well, mean and maximum values were lower than those found at the upgradient well. This result also may be due to the configuration of the clay units present. Because the specific conductance at the upgradient and third and fourth downgradient wells was relatively high among the sites sampled, and yet the chloride concentration is among the lowest, another ion may be contributing to the high specific conductance at this site.

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 Plateau 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 was 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; the gravel berm is 3–4 ft wide. The highway is very straight and flat at the site, bending to the west 1,000 ft to the northwest of the site.

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. From well logs obtained from ODNR, the bedrock can be seen to range in depth from 15 ft below land surface near the valley walls to more than 30 ft below land surface toward the river. 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. Individual well logs were constructed for each of the wells. A geologic cross-section of the site was constructed on the basis of these logs (fig. 47).

The 12-winter (1981–93) average annual use of deicing-chemicals in Richland County as a whole was 5,436 tons (table 3). The maximum for this 12-winter period was 8,914 tons in 1983–84, and the minimum for this period was 2,606 tons in 1982–83. The 3-winter (1990–93) average annual use of deicing-chemicals during the interim reporting period for this county as a whole was 4,864 tons. The maximum for this 3-winter period was 5,220 tons in 1990–91, and the minimum for this period was 4,660 tons in 1992–93. For all of Ohio, the 3-winter average annual use of deicing-chemicals was 8.0 ton/2-ln mi (16,000 lb/2-ln mi) (Ohio Department of Transportation, written commun., 1994). Data collected at this site indicate the 3-winter average annual use of deicing-chemicals was 7.64 ton/2-ln mi. (15,283 lb/2-ln mi.), which is nearly the State average. For the interim reporting period, a small amount of liquid calcium chloride ($CaCl_2$) also was applied to the highway in about 18 percent of the treatments, in addition to sodium chloride and abrasives.

Climate

The average annual precipitation for the area is 35.9 in. The average annual temperature for the area is 8.8°C (47.9°F), with the monthly normal high of 27.9°C (82.3°F) in July and the monthly normal low of -9.7°C (14.6°F) in January (National Oceanic and Atmospheric Administration, 1982). During the interim reporting period, annual precipitation data collected at the site averaged 37.8 in. The average annual snowfall is 30–40 in. for nearby reporting areas (Miller and Weaver, 1971).

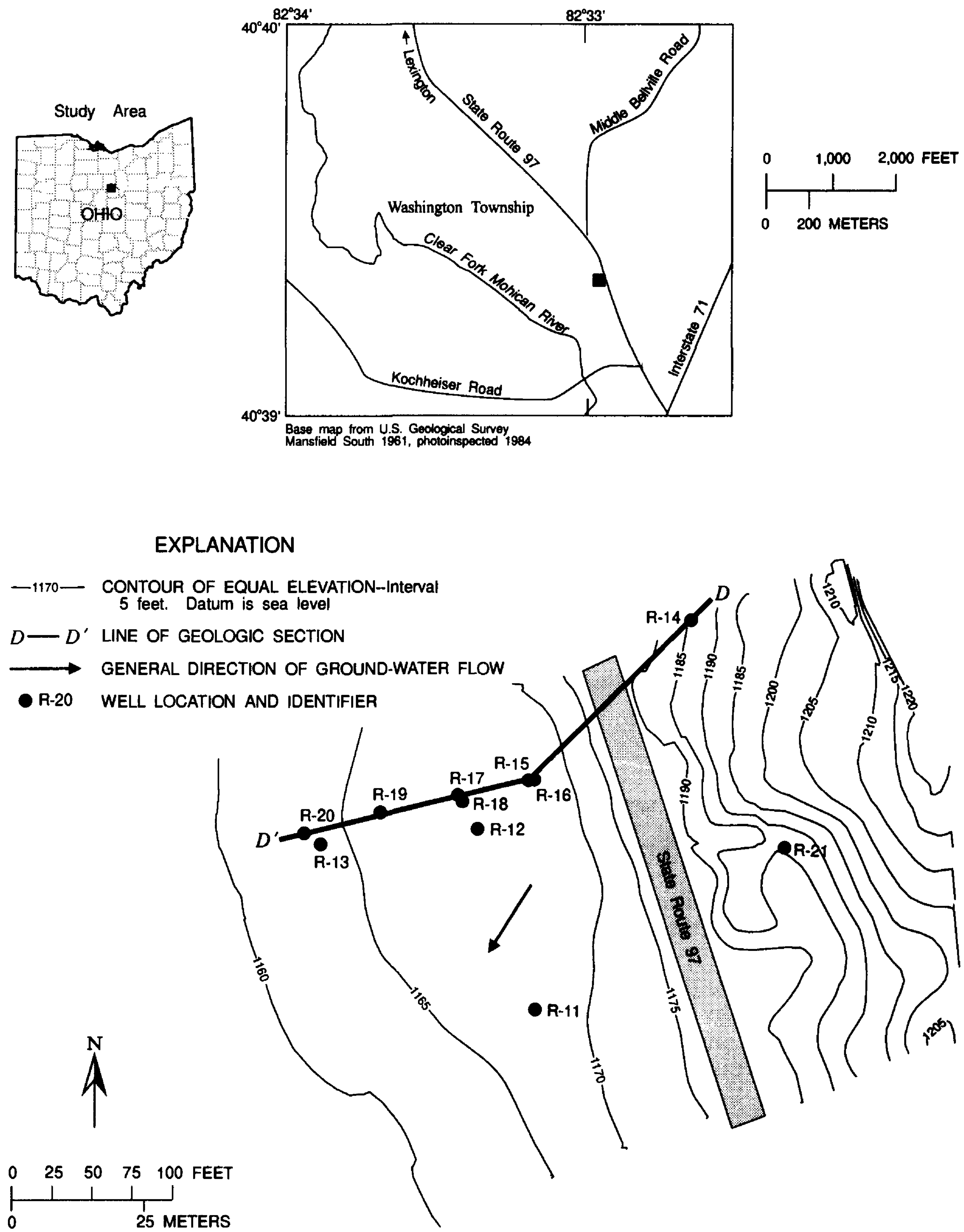
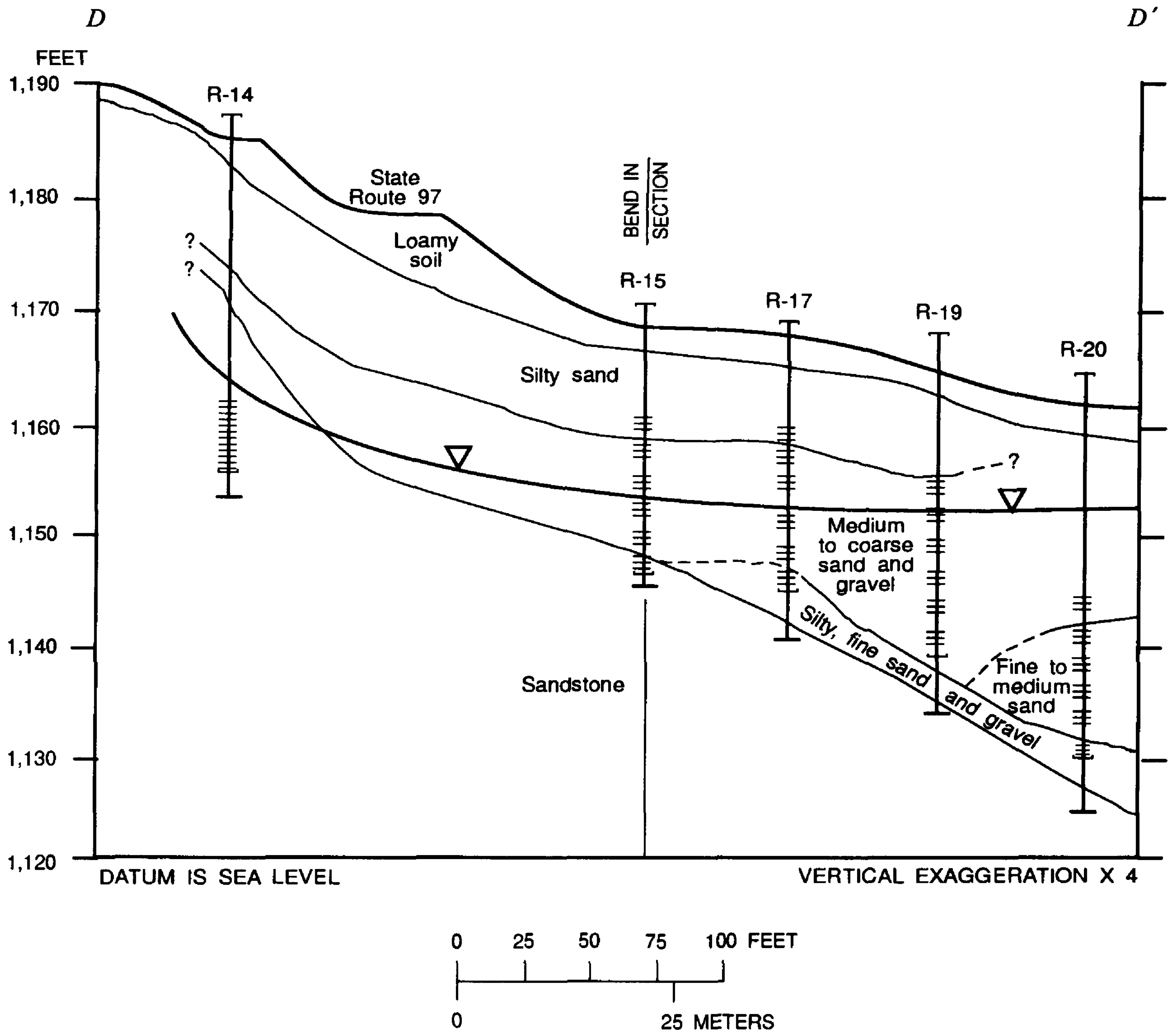


Figure 46. Topography, well locations, and ground-water flow direction at Richland County study site.



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

WELL SCREEN

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

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

Hydrogeology

The ground-water level is 11–17 ft below land surface throughout the year at this site. During the interim reporting period, the direction of flow varied from about 51° to 60° to the alignment of the highway, as determined by the triangulation method using available wells; average water-table slope is about 0.052. At this site the ground-water level responds to precipitation within 1 day, owing to the porous aquifer materials at the surface and the shallow water table.

Results of single-well aquifer tests (slug tests) on the aquifer indicate that the hydraulic conductivity is 5.2 ft/d. Assuming an average gradient of 0.052 and an effective porosity of 40 percent, the ground-water velocity was computed to be 0.68 ft/d.

The electrical conductivity of the subsurface materials was measured at the Richland County site on two occasions by use of the Geonics EM-34-3 at the 10-m spacing. The composition of the aquifer materials was inferred from these measurements and well logs from the site. Surveys were completed at this site in March 1992 and April 1993. Measurements downgradient from the highway ranged from 2 mS/m near the well farthest from the highway to 8 mS/m close to the highway, an indicator of very coarse, unconsolidated materials. Because of the steep gradient of a hill on the upgradient side of the highway, an upgradient survey was completed only once to verify the materials present. Minor changes in measurements from one survey to the next indicated a change in the specific conductance of the ground-water attributable only to changes in water quality. Analysis of the regular ground-water samples verified that slightly higher measurements are due, for the most part, to increased specific conductance of the ground water.

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 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. The movement of chloride and other deicing-related constituents from the highway with time are indicated by boxplots of laboratory-determined data (fig. 49).

Field-monitored characteristics

Specific conductance. Specific conductance of ground water varied considerably during the interim reporting period. A maximum of 645 μS/cm was recorded in January 1993, whereas a minimum of 157 μS/cm was recorded in March 1991. Annual extremes (based on water year) ranged from 436 μS/cm in September 1991 to 157 μS/cm in March 1991, 634 μS/cm in July 1992 to 306 μS/cm in May 1992, and 645 μS/cm in January 1993 to 219 μS/cm in May 1993. For comparison, the mean specific conductance of ground water from the upgradient well for the interim reporting period was 239 μS/cm. During periods of low precipitation, specific conductance generally rose slowly, especially when the ground-water level was low. Precipitation events caused release of deicing chemicals held in the soils and unsaturated zone to the water table, in turn causing the specific conductance to immediately increase and then decrease as the deicing chemicals flushed through the aquifer. This process was relatively brief because of the steep gradient at this site.

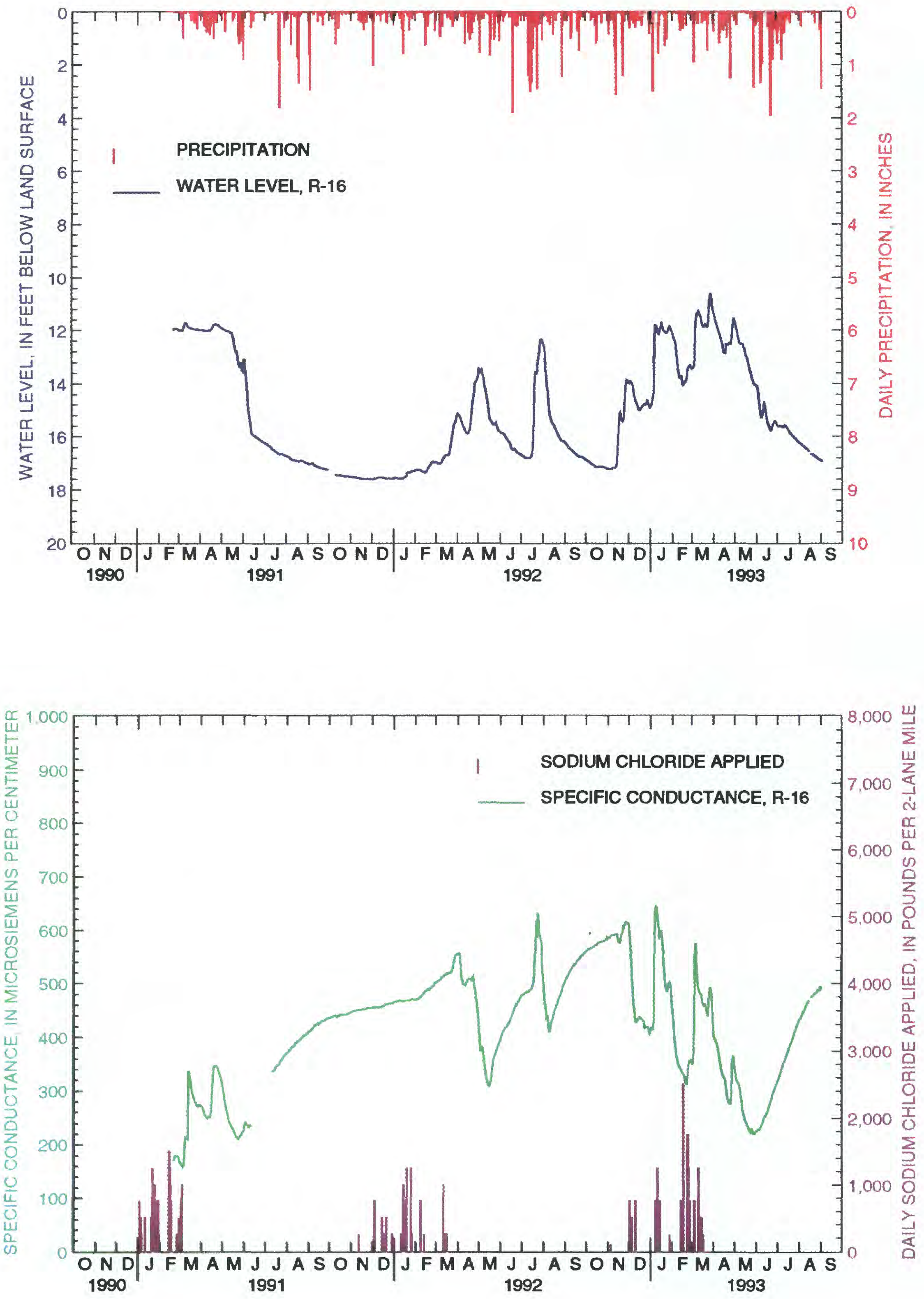


Figure 48. Ground-water levels, specific conductance of ground water, precipitation, and sodium chloride applied at the Richland County study site, Ohio.

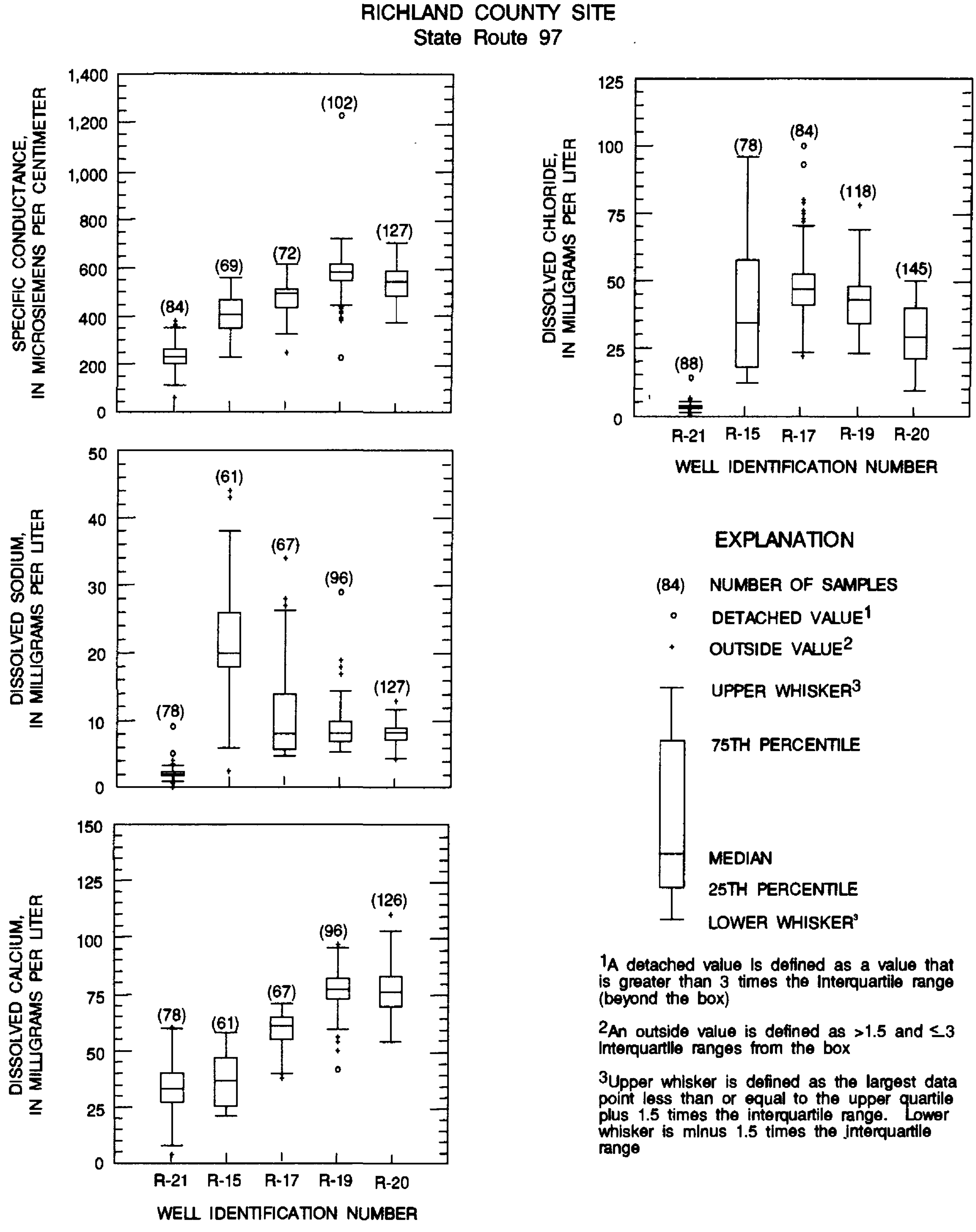


Figure 49. The distribution of specific conductance and concentrations of dissolved sodium, calcium, and chloride in ground water sampled at the Richland County study site, Ohio, January 1991-September 1993. (Plots are shown in downgradient order from left to right. Far left plot is upgradient from highway; others are downgradient.)

Air and soil temperature. During the interim reporting period the air temperature at this site ranged from 36.0°C in August 1991 to a minimum of -26.1°C in January 1992. The annual maximum for 1991 was 36.0°C in August, but the minimum for 1991 could not be accurately determined because measurements were not made until February 1991. Annual extremes (based on water year) for the remainder of the interim reporting period ranged from a maximum of 30.4°C in August 1992 to a minimum of -26.1°C in January 1992 and from a maximum of 33.0°C in August 1993 to a minimum of -24.6°C in February 1993.

During the interim reporting period, the soil temperature ranged from a maximum of 29.3°C in August 1993 to a minimum of 1.0°C in February 1992. The annual maximum for 1991 was 28.5°C in July, but the minimum for 1991 could not be accurately determined because measurements were not made until February 1991. Annual extremes (based on water year) for the remainder of the interim reporting period ranged from a maximum of 27.9°C in July 1992 to a minimum of 1.0°C in February 1992 and from a maximum of 29.3°C in August 1993 to a minimum of 4.6°C in February and March 1993. No soil temperature of 0°C or less was recorded on any day during that period; thus, frozen soil would not have inhibited infiltration of runoff water into the aquifer.

Laboratory-determined characteristics

The amount of deicing chemicals applied to the highway varied widely at the Richland County site. 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 are listed in table 14. 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 are shown in figure 49. Data shown are for the sampling period January 1991 through September 1993. Patterns that emerge from those data and require further discussion are noted below.

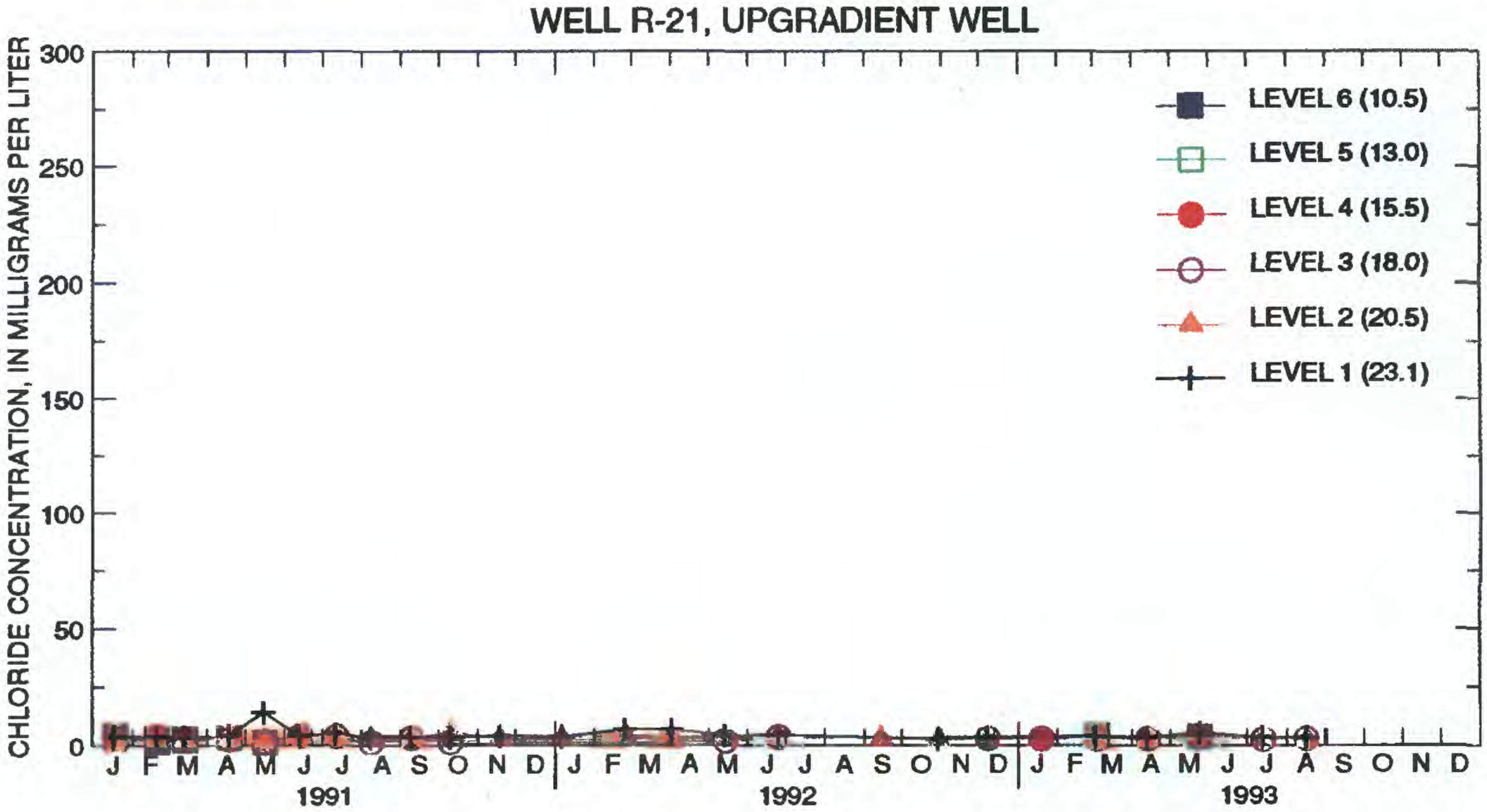
Chloride concentration. At the upgradient well, R-21, the mean concentration of chloride was 3 mg/L and the maximum was 14 mg/L. Concentrations were generally higher at the first two downgradient wells (mean, 41–49 mg/L; maximum, 96–100 mg/L). Concentrations remained fairly constant downgradient along 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 78 mg/L. By the fourth downgradient well, R-20, the mean concentration was 30 mg/L and the maximum was 50 mg/L. Thus, 150 ft downgradient from the highway, the mean concentration at the fourth downgradient well was about 10 times the upgradient or background concentration. Although the concentrations are relatively low overall, a pattern of movement through the aquifer can be observed.

Dissolved chloride concentrations from each of six sampling levels in each well at the site are shown in figure 50. 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, deicing-chemical-laden water moves quickly throughout the saturated zone, and the chloride concentration approaches background levels between deicing-chemical applications more frequently than at the other sites.

Soil samples were collected at this site in August 1993. The extract from the soil- sample preparation method was analyzed at the NWQL for dissolved chloride concentration. The chloride concentration of the samples collected within 15 ft of the highway was 22–39 mg/L and decreased to 3 mg/L by 70 ft downgradient from the highway.

Table 14. Water-quality data for multilevel wells at the Richland County site, Ohio, January 1991 through August 1993
[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; N, number of samples; UG, upgradient; DG, downgradient]

Well Nsme	Position	Ststistic	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Chloride, dissolved (mg/L)	Bromide, dissolved (mg/L)
			Property or constituents				
R-21	UG	Maximum	384	60	9	14	0.04
		Minimum	68	4	0.1	0.1	<0.01
		Mean	239	34	2	3	0.02
		Median	237	33	2	3	0.02
		N	84	78	78	88	89
R-15	1st DG	Maximum	563	58	44	96	0.12
		Minimum	231	21	3	12	<0.01
		Mean	403	36	22	41	0.03
		Median	409	37	20	34	0.02
		N	69	61	61	78	75
R-17	2nd DG	Maximum	618	71	34	100	0.08
		Minimum	249	38	5	22	<0.01
		Mean	484	59	11	49	0.04
		Median	496	61	8	47	0.03
		N	72	67	67	84	83
R-19	3rd DG	Maximum	1,230	97	29	78	0.09
		Minimum	230	42	5	23	<0.01
		Mean	572	76	9	42	0.03
		Median	586	77	8	43	0.03
		N	102	96	96	118	117
R-20	4th DG	Maximum	703	110	13	50	0.10
		Minimum	374	54	4	9	<0.01
		Mean	541	77	8	30	0.03
		Median	544	76	8	29	0.03
		N	127	126	127	145	145



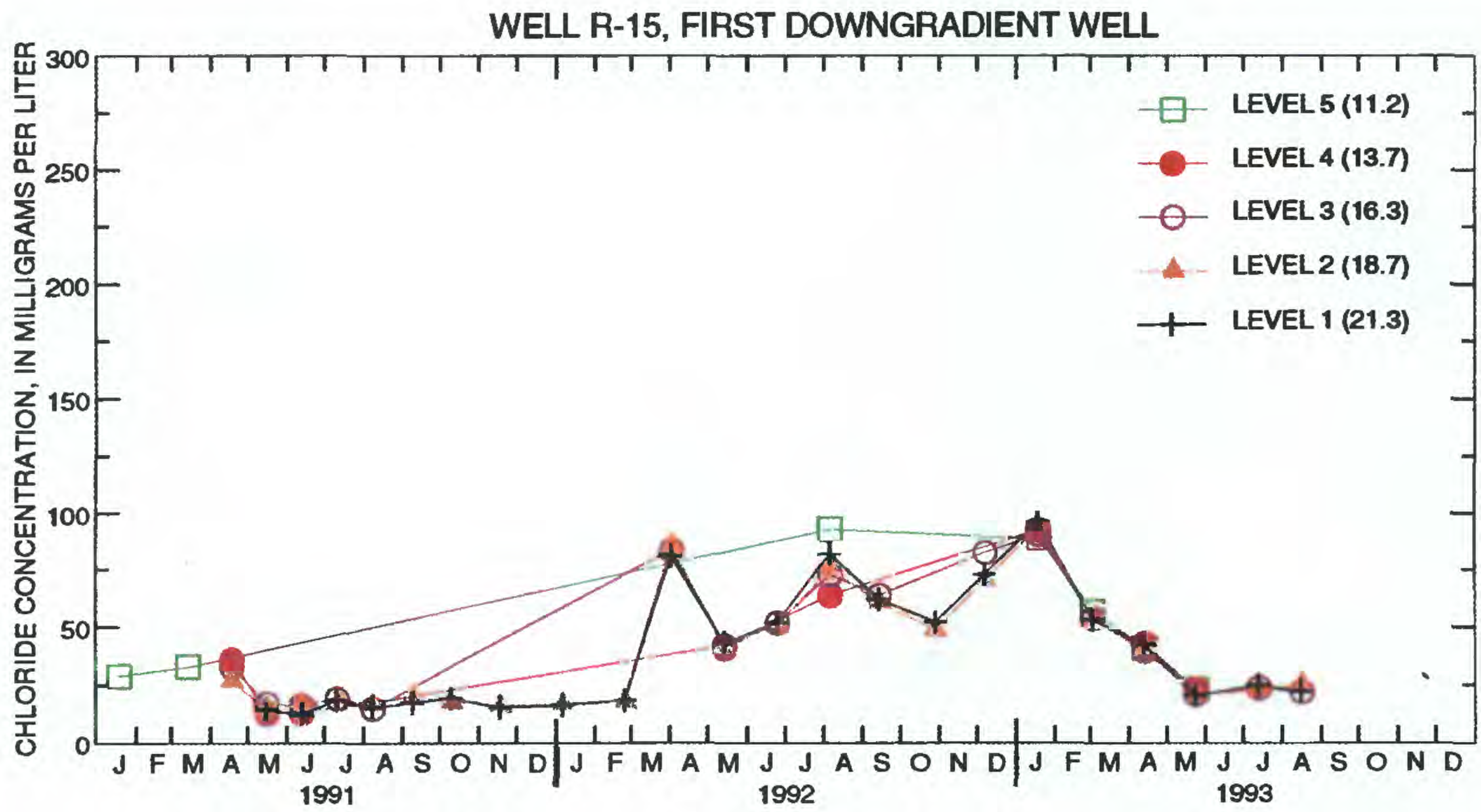
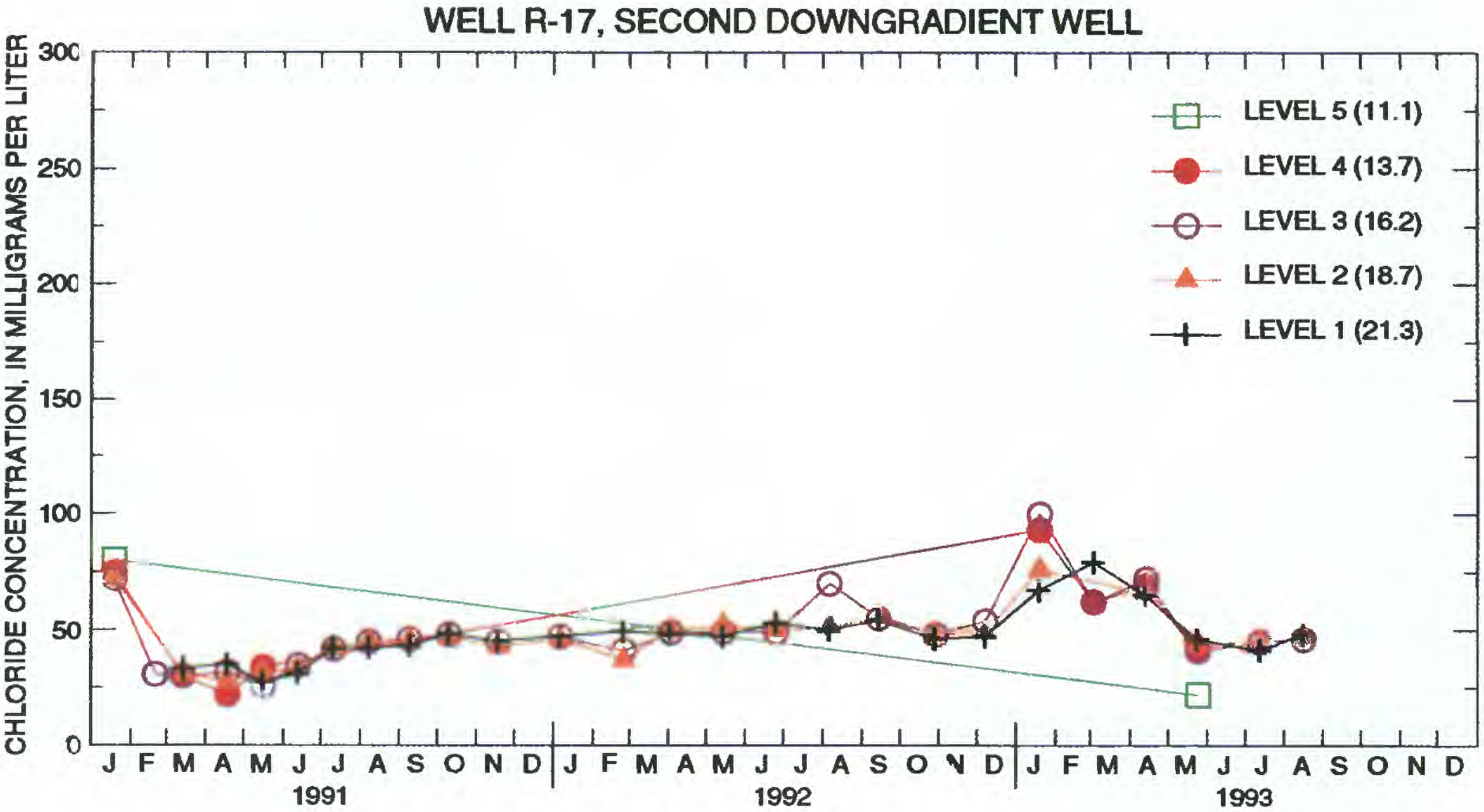


Figure 50. Dissolved chloride concentration, by level, for multilevel wells at the Richland County study site, Ohio. (Number in parentheses is depth, in feet below land surface.)



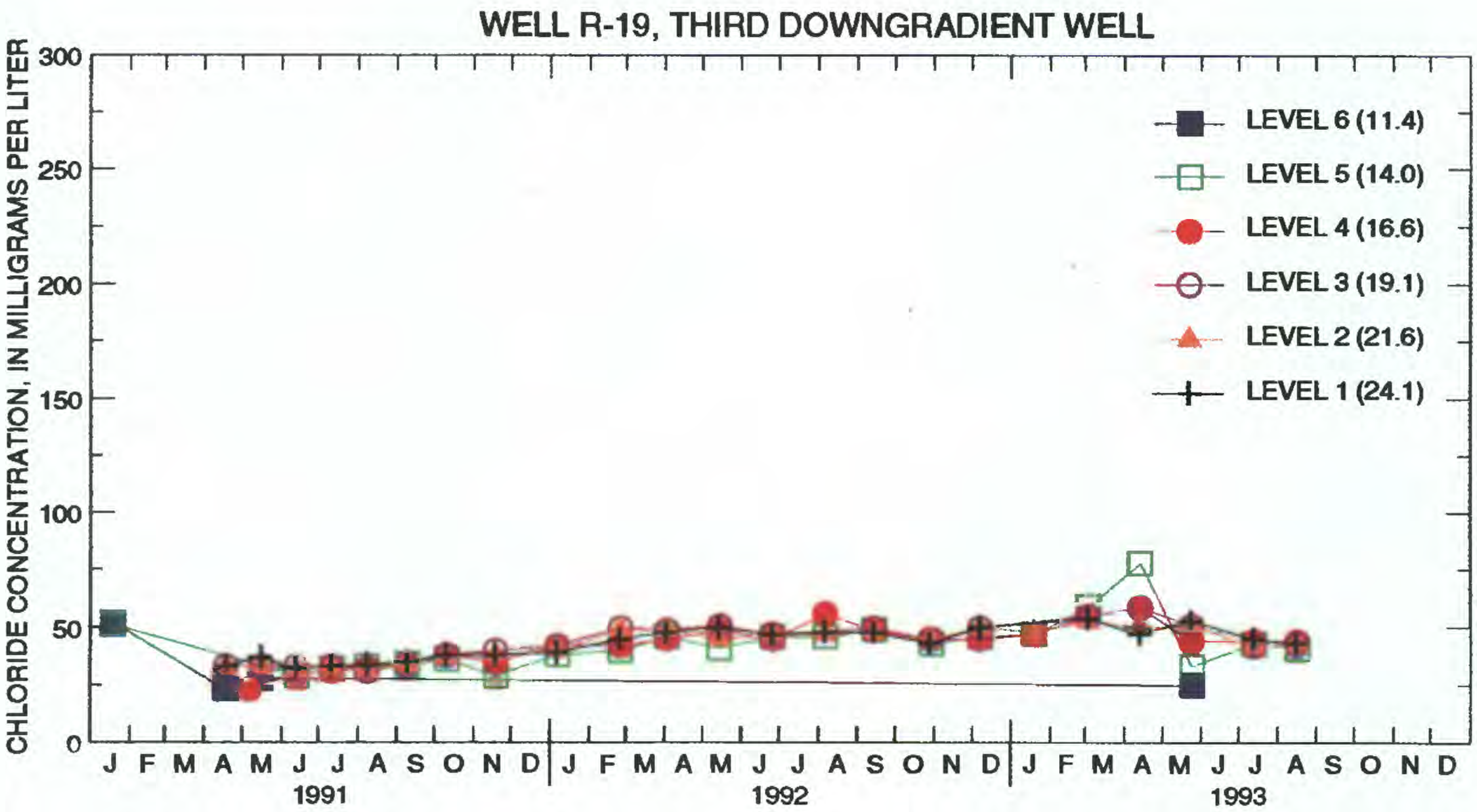


Figure 50. Dissolved chloride concentration, by level, for multilevel wells at the Richland County study site, Ohio--Continued.

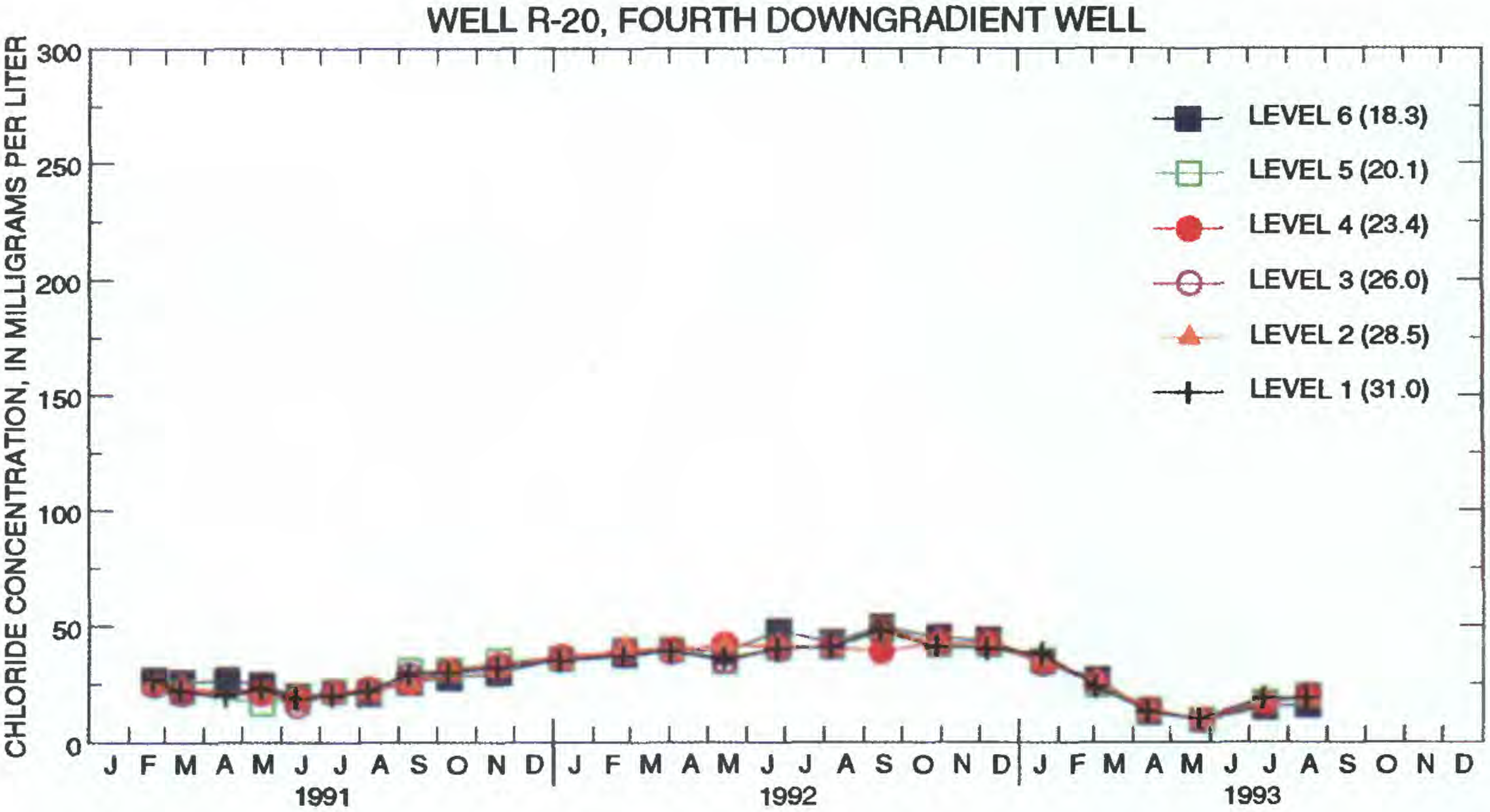


Figure 50. Dissolved chloride concentration, by level, for multilevel wells at the Richland County study site, Ohio--Continued.

Sodium concentration. At the upgradient well, R-21, the mean concentration of sodium was 2 mg/L, and the maximum was 9 mg/L. Concentrations were generally higher at the first downgradient well (mean, 22 mg/L; maximum, 44 mg/L). The mean concentration remained fairly constant 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 8 mg/L and the maximum 13 mg/L. Thus, 150 ft downgradient from the highway, the mean concentration at the fourth downgradient well was about four times the upgradient or background concentration.

Specific conductance. At the upgradient well, R-21, the mean specific conductance was 239 µS/cm and the maximum was 384 µS/cm. Mean values were fairly constant throughout the four downgradient wells (mean, 403–572 µS/cm), although the maximum values ranged from 563–1,230 µS/cm, the highest occurring at the third downgradient well. Therefore, 150 ft downgradient from the highway, the mean specific conductance at the fourth downgradient well was about twice the upgradient or background value. Specific conductance follows the same pattern as the calcium concentration does.

SUMMARY

The U.S. Geological Survey (USGS), in cooperation with the Ohio Department of Transportation (ODOT) and the Federal Highway Administration is studying the effects of highway-deicing chemicals on shallow ground-water throughout Ohio. 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. The study began in January 1988 and is planned to continue through 2001.

The interim reporting period covered in this report is January 1988 through September 1993. Results of the first 3 years of water-quality data collection (January 1991 through September 1993), as well as the environmental setting and hydrogeology of each of the eight sites, are presented.

Selected water-quality characteristics were monitored by use of multilevel sampling wells on the upgradient and downgradient sides of the highway. For this study, samples are being collected every 4 to 6 weeks. Chloride concentration is being used as a chemically conservative tracer to track the movement of deicing chemicals in the ground water through time. Bromide:chloride ratios calculated at each site helped to determine that deicing chemicals, not brine or formation ground water, were the source of increased sodium and chloride concentration (when present) at each site.

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

More than 5,000 water samples were collected during the interim reporting period. All 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 (Shindel and others, 1991-93). Data collection is planned to continue through September 1999. Water-quality sampling, therefore, is planned for a total of 9 years, 1991–99. A final report is planned to follow in 2001.

Ashland County. The Ashland County site is on SR 3 near Loudonville, Ohio. It is second priority for ODOT deicing. This site received an annual average of 10,700 lb/2-ln mi of deicing chemicals for the interim reporting period. Snowfall averages 30–40 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 a dense gray clay at a depth of 13–16 ft and bedrock at a depth of 17–43 ft. The ground-water level varies from 1–7 ft below land surface throughout the year. From aquifer tests, the hydraulic conductivity was computed to be 4 ft/d. Assuming an average gradient of 0.011 and an effective porosity of 40 percent, the ground-water velocity is 0.11 ft/d at this site.

At the upgradient well, the mean dissolved chloride concentration was 25 mg/L and the maximum was 82 mg/L. Concentrations were generally higher at the first three downgradient wells (mean, 47–77 mg/L; maximum 77–110 mg/L). At 150 ft downgradient from the highway, the mean concentration at the fourth downgradient well (23 mg/L) was about equal to the background concentration. The mean specific conductance measured 607 μS/cm at the upgradient well; the maximum was 959 μS/cm. Values remained fairly constant downgradient along the flowpath through the third downgradient well (mean 678–751 μS/cm; maximum 893–1,000 μS/cm). At a distance of 150 ft downgradient from the highway, the mean value was about the same as the background value.

Ashtabula County. The Ashtabula County site is on SR 84 near Kingsville, Ohio. It is 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 38,867 lb/2-ln-mi for the interim reporting period). Snowfall averages 60–70 in/yr for nearby reporting areas. The aquifer 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 water level is 5–10 ft below land surface. From aquifer tests, the hydraulic conductivity was computed to be 2.3 ft/d. Assuming an average gradient of 0.035 and an effective porosity of 42 percent, the ground-water velocity was computed to be 0.19 ft/d at this site.

At the upgradient well, the mean dissolved chloride concentration was 13 mg/L and the maximum was 120 mg/L. Concentrations were highest at the first downgradient well (mean, 487 mg/L; maximum 1,400 mg/L). At 150 ft downgradient from the highway, the mean concentration at the fourth downgradient well (107 mg/L) was eight times the background concentration. The mean specific conductance was 493 μS/cm at the upgradient well, and the maximum was 1,020 μS/cm. Values were highest at the first downgradient well (mean 1,838 μS/cm; maximum 3,890 μS/cm). At a distance of 150 ft downgradient from the highway, the mean value was 1.5 times the background value.

Champaign County. The Champaign County site is on SR 29 near Urbana, Ohio. It is second priority for ODOT deicing. This site received an annual average of 5,076 lb/2-ln-mi of deicing chemicals for the interim reporting period. Snowfall averages 20–25 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 water level is 6–11 ft below land surface throughout the year. From aquifer tests, the hydraulic conductivity was computed to be 47.4 ft/d. Assuming an average gradient of 0.001 and an effective porosity of 35 percent, the ground-water velocity was computed to be 0.14 ft/d at this site.

At the upgradient well, the mean dissolved chloride concentration was 25 mg/L, and the maximum was 32 mg/L. Mean concentrations were about twice that of the upgradient well at all four downgradient wells (38–50 mg/L). At 150 ft downgradient from the highway, the mean concentration at the fourth downgradient well (48 mg/L) was about two times the background concentration. The mean specific conductance was 699 μS/cm at the upgradient well, and the maximum was 790 μS/cm. Values were virtually constant at all four downgradient wells (mean 773–876 μS/cm). At a distance of 150 ft downgradient from the highway the mean value was 1.2 times the background value.

Clark County. The Clark County site is on SR 4 near Springfield, Ohio. It is first priority for ODOT deicing. This site received an annual average of 6,105 lb/2-ln-mi of deicing chemicals for the interim reporting period. Snowfall averages 25–30 in/yr for nearby reporting areas. The aquifer materials consist of medium to coarse sand with gravel and large cobbles. Dolomitic bedrock is present at a depth of about 160 ft below land surface. The water level is 19–23 ft below land surface throughout the year. From aquifer tests, the hydraulic conductivity was computed to be 36 ft/d. Assuming an average gradient of 0.011 and an effective porosity of 35 percent, the ground-water velocity was computed to be 1.13 ft/d at this site.

At the upgradient well, the mean dissolved chloride concentration was 12 mg/L and the maximum was 45 mg/L. Concentrations were slightly higher at all four downgradient wells (mean, 15–31 mg/L; maximum 30–54 mg/L). At 150 ft downgradient from the highway, the mean concentration at the fourth downgradient well (15 mg/L) was about the same as the background concentration. The mean specific conductance was 642 μS/cm at the upgradient well, and the maximum was 832 μS/cm. Values were slightly higher at all four downgradient wells (mean 637–738 μS/cm; maximum 836–885 μS/cm). At a distance of 150 ft downgradient from the highway, the mean value was about the same as the background value.

Lucas County. The Lucas County site is on SR 2 near Holland, Ohio. It is first priority for ODOT deicing. This site received an annual average of 16,883 lb/2-ln-mi for the interim reporting period. Snowfall averages 30–40 in/yr for nearby reporting areas. The aquifer consists of fine to medium grained sand to a depth of 31–35 ft. Dolomitic bedrock is present at a depth of about 70 ft. The water level is 4–8 ft below land surface throughout the year. From aquifer tests, the hydraulic conductivity was computed to be 6.3 ft/d. Assuming an average gradient of 0.004 and an effective porosity of 43 percent, the ground-water velocity was computed to be 0.06 ft/d at this site.

At the upgradient well, the mean dissolved chloride concentration was 32 mg/L and the maximum was 150 mg/L. The concentration at the lowest level (level 1) in the upgradient well was uncharacteristically high during specific times each year. None of the other levels showed this pattern. The maximum concentrations shown for LU-21 reflect the high concentrations at the lowest levels; therefore, the median concentrations may be more representative of the upgradient conditions. Concentrations were highest at the first downgradient well (mean, 111 mg/L; maximum 670 mg/L). At 150 ft downgradient from the highway, the median concentration at the fourth downgradient well was about six times the upgradient or background (median) concentration. The mean specific conductance was 326 µS/cm at the upgradient well, and the maximum was 903 µS/cm. Values were highest at the first downgradient well (mean 697 µS/cm; maximum 2,250 µS/cm). At a distance of 150 ft downgradient from the highway, the mean value was 1.8 times the background value.

Pickaway County. The Pickaway County site is on SR 104 near Circleville, Ohio. It is second priority for ODOT deicing. This site received an annual average of 5,050 lb/2-ln-mi of deicing chemicals for the interim reporting period. Snowfall averages 20–30 in/yr for nearby reporting areas. Aquifer materials 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 water level is 7–13 ft below land surface throughout the year. From aquifer tests, the hydraulic conductivity was computed to be 31.6 ft/d. Assuming an average gradient of 0.003 and an effective porosity of 40 percent, the ground-water velocity was computed to be 0.24 ft/d at this site.

At the upgradient well, the mean dissolved chloride concentration was 15 mg/L and the maximum was 27 mg/L. Concentrations were slightly higher at all of the downgradient wells (mean, 17–20 mg/L; maximum 22–39 mg/L). At 150 ft downgradient from the highway, the mean concentration at the fourth downgradient well (20 mg/L) was about 1.3 times the background concentration. The mean specific conductance was 511 µS/cm at the upgradient well, and the maximum was 684 µS/cm. Values were generally constant throughout the four downgradient wells (mean 491–544 µS/cm; maximum 582–688 µS/cm). At a distance of 150 ft downgradient from the highway, the mean value was about the same as the background concentration.

Portage County. The Portage County site is on SR 14 near Ravenna, Ohio. It is first priority for ODOT deicing. This site received an annual average of 19,490 lb/2-ln-mi of deicing chemicals for the interim reporting period. Snowfall averages 50–60 in/yr for nearby reporting areas. Aquifer materials 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 water level is 5–9 ft below land surface throughout the year. From aquifer tests, the hydraulic conductivity was computed to be 30 ft/d. Assuming an average gradient of 0.007 and an effective porosity of 38 percent, the ground-water velocity was computed to be 0.55 ft/d at this site.

At the upgradient well, the mean dissolved chloride concentration was 6 mg/L and the maximum was 13 mg/L. Concentrations were significantly higher at the first two downgradient wells (mean, 369–496 mg/L; maximum 1,100–1,600 mg/L). At the third and fourth downgradient wells, concentrations returned to near background (mean 5–19 mg/L; maximum 27–110 mg/L). These wells are completed just above a clay confining unit but are slightly shallower than the first two downgradient wells. The fate of the ground water with the elevated chloride concentrations is unknown after a distance of about 100 ft downgradient from the highway; therefore, the concentrations at the farthest downgradient wells cannot be accurately compared specifically with those at the upgradient well. The mean specific conductance measured 580 μS/cm at the upgradient well and the maximum was 1,590 μS/cm. As with chloride concentration, specific conductance was significantly higher at the first two downgradient wells (mean 1,569–1,869 μS/cm; maximum 3,510–5,230) than at the last two downgradient wells.

Richland County. The Richland County site is on SR 97 near Lexington, Ohio. It is second priority for ODOT deicing. This site received an annual average of 15,283 lb/2-ln-mi of deicing chemicals for the interim reporting period. Snowfall averages 30–40 in/yr from nearby reporting areas. The aquifer materials 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 water level is 11–17 ft below land surface throughout the year. From aquifer tests the hydraulic conductivity was computed to be 5.2 ft/d. Assuming an average gradient of 0.052 and an effective porosity of 40 percent, the ground-water velocity was computed to be 0.68 ft/d at this site.

At the upgradient well, the mean dissolved chloride concentration was 3 mg/L and the maximum was 14 mg/L. Concentrations were generally higher at the first two downgradient wells (mean, 41–49 mg/L; maximum 96–100 mg/L). At 150 ft downgradient from the highway, the mean concentration at the fourth downgradient well (30 mg/L) was about 10 times the background concentration. The mean specific conductance was 239 μS/cm at the upgradient well, and the maximum was 384 μS/cm. Mean values were fairly constant throughout the four downgradient wells (mean, 403–572 μS/cm), although the maximum values ranged from 563–1,230 μS/cm, the highest occurring at the third downgradient well. However, 150 ft downgradient from the highway, the mean specific conductance at the fourth downgradient well was about twice the background value.

REFERENCES CITED

Backman, L., 1980, Environmental effects of the use of salt on winter roads: Linkoping, Sweden, translated from the National Road and Traffic Research Institute Report 97, S-581 01.

Bair, E.S., and Digel, R.K., 1990, Subsurface transport of inorganic and organic solutes from experimental road spreading of oil-field brine: Ground Water Monitoring Review, v. 10, no. 3, p. 94-105.

Bond, R.H., and Straub, C.P., 1973, Genetic types of subterranean waters in relation to their salinity *in* Handbook of environmental control, v. 3, Water supply and treatment: Cleveland, Ohio, CRC Press, p.85.

Bouwer, Herman, and Rice, R.C., 1976, A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells: Water Resources Research, v. 12, no. 3, p.423-428.

Breen, K.J., Angelo, C.G., Masters, R.W., and Sedam, A.C., 1985, Chemical and isotopic characteristics of brines from three oil-and gas-producing sandstones in eastern Ohio, with applications to the geochemical tracing of brine sources: U.S. Geological Survey Water-Resources Investigations Report 84-4314, 58 p.

Breen, K.J., and Dumouchelle, D.H., 1991, Geohydrology and quality of water in aquifers in Lucas, Sandusky, and Wood Counties, northwestern Ohio: U.S. Geological Survey Water-Resources Investigations Report 91-4024, 234 p.

Campbell, F.R., 1973, Village of Stittsville salt contamination of private well water supplies: Ontario Ministry of the Environment.

Church, P.E., and Friesz, P.J., 1993, Effectiveness of highway drainage systems in preventing road-salt contamination of groundwater–Preliminary findings: Transportation Research Record 1420, p. 56-64

Clifford, M.J., 1973, Silurian rock salt of Ohio: Ohio Department of Natural Resources, Division of Geological Survey Report of Investigations 90, 42 p.

Craun, G.F., 1984, Health aspects of ground-water pollution, *in* Bitton, G., and Gerba, C.P., eds., Groundwater pollution microbiology: New York, John Wiley, p. 135-179.

DeBrosse, T.A., and Vohwinkle, J.C., 1974, Oil and gas fields of Ohio: Ohio Department of Natural Resources, Division of Geological Survey map report, scale 1:63,360.

Diment, W.H., Bubeck, R.C., and Deck, B.L., 1973, Some effects of de-icing salts on Irondequoit Bay and its drainage basin, *in* Environmental degradation by de-icing chemicals and effective countermeasures: Highway Research Record 425, p. 23-35.

Duda, A.M., 1989, Groundwater contamination in the Great Lakes basin–Implications for multimedia remedial actions: Chicago-Kent Law Review, v. 65, p. 465-478.

Eberts, S.M., 1991, Geohydrology and water quality in northern Portage County, Ohio, in relation to deep-well brine injection: U.S. Geological Survey Water-Resources Investigations Report 90-4158, 63 p.

Eberts, S.M., Bair, E.S., and de Roche, J.T., 1990, Geohydrology, ground-water quality, and simulated ground-water flow, Geauga County, Ohio: U.S. Geological Survey Water-Resources Investigations Report 90-4026, 117 p.

Eisen, C., and Anderson, M.P., 1980, The effects of urbanization on ground-water quality Milwaukee, Wisconsin, U.S.A., *in* Jackson, R.E., ed., Aquifer contamination and protection: Paris, UNESCO, p. 378-390.

Eyles, N., and Howard, W.K.F., 1988, A hydrochemical study of urban landslides caused by heavy rain: Canadian Geotechnical Journal, v. 25, p. 455-466.

Fenneman, N.M., 1946, Physical divisions of the United States: U.S. Geological Survey, scale 1: 7,000,000.

Feulner, A.J., 1960, Ground water resources of Champaign County, Ohio: Unpublished report on file at the Columbus, Ohio offices of the Ohio Department of Natural Resources, Division of Water, and the U.S. Geological Survey, fig. 6.

Field, R., Struzeski, E.J., Masters, H.E., and Tafuri, A.N., 1974, Water pollution and associated effects from street salting: American Society of Civil Engineers Journal of the Environmental Engineering Division, v. 100, no. EE2, p. 459-477.

Fishman, M.J., and Friedman, L.C., eds., 1989, Methods for determination of inorganic substances in water and fluvial sediments (3d ed.): U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. A1, 545 p.

Frost, L.R., Pollock, S.J., and Wakelee, R.F., 1981, Hydrologic effects of highway-deicing chemicals in Massachusetts: U.S. Geological Survey Open-File Report 81-209, 56 p.

Granato, G.E., 1995, Deicing chemicals as a source of constituents in highway runoff: Transportation Research Record Preprint 960645, p. 1-15.

Granato, G.E., Church, P.E., and Stone, V.J., 1995, Mobilization of major and trace constituents of highway runoff in groundwater potentially caused by deicing chemical migration: Transportation Research Record 1483, p. 92-104.

Hanes, R.E., Zelazny, L.W., and Blaser, R.E., 1970, Effects of deicing salts on water quality and biota—Literature Review and Recommended Research: National Cooperative Highway Research Program, Highway Research Board Report 91, p. 70.

Hawkins, R.H., 1976, Salt storage and runoff in urban watershed: American Society of Civil Engineers Journal of the Environmental Engineering Division, v. 102 no. EE4, p. 737-743.

Hem, J.D., 1989, Study and interpretation of the chemical characteristics of natural water (3d ed.): U.S. Geological Survey Water Supply Paper 2254, 263 p.

Hodge, R.A., 1989, Groundwater in the Great Lakes basin–The natural system, use and abuse, and policy implications: Chicago-Kent Law Review, v. 65, p. 439-464.

Howard, K.W.F., Boyce, J.I., Livingstone, S.J., and Salvatori, S.L., 1993, Road salt impacts on ground-water quality—the worst is still to come!: GSA Today (Geological Society of America), v. 3, no. 12, p. 301, 319-321.

Howard, K.W.F., and Haynes, J., 1993, Urban geology 3. Groundwater contamination due to road de-icing chemicals—salt balance implications: Geoscience Canada, v. 20, no.1, p. 1-8.

Huling, E.E., and Hollocher, T.C., 1972, Groundwater contamination by roadsalt– Steady-state concentrations in east-central Massachusetts: Science, v. 176, p. 288-290.

Hutchinson, F.E., 1966, Accumulation of road salt ions in soils along Maine highways: Maine Farm Research, October 1966, p. 13-16.

——1967, The relationship of road salt applications to sodium and chloride ion levels in the soil bordering major highways *in* Environmental considerations in use of deicing chemicals: Highway Research Record 193, p. 1-7.

——1970, Environmental pollution from highway deicing compounds: Journal of Soil and Water Conservation, v. 25, no. 4, p. 144-146.

International Joint Commission, 1988, Revised Great Lakes Water Quality Agreement of 1978, as amended by Protocol signed November 18, 1987: 130 p.

Jones, P.H., Jeffrey, B.A., Watler, P.K., and Hutchon, H., 1986, Environmental impact of road salting—State of the art: Ontario Ministry of Transportation and communications Research Report RR237, 53 p.

Kaufman, W.J., and Orlob, G.T., 1956, Measuring ground water movement with radioactive and chemical tracers: American Water Works Association Journal, v. 48, p. 559-572.

Knuth, Martin, Jackson, J.L., and Whittemore, D.O., 1990, An integrated approach to identifying the salinity source contaminating a ground-water supply: Ground Water, v. 28, p. 207-214.

Kriz, J., 1995, Bedrock topography of the Jelloway, Ohio, quadrangle: Ohio Department of Natural Resources, Geological Survey Open-File Map BT-C3E3, scale 1:24,000.

Kunkle, S.H., 1971, Effects of road salt on a Vermont stream *in* Street Salting–Urban Water Quality Workshop, State University of New York College of Forestry at Syracuse, Proceedings: p. 48-61.

Lamborn, R.E., 1952, Additional analyses of brines from Ohio: Ohio Department of Natural Resources, Division of Geological Survey Report of Investigations 11, 56 p.

Larsen, G.E., 1994a, Bedrock geology of the Whitehouse quadrangle: Ohio Department of Natural Resources, Geological Survey Open-File Map BG-D4E7, scale 1:24,000.

——1994b, Bedrock topography of the Whitehouse quadrangle: Ohio Department of Natural Resources, Geological Survey Open-File Map BT-D4E7, scale 1:24,000.

McConnell, H.H., and Lewis, J., 1972, Add salt to taste: Environment, v. 14, no. 9, p.38-44.

Miller, M.E., and Weaver, C.R., 1971, Snow in Ohio: Wooster, Ohio, Ohio Agricultural Research and Development Center Research Bulletin 1044, 23 p.

Moses, C., 1980, Sodium in medicine and health–A monograph: Baltimore, Reese Press, 122 p.

Northeast Ohio Four County Regional Planning and Development Organization, 1978, Clean Water Report, volume 1–Baseline report and environmental assessment: Akron, Ohio.

National Oceanic and Atmospheric Administration, 1982, Monthly normals of temperature, precipitation, and heating and cooling degree days, 1951-80—Ohio: Asheville, N.C., National Climatic Center, Climatography of the United States, no. 81, 16 p.

Norris, S.E., Cross, W.P., Goldthwait, R.P., and Sanderson E.E., 1952, The water resources of Clark County, Ohio: Ohio Department of Natural Resources, Division of Water Bulletin 22, 82 p.

Northeast Ohio Brine Disposal Task Force, 1984, Brine disposal in northeast Ohio, a report on the problem and recommendations for action: Cleveland, Ohio, Northeast Ohio Areawide Coordinating Agency, 21 p.

Ontario Ministry of the Environment, 1991, Parameters System Listing (PALIS): Water Resources Branch Report, Drinking Water Section, 80 p.

Page, A.L., Miller, R.H., and Keeney, D.R., eds., 1982, Methods of soil analysis, Part 2, chemical and microbiological properties (2d ed.): Madison, Wis., American Society of Agronomy, Soil Science Society of America, 1,159 p.

Pettyjohn, W.A., 1971, Water pollution by oil-field brines and related industrial wastes in Ohio: Ohio Journal of Science, v. 71, no. 5, p. 257-269.

Pickens, J.F., Cherry, J.A., Coupland, R.M., Grisak, G.E., Merritt, W.F., and Risto, B.A., 1981, A multilevel device for ground-water sampling: Ground Water Monitoring Review, v. 1, no. 1. p. 48-51.

Pilon, P.E., and Howard, K.W.F., 1987, Contamination of subsurface waters by road de-icing salts: Water Pollution Research Journal of Canada, v. 22, p. 157-171.

Prior, G.A. and Berthouex, P.M., 1967, A study of salt pollution of soil by highway salting *in* Environmental considerations in use of deicing chemicals: Highway Research Record 193, p. 8-21.

Qayyum, M.A., 1962, Salt concentration gradients in soils and their effects on moisture movement and salt evaporation: Soil Science, v. 93, p. 333-342.

Residuals Management Technology, Inc., 1985, Field measurement methods for hydrologic investigators–A critical review of the literature: Palo Alto, Calif., Electric Power Research Institute, EPRI EA-4301, 305 p.

Ronen, D. Magaritz, M., and Levy, I., 1987, An *in situ* multilevel sampler for preventive monitoring and study of hydrochemical profiles in aquifers: Ground Water Monitoring Review v. 7, no. 4, p. 69-74.

Salt Institute, 1983, Survey of salt, calcium chloride and abrasives use in the United States and Canada for 81/82 and 82/83: Alexandria, VA, 18 p.

Schraufnagel, F.H., 1967, Pollution aspects associated with chemical de-icing *in* Environmental considerations in use of deicing chemicals: Highway Research Record 193, p. 22-33.

Shrake, D.L., 1993a, Preliminary bedrock geology of the Williamsport, Ohio quadrangle: Ohio Department of Natural Resources, Geological Survey Open-File Map BG-B4E1, scale 1:24,000.

——1993b, Preliminary bedrock topography of the Williamsport, Ohio quadrangle: Ohio Department of Natural Resources, Geological Survey Open-File Map BT-B4E1, scale 1:24,000.

Slucher, E.R., and Larsen, G.E., 1996, Preliminary bedrock geology of the Kent, Ohio quadrangle: Ohio Department of Natural Resources, Geological Survey Open-File Map BG-D2B3, scale 1:24,000.

Stith, D.A., 1979, Brine analyses 1972-1974: Ohio Department of Natural Resources, Division of Geological Survey Open-File Report 79-1, 39 p.

Stout, Wilber, Lamborn, R.E., and Schaaf, Downs, 1932, Brines of Ohio: Ohio Geological Survey of Ohio Bulletin 37, 123 p.

Swinford, E.M., 1995, Bedrock geology of the Jelloway, Ohio quadrangle: Ohio Department of Natural Resources, Geological Survey Open-File Map BG-C3E3, scale 1:24,000.

Swinford, E.M., and Larsen, G.E., 1996, Bedrock topography of the Kent, Ohio quadrangle: Ohio Department of Natural Resources, Geological Survey Open-File Map BT-D2B3, scale 1:24,000.

Terry, R.C., 1974, Road salt, drinking water and safety–Improving public policy and practice: Cambridge, Mass., Ballinger Publishing Company, p. 171.

Toler, L.G., and Pollock, S.J., 1974, Retention of chloride in the unsaturated zone: U.S. Geological Survey Journal of Research, v. 2, p. 119-123.

Totten, S.M., 1973, Glacial geology of Richland County, Ohio: Ohio Department of Natural Resources, Division of Geological Survey. Report of Investigations 88, 55 p.

Tuthill, R.W., and Calabrese, E.J., 1979, Elevated sodium levels in the public drinking water as a contributor to elevated blood pressure levels in the community: Archives of Environmental Health, v. 34, p. 197-203.

U.S. Department of Agriculture, 1954, Diagnosis and improvements of saline and alkali soils: U.S. Salinity Laboratory Staff Agriculture Handbook No. 60.

U.S. Department of Agriculture, Soil Conservation Service, 1958, Soil survey–Clark County, Ohio: Sheet 2.

——1971, Soil survey–Champaign County, Ohio: Map 29.

——1973, Soil survey of Ashtabula County, Ohio: Map 12.

——1975, Soil survey of Richland County, Ohio: Map 56.

——1978, Soil survey of Portage County, Ohio: Map 26.

——1980a, Soil survey of Ashland County, Ohio: Map 52.

——1980b, Soil survey of Lucas County, Ohio: Map 27.

——1980c, Soil survey of Pickaway County, Ohio: Map 43.

U.S. Environmental Protection Agency, 1971, Environmental impact of highway deicing: Water Pollution Control Research Report 11040GKK, 120 p.

White, G.W., 1977, Glacial geology of Ashland County, Ohio: Ohio Department of Natural Resources, Division of Geological Survey Report of Investigations 101, scale 1 inch equals about 1 mile.

White, G.W., Totten, S.M., 1979, Glacial geology of Ashtabula County, Ohio: ODNR, Division of Geological Survey, Report of Investigations 112, 48 p.

Whittemore, D.O., 1982, Identification of saltwater sources affecting groundwater in the Blood Orchard area, Sedgwick County, Kansas: Kansas Geological Survey Open-File Report 82-9, 16 p.

——1984, Geochemical identification of salinity sources, *in* French, R.H., ed., Salinity in watercourses and reservoirs: Stoneham, Mass., Ann Arbor Science, Butterworth Publishers, p. 505-514.

——1988, Bromide as a tracer in ground-water studies: Geochemistry and analytical determination *in* Ground Water Geochemistry Conference, Denver Colo., Proceedings: Dublin, Ohio, National Water Well Association, p. 339-359.

World Health Organization, 1984, Guidelines for drinking water quality–volume. 1, recommendations: Geneva, 130 p.

Wulkowicz, G.M., and Saleem, Z.A., 1974, Chloride balance of an urban basin in the Chicago area: Water Resources Research, v. 10, p. 974-982.

APPENDIXES

Elemental analysis of formation materials

Appendix A. Elemental analysis of formation materials at the Ashland County site, Ohio.

Well characteristics and constituents determined	Well Number			
	AS-8(D)	AS-9(E)	AS-9(E)	AS-8(D)
Depth	5-6.5'	2.5-4'	7.5-9'	12.5-14'
Elevation	928	927	922	920
Materials	sand/silt	sand/silt	sand/silt	sand/silt
Aluminum %-s	3.17	3.24	4.16	4.07
Calcium	1.54	.41	.45	.33
Iron	5.23	3.08	3.22	3.12
Potassium	1.14	1.07	1.45	1.48
Magnesium	1	.27	.38	.35
Sodium	.53	.57	.55	.53
Phosphorus	.05	.05	.05	.03
Titanium	.16	.15	.22	.25
Manganese ppm-s	524.	311	828	543
Silver	<2	<2	<2	<2
Arsenic	30	20	10	10
Gold	<8	<8	<8	<8
Boron	---	---	---	---
Barium	257	241	394	367
Beryllium	<1	1	1	1
Bismuth	<10	<10	<10	<10
Cadmium	<2	<2	<2	<2
Cerium	37	44	68	60
Cobalt	14	10	11	11
Chromium	44	30	44	40
Copper	29	11	15	14
Europium	<2	<2	<2	<2
Gallium	8	7	10	10
Germanium	---	---	---	---
Holmium	<4	<4	<4	<4
Lanthanum	18	20	32	28
Lithium	25	26	36	32
Molybdenum	<2	<2	<2	<2
Niobium	<4	<4	<4	5
Neodymium	19	22	33	28
Nickel	42	19	26	27
Lead	37	17	20	20
Scandium	6	5	7	7
Tin	<10	<10	<10	<10
Strontium	83	72	87	77
Tantalum	<40	<40	<40	<40
Thorium	7	6	8	9
Uranium	<100	<100	<100	<100

Appendix A. Elemental analysis of formation materials at the Ashland County site, Ohio.—Continued

Well characteristics and constituents determined	Well Number			
	AS-8(D)	AS-9(E)	AS-9(E)	AS-8(D)
Vanadium	60	49	71	68
Tungsten	---	---	---	---
Yttrium	14	15	19	18
Ytterbium	2	2	2	2
Zinc	52	60	69	68
Zirconium	---	---	---	---

Appendix B. Elemental analysis of formation materials at the Ashtabula County site, Ohio.

Well characteristics and constituents determined		Well Number				
		AB-129(D)	AB-132(G)	AB-131(F)	AB-129(D)	AB-130(E)
Depth		2.5-4'	12.5-14'	2.5-4'	15-16.5'	15-16.5'
Elevation		767	763	757	755	lconfining 750
Materials		sand/silt	sand/silt	silt/cl	sand/silt	sand/silt/cl
Aluminum	%-s	3.71	5.04	4.47	4.56	5.05
Calcium		.59	.46	.52	2.81	2.91
Iron		2.06	4.59	3.14	2.99	3.55
Potassium		1.17	1.70	1.46	1.53	1.70
Magnesium		.41	.56	.44	.95	1.07
Sodium		.81	.71	.77	.71	.69
Phosphorus		.03	.06	.04	.04	.04
Titanium		.16	.28	.24	.22	.26
Manganese	ppm-s	350	630	573	343	440
Silver		<2	<2	<2	<2	<2
Arsenic		<10	<10	<10	<10	<10
Gold		<8	<8	<8	<8	<8
Boron		---	---	---	---	---
Barium		322	334	444	286	189
Beryllium		1	2	1	1	1
Bismuth		<10	<10	<10	<10	<10
Cadmium		<2	<2	<2	<2	<2
Cerium		31	58	52	43	51
Cobalt		7	16	11	11	14
Chromium		29	53	41	43	52
Copper		10	44	24	24	25
Europium		<2	<2	<2	<2	<2
Gallium		8	12	10	11	12
Germanium		---	---	---	---	---
Holmium		<4	<4	<4	<4	<4
Lanthanum		15	28	25	23	26
Lithium		20	36	27	39	42
Molybdenum		<2	<2	<2	<2	<2
Niobium		<4	6	4	<4	6
Neodymium		15	28	25	23	25
Nickel		16	37	23	25	30
Lead		10	26	15	14	22
Scandium		5	10	8	8	9
Tin		<10	<10	<10	<10	<10
Strontium		125	104	117	127	123
Tantalum		<40	<40	<40	<40	<40
Thorium		8	8	7	7	8

Appendix B. Elemental analysis of formation materials at the Ashtabula County site, Ohio—Continued

Well characteristics and constituents determined	Well Number				
	AB-129(D)	AB-132(G)	AB-131(F)	AB-129(D)	AB-130(E)
Uranium	<100	<100	<100	<100	<100
Vanadium	40	73	61	56	67
Tungsten	---	---	---	---	---
Yttrium	13	22	20	15	18
Ytterbium	2	2	3	2	3
Zinc	54	216	75	67	203
Zirconium	---	---	---	---	---

Appendix C. Elemental analysis of formation materials at the Champaign County site, Ohio.

Well characteristic and constituents determine	Well Number				
	CH-39(D)	CH-36(A)	CH-37(B)	CH-36(A)	CH-39(D)
Depth	2.5-4'	7.5-9	12.5-14'	20-21.5'	25-26.5'
Elevation	1027.5	1021.5	1015.5	1009	1005
Materials	silt/cl	sand/g	1015.5	sand/gr	sand/gr
Aluminum %-S	4.95	1.59	1.66	1.89	1.95
Calcium	2.31	18.8	19.2	17.	17.2
Iron	2.90	.98	1.18	1.24	1.17
Potassium	1.73	.67	.62	.71	.86
Magnesium	1.38	7.36	7.55	6.09	5.72
Sodium	.77	.33	.37	.60	.51
Phosphorus	.05	.02	.02	.02	.02
Titanium	.24	.06	.08	.05	.07
Manganese ppm-s	755	202	301	224	286
Silver	<2	<2	<2	<2	<2
Arsenic	10	<10	<10	<10	<10
Gold	<8	<8	<8	<8	<8
Boron	---	---	---	---	---
Barium	496	109	125	117	165
Beryllium	1	<1	<1	<1	<1
Bismuth	<10	<10	<10	<10	<10
Cadmium	<2	<2	<2	<2	<2
Cerium	52	13	12	19	13
Cobalt	13	4	6	5	5
Chromium	48	14	14	15	15
Copper	20	9	9	14	8
Europium	<2	<2	<2	<2	<2
Gallium	11	4	<4	6	<4
Germanium	---	---	---	---	---
Holmium	<4	<4	<4	<4	<4
Lanthanum	29	9	9	8	10
Lithium	29	13	14	13	12
Molybdenum	4	3	2	3	3
Niobium	6	<4	4	<4	5
Neodymium	26	11	12	13	11
Nickel	26	8	10	12	10
Lead	22	6	7	5	7
Scandium	8	2	3	3	3
Tin	<10	<10	<10	<10	<10
Strontium	115	169	148	153	169
Tantalum	<40	<40	<40	<40	<40
Thorium	7	<4	<4	<4	<4
Uranium	<100	<100	<100	<100	<100

Appendix C. Elemental analysis of formation materials at the Champaign County site, Ohio—Continued

Well characteristic and constituents determine	Well Number				
	CH-39(D)	CH-36(A)	CH-37(B)	CH-36(A)	CH-39(D)
Vanadium	72	25	24	22	25
Tungsten	---	---	---	---	---
Yttrium	18	6	6	7	7
Ytterbium	2	<1	<1	<1	<1
Zinc	79	17	14	16	15
Zirconium	---	---	---	---	---

Appendix D. Elemental analysis of formation materials at the Clark County site, Ohio.

Well characteristics and constituents determined	Well Number					
	CL-132(A)	CL-132(A)	CL-132(A)	CL-132(A)	CL-134(C)	CL-134(C)
Depth	2.5-4'	10-11.5'	17.5-1'	20-21.5'	7.5-9'	17.5-19
Elevation	1019.5	1012	1004.5	1004	1023.5	1013.5
Materials	sand/silt/gr	sand/gr	sand/gr	sand/gr	sand/silt/gr	sand/silt/gr
Aluminum %-s	6.28	2.01	2.18	1.58	3.23	2.07
Calcium	2.57	16.2	15.9	18.5	11.5	16.2
Iron	4.29	1.26	1.39	1.25	1.83	1.71
Potassium	1.71	.82	.87	.66	1.23	.77
Magnesium	1.46	5.31	5.42	6.77	4.09	5.76
Sodium	.62	.48	.57	.33	.69	.61
Phosphorus	.06	.03	.03	.02	.03	.02
Titanium	.25	.06	.09	.05	.11.	.1
Manganese ppm-s	791	323	322	367	424	457
Silver	<2	<2	<2	<2	<2	<2
Arsenic	10	<10	<10	10	<10	<10
Gold	<8	<8	<8	<8	<8	<8
Boron	---	---	---	---	---	---
Barium	392	163	196	131	265	145
Beryllium	2	<1	<1	<1	<1	<1
Bismuth	<10	<10	<10	<10	<10	<10
Cadmium	<2	<2	<2	<2	<2	<2
Cerium	56	17	19	16	33	16
Cobalt	15	5	6	5	7	7
Chromium	63	17	19	14	25	19
Copper	29	11	12	12	15	14
Europium	<2	<2	<2	<2	<2	<2
Gallium	14	4	5	4	9	5
Germanium	---	---	---	---	---	---
Holmium	<4	<4	<4	<4	<4	<4
Lanthanum	28	11	11	9	17	12
Lithium	38	15	15	15	20	14
Molybdenum	5	3	3	3	<2	3
Niobium	10	5	<4	<4	<4	4
Neodymium	29	13	13	12	20	13
Nickel	32	14	13	11	18	13
Lead	22	8	18	8	12	13
Scandium	12	3	3	3	5	4
Tin	<10	<10	<10	<10	<10	<10
Strontium	111	173	180	152	163	161
Tantalum	<40	<40	<40	<40	<40	<40
Thorium	8	<4	<4	<4	4	<4

Appendix D. Elemental analysis of formation materials at the Clark County site, Ohio.—Continued

Well characteristics and constituents determined	Well Number					
	CL-132(A)	CL-132(A)	CL-132(A)	CL-132(A)	CL-134(C)	CL-134(C)
Uranium	<100	<100	<100	<100	<100	<100
Vanadium	101	26	27	22	42	29
Tungsten	---	---	---	---	---	---
Yttrium	20	8	8	6	12	9
Ytterbium	2	<1	<1	<1	1	<1
Zinc	95	30	25	23	40	31
Zirconium	---	---	---	---	---	---

Appendix E. Elemental analysis of formation materials at the Lucas County site, Ohio.

Well characteristic and constituents determined	Well number		
	LU-18(B)	LU-19(C)	LU-17(A)
Depth	10-11.5'	25-26.5'	35-36.5'
Elevation	665	650	640
Materials	sand	sand	silt/cl (confining)
Aluminum %-s	2.65	2.98	5.00
Calcium	.60	4.96	7.13
Iron	.57	.85	2.72
Potassium	1.08	1.25	1.93
Magnesium	.20	.88	2.81
Sodium	.94	1.08	.79
Phosphorus	.01	.02	.05
Titanium	.07	.09	.22
Manganese ppm-s	99	200	584
Silver	<2	<2	<2
Arsenic	<10	<10	<10
Gold	<8	<8	<8
Boron	---	---	---
Barium	306	345	456
Beryllium	<1	<1	<1
Bismuth	<10	<10	<10
Cadmium	<2	<2	<2
Cerium	15	15	52
Cobalt	4	4	13
Chromium	13	15	52
Copper	2	1	23
Europium	<2	<2	<2
Gallium	5	6	12
Germanium	---	---	---
Holmium	<4	<4	<4
Lanthanum	7	9	27
Lithium	6	6	33
Molybdenum	<2	<2	<2
Niobium	<4	<4	4
Neodymium	5	8	25
Nickel	6	5	30
Lead	6	7	16
Scandium	2	3	8
Tin	<10	<10	<10
Strontium	134	189	183
Tantalum	<40	<40	<40

Appendix E. Elemental analysis of formation materials at the Lucas County site, Ohio.—Continued

Well characteristic and constituents determined	Well number		
	LU-18(B)	LU-19(C)	LU-17(A)
Thorium	<4	<4	7
Uranium	<100	<100	<100
Vanadium	14	21	77
Tungsten	---	---	---
Yttrium	5	6	16
Ytterbium	<1	<1	2
Zinc	13	10	63
Zirconium	---	---	---

Appendix F. Elemental analysis of formation materials at the Pickaway County site, Ohio.

Well characteristic and constituents determined	Well number		
	PK-44(A)	PK-44(A)	PK-44(A)
Depth	5-6.5'	17.5-19	27.5-29'
Elevation	675	662	652
Materials	sand	silt	sand
Aluminum %-s	3.68	2.75	2.35
Calcium	9.39	12.4	15.8
Iron	2.59	2.81	1.67
Potassium	1.43	1.12	.97
Magnesium	3.31	3.62'	5.22
Sodium	.54	.56	.39
Phosphorus	.04	.03	.02
Titanium	.17	.11	.09
Manganese ppm-s	316	335	363
Silver	<2	<2	<2
Arsenic	<10	20	<10
Gold	<8	<8	<8
Boron	---	---	---
Barium	268	255	254
Beryllium	1	<1	<1
Bismuth	<10	<10	<10
Cadmium	<2	<2	<2
Cerium	48	25	20
Cobalt	10	8	8
Chromium	37	23	21
Copper	22	21	17
Europium	<2	<2	<2
Gallium	9	6	6
Germanium	---	---	---
Holmium	<4	<4	<4
Lanthanum	26	15	12
Lithium	26	16	16
Molybdenum	4	6	4
Niobium	<4	<4	<4
Neodymium	25	16	14
Nickle	24	20	20
Lead	14	12	10
Scandium	6	4	4
Tin	<10	<10	<10
Strontium	133	167	156
Tantalum	<40	<40	<40
Thorium	5	<4	<4
Uranium	<100	<100	<100

Appendix F. Elemental analysis of formation materials at the Pickaway County site, Ohio.—Continued

Well characteristic and constituents determined	Well number		
	PK-44(A)	PK-44(A)	PK-44(A)
Vanadium	58	39	35
Tungsten	---	---	---
Yttrium	14	12	9
Ytterbium	2	1	1
Zinc	77	67	43
Zirconium	---	---	---

Appendix G. Elemental analysis of formation materials at the Portage County site, Ohio.

Well characteristic and constituents determined	Well number		
	PO-111(A)	PO-113(C)	PO-112(B)
Depth	5-6.5'	5-6.5'	10-11.5'
Elevation	1069	1066	1065
Materials	sand	sand	silt/cl
Aluminum %-s	1.95	1.66	5.05
Calcium	.82	1.37	1.45
Iron	1.32	1.32	3.31
Potassium	.73	.68	1.69
Magnesium	.32	.31	.88
Sodium	.36	.31	.68
Phosphorus	.02	.02	.05
Titanium	.09	.07	.28
Manganese ppm-s	205	167	417
Silver	<2	<2	<2
Arsenic	<10	<10	20
Gold	<8	<8	<8
Boron	---	---	---
Barium	144	139	309
Beryllium	<1	<1	2
Bismuth	<10	<10	<10
Cadmium	<2	<2	<2
Cerium	26	26	58
Cobalt	4	4	13
Chromium	15	13	54
Copper	11	13	18
Europium	<2	<2	<2
Gallium	5	<4	13
Germanium	---	---	---
Holmium	<4	<4	<4
Lanthanum	12	12	29
Lithium	15	13	43
Molybdenum	<2	<2	<2
Niobium	<4	<4	7
Neodymium	11	11	29
Nickel	10	9	28
Lead	9	10	15
Scandium	3	3	9
Tin	<10	<10	<10
Strontium	52	51	83
Tantalum	<40	<40	<40

Appendix G. Elemental analysis of formation materials at the Portage County site, Ohio.—Continued

Well characteristic and constituents determined	Well number		
	PO-111(A)	PO-113(C)	PO-112(B)
Thorium	<4	<4	11
Uranium	<100	<100	<100
Vanadium	20	19	67
Tungsten	---	---	---
Yttrium	8	7	17
Ytterbium	<1	<1	2
Zinc	39	46	65
Zirconium	---	---	---

Appendix H. Elemental analysis of formation materials at the Richland County site, Ohio.

Well characteristics and constituents determined	Well number				
	R-12(B)	R-12(B)	R-13(C)	R-11(A)	R-13(C)
Depth	2.5-4'	12.5-14'	15-16.5	25-26.5'	25-26.5'
Elevation	1167	1157	1145	1145	1135
Materials	sand/silt	sand	sand	sandstone	sand/silt
Aluminum %-s	4.56	4.68	2.52	1.64	3.95
Calcium	.48	.64	.47	.08	.66
Iron	2.95	5.45	1.95	1.23	4.12
Potassium	1.57	1.67	1.13	1.17	1.48
Magnesium	.42	.56	.26	.08	.47
Sodium	.61	.61	.48	.12	.64
Phosphorus	.06	.08	.03	.02	.08
Titanium	.25	.21	.14	.07	.22
Manganese ppm-S	829	1,050	271	1,070	867
Silver	<2	<2	<2	<2	<2
Arsenic	10	40	<10	<10	20
Gold	<8	<8	<8	<8	<8
Boron	---	---	---	---	---
Barium	434	308	243	242	264
Beryllium	1	2	<1	<1	1
Bismuth	<10	<10	<10	<10	<10
Cadmium	<2	<2	<2	<2	<2
Cerium	55	65	34	18	58
Cobalt	11	17	6	4	12
Chromium	45	51	16	13	43
Copper	16	35	12	6	28
Europium	<2	<2	<2	<2	<2
Gallium	11	12	6	<4	10
Germanium	---	---	---	---	---
Holmium	<4	<4	<4	<4	<4
Lanthanum	25	28	15	8	26
Lithium	29	32	15	14	25
Molybdenum	<2	7	<2	<2	4
Niobium	5	5	<4	<4	5
Neodymium	24	31	16	8	33
Nickel	28	50	13	9	31
Lead	21	57	14	11	35
Scandium	7	10	4	2	7
Tin	<10	<10	<10	<10	<10
Strontium	95	80	79	31	95
Tantalum	<40	<40	<40	<40	<40
Thorium	8	9	4	<4	7

Appendix H. Elemental analysis of formation materials at the Richland County site, Ohio.—Continued

Well characteristics and constituents determined	Well number				
	R-12(B)	R-12(B)	R-13(C)	R-11(A)	R-13(C)
Uranium	<100	<100	<100	<100	<100
Vanadium	68	111	39	25	71
Tungsten	---	---	---	---	---
Yttrium	16	25	12	5	24
Ytterbium	2	3	2	<1	3
Zinc	74	162	66	17	130
Zirconium	---	---	---	---	---