Effectiveness of Highway-Drainage Systems in Preventing Contamination of Ground Water by Road Salt, Route 25, Southeastern Massachusetts—Description of Study Area, Data Collection Programs, and Methodology

By PETER E. CHURCH, DAVID S. ARMSTRONG, GREGORY E. GRANATO, VICTORIA J. STONE, KIRK P. SMITH, and PAUL L. PROVENCHER

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CONVERSION FACTORS, VERTICAL DATUM, ABBREVIATED WATER-QUALITY UNITS, AND OTHER DEFINITIONS

Multiply	By	To obtain
cubic foot (ft^3)	0.02832	cubic meter
cubic foot (ft^3)	28.325	liter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
degree Fahrenheit (°F)	5/9 × (°F-32)	degree Celsius
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
inch (in.)	2.54	centimeter
mile (mi)	1.609	kilometer
pound (lb)	0.4536	kilogram
square mile (mi^2)	2.590	square kilometer

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

Abbreviated water-quality units used in this report: Chemical concentrations and water temperature are given in metric units. Chemical concentration is given in milligrams per liter (mg/L), a unit expressing the concentration of chemical constituents in solution as mass (milligrams) of solute per unit volume (liter) of water. For concentrations less than 7,000 mg/L, the numerical value is the same as for concentrations in parts per million.

Specific conductance of water is expressed in microsiemens per centimeter at 25 degrees Celsius (µS/cm). This unit is equivalent to micromhos per centimeter at 25 degrees Celsius (µmho/cm), formerly used by the U.S. Geological Survey.

The lane mile is an areal measurement of road surface. The lane mile is one traffic lane (12 ft wide), extending for 1 mile along a road. When applied to highways, this measurement unit includes paved borders and breakdown lanes. Therefore, State Route 25 has 8.33 lane miles per mile of 6-lane highway. This includes the 6 traffic lanes, the borders adjacent to the median strip, and the 2 break-down lanes.

Effectiveness of Highway-Drainage Systems in Preventing Contamination of Ground Water by Road Salt, Route 25, Southeastern Massachusetts—Description of Study Area, Data-Collection Programs, and Methodology

By Peter E. Church, David S. Armstrong, Gregory E. Granato, Victoria J. Stone, Kirk P. Smith, *and* Paul Provencher

ABSTRACT

Four test sites along a 7-mile section of Route 25 in southeastern Massachusetts, each representing a specific highway-drainage system, were instrumented to determine the effectiveness of the drainage systems in preventing contamination of ground water by road salt. One of the systems discharges highway runoff onsite through local drainpipes. The other systems use trunkline drainpipes through which runoff from highway surfaces, shoulders, and median strips is diverted and discharged into either a local stream or a coastal waterway. Route 25 was completed and opened to traffic in the summer of 1987. Road salt was first applied to the highway in the winter of 1987-88.

The study area is on a thick outwash plain composed primarily of sand and gravel. Water-table depths range from 15 to 60 ft below land surface at the four test sites. Ground-water flow is in a general southerly direction, approximately perpendicular to the highway. Streamflow in the study area is controlled primarily by ground-water discharge. Background concentrations of dissolved chloride, sodium, and calcium—the primary constituents of road salt—are similar in ground water and surface water and range from 5 to 20, 5 to 10, and 1 to 5 milligrams per liter, respectively.

Data-collection programs were developed for monitoring the application of road salt to the highway, the quantity of road-salt water entering the ground water, diverted through the highway-drainage systems, and entering a local stream. The Massachusetts Highway Department monitored road salt applied to the highway and reported these data to the U.S. Geological Survey. The U.S. Geological Survey designed and operated the ground-water, highway-drainage, and surface-water data-collection programs. A road-salt budget will be calculated for each test site so that the effectiveness of the different highway-drainage systems in preventing contamination of ground water by road salt can be determined.

INTRODUCTION

Road-salt contamination of public and private water supplies is a serious and costly problem in the Northern United States, Canada, and Europe. Nationwide, about 10 million dollars are spent annually by State and local governments to prevent and remediate road-salt contamination problems (Transportation Research Board, 1991). The Massachusetts Highway Department (MHD) received reports of road-salt contamination of public and private water supplies from 100 of the 351 municipalities in the State from 1983 through 1990. The MHD spent about 2.5 million dollars to investigate and remediate these reports during this period (Pollock, 1991). Road-salt contamination of public-water supplies may be reduced by applying alternative deicing chemicals, by establishing low-salt application areas, or by diverting highway runoff to areas less likely to affect water supplies.

The U.S. Geological Survey (USGS), in cooperation with the MHD, began a study in January 1979 to determine the effectiveness of four types of highway-drainage systems in preventing contamination of ground water from road salt. The effects on a local stream of discharge from two of these drainage systems was added to the project objectives in 1982. The highway-drainage systems were incorporated into the design of a 7-mile, six-lane section of Route 25 in southeastern Massachusetts (fig. 1) completed in 1987. These drainage systems, each designed for a different level of highway-runoff control, were included in the highway construction plans because of the proximity of this proposed highway to the sources of public ground-water supplies of Wareham and Bourne. One of the drainage systems is an open drainage system, typical of many highways where highway runoff is discharged to the local land surface. The other drainage systems were designed to divert highway runoff away from adjacent public-water supplies. Two of these drainage systems are new designs that were tested for the first time in this investigation. The methods by which diverted highway runoff is collected, and the corresponding cost of highway construction, differ between drainage systems. The most expensive, and potentially the most effective drainage system, added about 2.5 million dollars per mile to construction costs for that section of highway (Transportation Research Board, 1991), [equating to] about 20 percent of the cost.

Purpose and Scope

The purpose of this report is to describe the highway-drainage systems being tested, the study area, and the data-collection programs and methods by which the effectiveness of each highway-drainage system in preventing road-salt contamination are determined. Description of the data collection programs covers the period from 1979 to 1995, during which many changes to the original project design were made.

Approach

Four different highway-drainage systems on Route 25 were selected for study. Data-collection programs were developed for monitoring road-salt application to Route 25, selection of test sites representative of each of the four highway-drainage systems, monitoring of the constituents of road salt in ground water and in highway runoff diverted from the test sites through the highway-drainage systems, and monitoring of the constituents of road salt entering a local stream. Methods were developed for computing road-salt loads in ground water and road-salt loads diverted from the test sites through the highway-drainage systems (Church and Friesz, 1993a).

The quantity of road salt (consisting primarily of sodium chloride and secondarily of calcium chloride) applied to the highway was monitored by the MHD. Road salt was applied during winter storms by trucks equipped with calibrated spreaders. The date(s), number of applications, and spreading rates recorded for each storm were forwarded to the USGS.

Observation wells were installed along proposed alignments of Route 25 for test site selection. A site was selected for each highway-drainage design where the direction of ground-water flow was about perpendicular to the highway. Networks of monitoring wells were installed at each selected site for measurement of water levels and collection of water samples upgradient (background) and downgradient (potentially contaminated) from Route 25. Water samples were analyzed for dissolved concentrations of chloride, sodium, and calcium. Water-quality data, water-level data, and estimated hydraulic conductivities are used to compute road-salt loads in ground water at each test site.

Highway-drainage monitoring stations were installed within the drainage systems for continuous measurement and recording of stage and specific conductance of highway runoff. Samples of runoff were analyzed for dissolved concentrations of chloride, sodium, and calcium. Relations between stage and discharge and between specific conductance and road-salt constituent concentrations are used to determine the amount of road salt diverted from the test sites through the highway-drainage systems.

Two streamflow-gaging stations were installed on Red Brook, one upgradient and the other downgradient from Route 25, where stage and specific conductance were monitored. Water samples collected at each of these stations were analyzed for dissolved concentrations of chloride, sodium, and calcium. Relations between stage and discharge and between specific conductance and chloride concentration were developed.

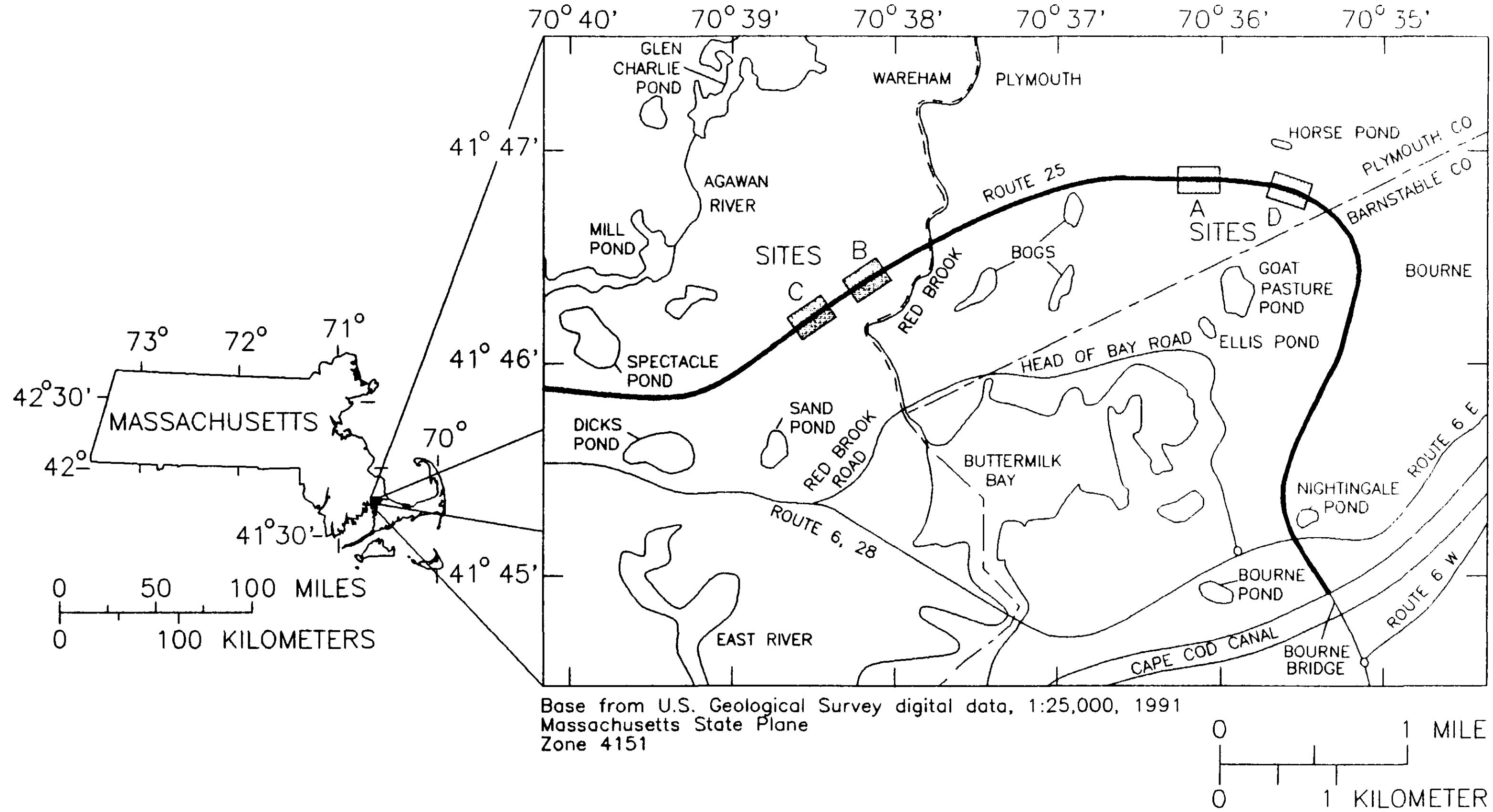


Figure 1. Location of study area and test sites A, B, C, and D, along Route 25 in southeastern Massachusetts.

Acknowledgments

The authors thank the Research and Materials Division and the Wareham Office of the Massachusetts Highway Department for providing ongoing logistical support during this study, including drilling and well installation, surveying, and recording of road-salt application data. The authors also thank the personnel of Research and Materials Division of the MHD and the Department of Transportation, Federal Highway Administration (FHWA), for their comments and suggestions in the development of the study approach. Appreciation is extended to landowners who granted permission for observation wells to be installed and monitored and who permitted entry to their private properties for this investigation.

HIGHWAY-DRAINAGE SYSTEMS

Four types of highway-drainage systems were constructed along Route 25, each designed for a specific level of runoff control from the highway surfaces, shoulders, and median strip. The sites were designated A, B, C, and D, in order of increasing highway-runoff control. Sites A and D are in the towns of Plymouth and Bourne (fig. 2) and sites B and C are in the town of Wareham (fig. 3).

All four sites are between the same two highway interchanges with no intervening access. Flow of traffic and application of road salt during winter storms is likely to be uniform at all sites. Ground-water velocities, water-table gradients and the sand and gravel material composing the aquifer beneath the highway differ little between sites. Highway gradient, however, ranges from about 0.005 at site D to 0.02 at site C. Depth to water table from the highway surface ranges from about 15 ft at site B to 60 ft at site A. The type of highway-drainage system is the most substantial difference between each site.

The roadway surface at all sites is crowned to allow highway runoff to flow toward the highway shoulders and the median strip. The top of the highway pavement is composed of a permeable bituminous (asphaltic) concrete, referred to as popcorn pavement, designed to limit ponding of water on the highway surface. This permeable layer is underlain by an 8-inch-thick layer of consolidated bituminous concrete designed to be at least 95-percent impervious to water infiltration (L.C. Stevens, Jr., P. E., Massachusetts Highway Department, written commun., 1990). Rainfall and salt-laden water from melting snow and ice penetrate the 1-inch-thick popcorn pavement and then flow laterally to the edges of the roadways. The quantity of salt-laden water percolating through the underlying layer of consolidated bituminous concrete is assumed to be small and uniform at all test sites. The extent to which the water flows onto the shoulders or the median strip is controlled by the drainage systems.

Site A represents an open-drainage system (fig. 4A) where local ground water is unprotected from contamination by highway runoff. This drainage system, also referred to as country drainage, is typical of rural highways. Highway runoff in this open-drainage system is collected in catch basins and drop inlets, and discharged to the local land surface through concrete drainpipes. Catch basins are concrete basins beneath the edge of the highway that are covered with steel grates at the pavement surface. Drop inlets are similar to catch basins but have side inlets at the land surface in addition to steel grates. The edges of the roadways are sloped slightly in towards the highway to help direct highway runoff into the catch basins at the pavement surface. The drop inlets are on highway shoulders and median strips for collection of overland flow. At site A, two catch basins are on the northern edge of the westbound roadway, and four catch basins are on the southern edge of the eastbound roadway. One of two drop inlets in the median strip is connected to a catch basin on the westbound roadway and the other to a catch basin on the eastbound roadway. All outlets of the drainage fixtures at site A are within the test site. All highway runoff to the shoulders and most runoff to the median strip—whether from direct overland flow, melting of snow plowed from the highway surface, or spray caused by vehicular traffic—is allowed to percolate through the soil adjacent to the highway. Road salt percolating to the ground water from the highway pavement, shoulders, and median strip should be as uniform line sources along the highway. However, concentrations of local highway runoff at the catch basin and drop inlets commonly cause variations in salt loading to ground water along the highway at site A.

Site B is a closed-drainage system (fig. 4*B*) designed so that some of the runoff from the highway pavement is diverted to a collection system and prevented from percolating to the water table. Highway runoff is collected in catch basins installed at the highway surface every 300 to 600 ft on both edges

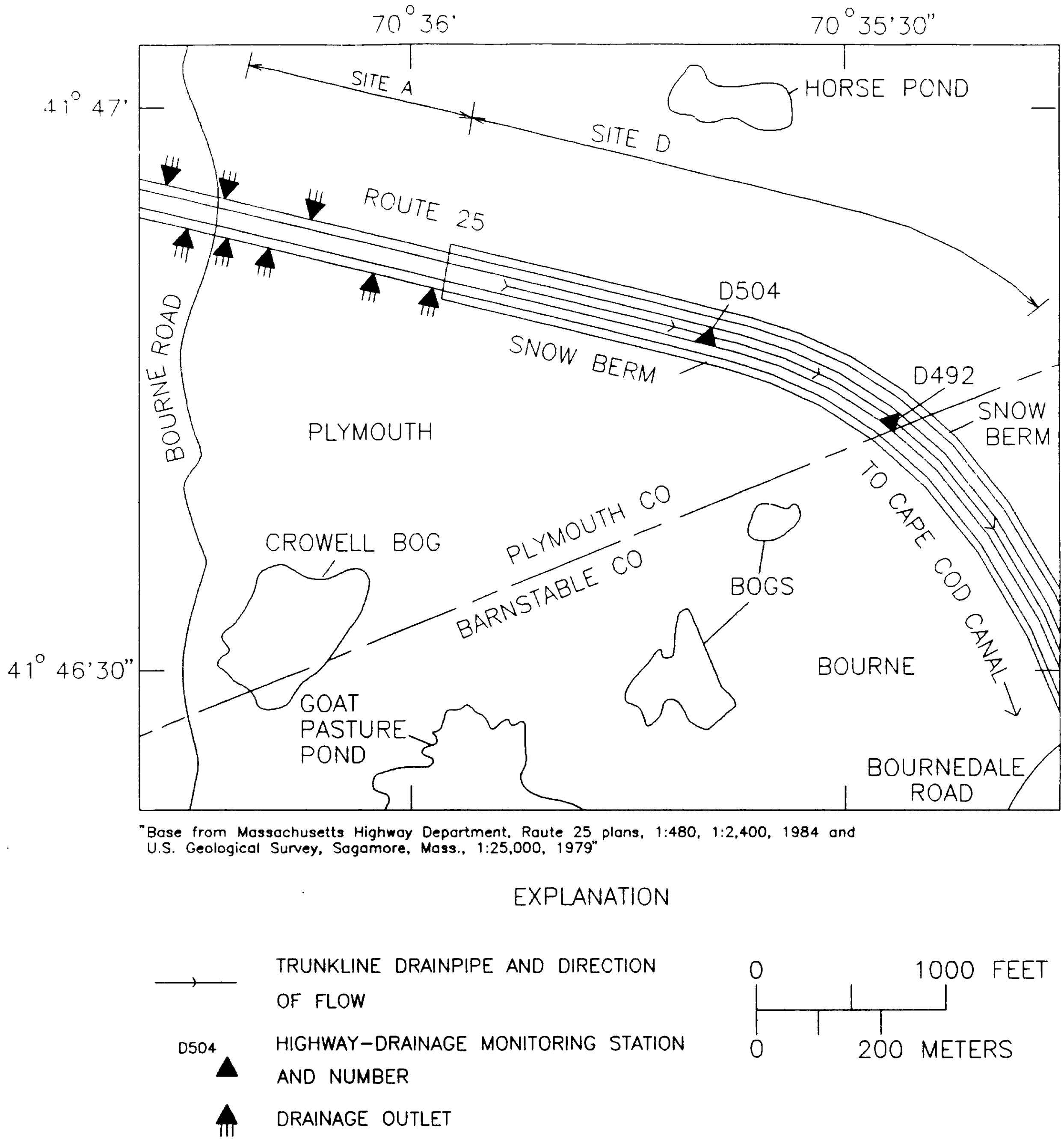


Figure 2. Location of site A, open-drainage system; site D, full snow-berm drainage system; and monitoring stations; Route 25, southeastern Massachusetts.

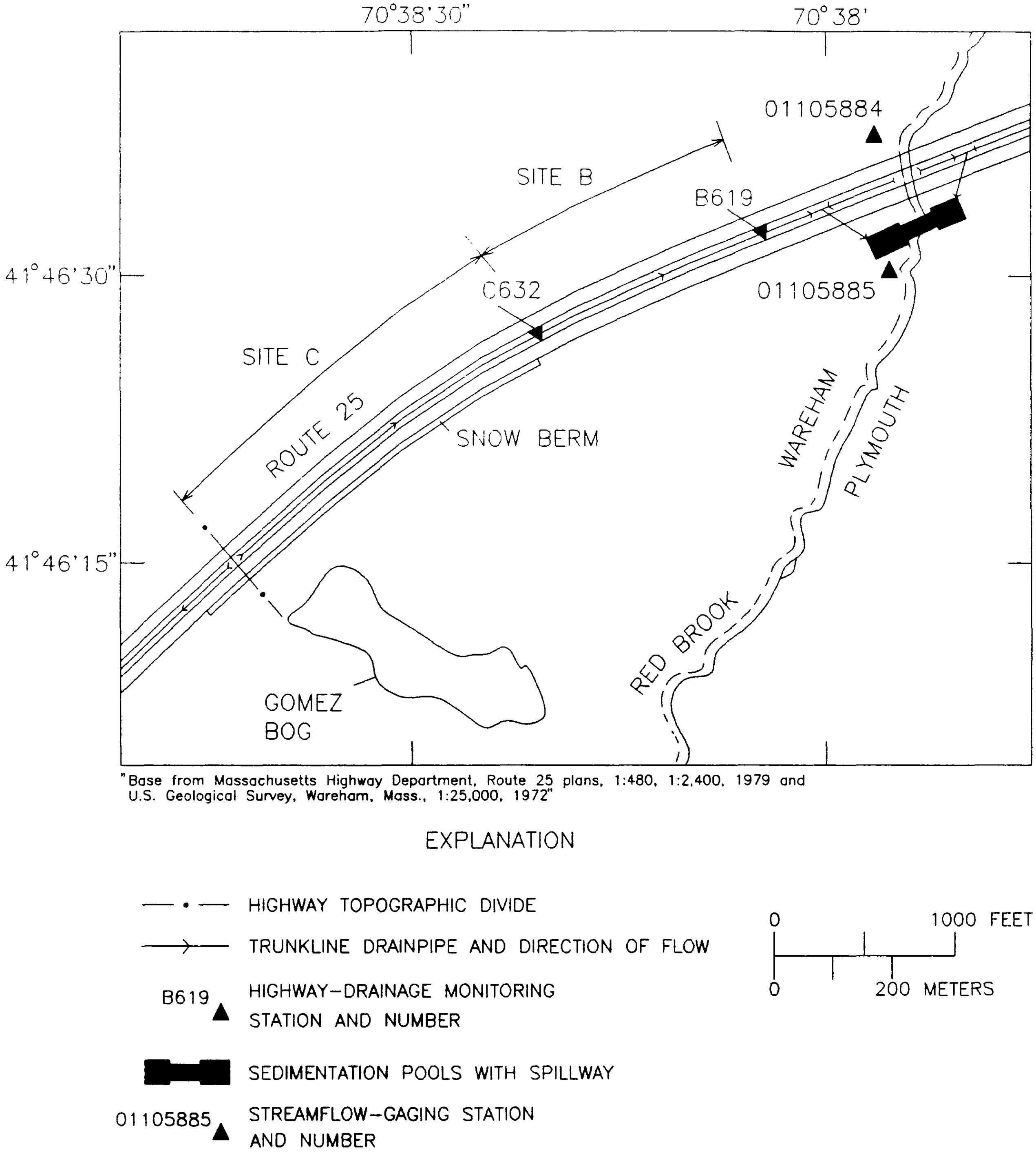


Figure 3. Location of site B, closed-drainage system; site C, closed-drainage system with partial snow berm; and monitoring stations; Route 25, southeastern Massachusetts.

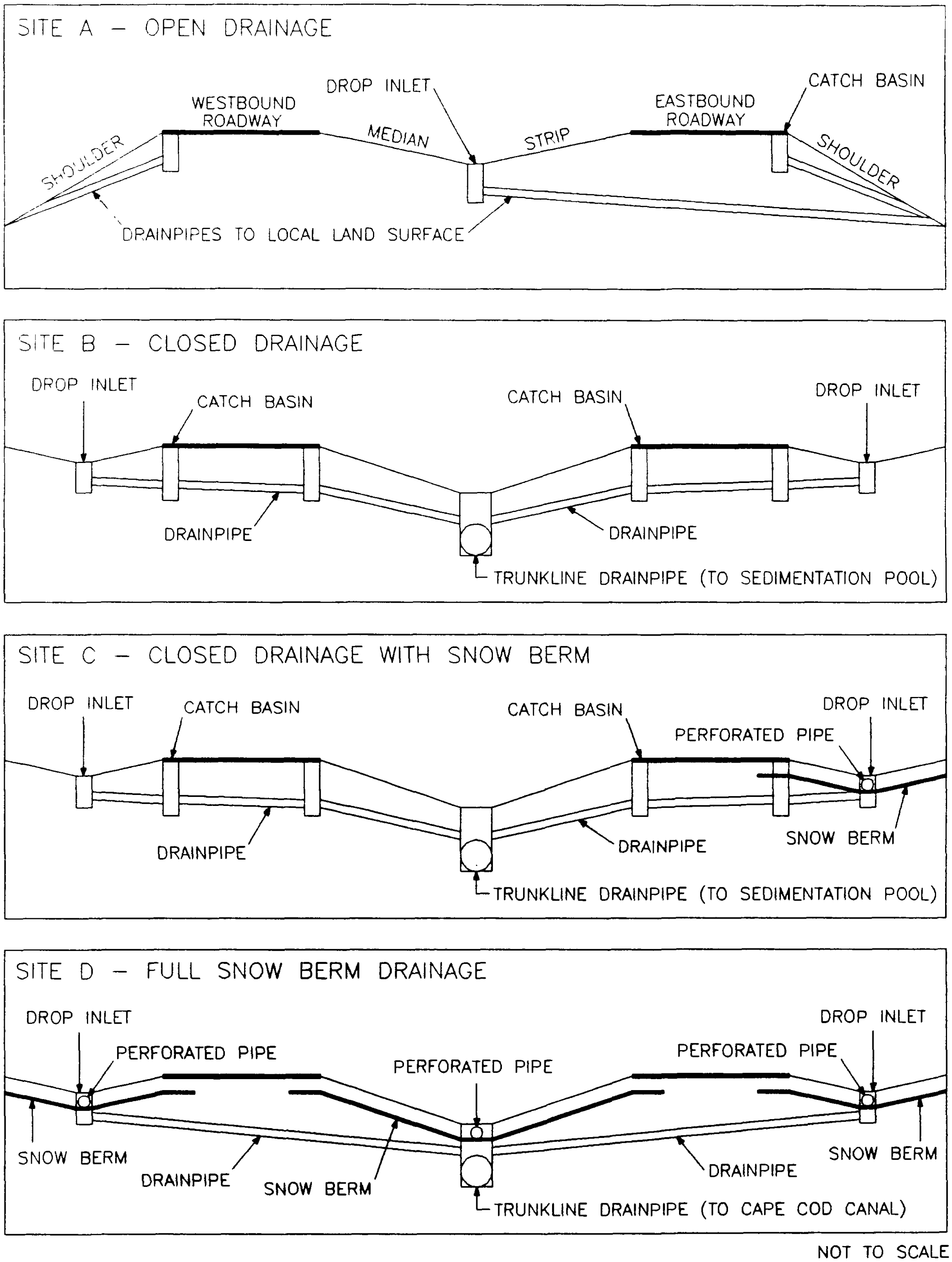


Figure 4. Schematic sections of highway-drainage designs, Route 25, southeastern Massachusetts. *A*. open drainage; *B*. Closed drainage; *C*. Closed drainage with snow berm; *D*. Full snow-berm drainage.

of both roadways. Highway-runoff is piped beneath the highway to a trunkline drainpipe beneath the median strip and is eventually discharged into a sedimentation pool (fig. 3). Outflow from the pool enters a local stream, Red Brook, about 1 mi upstream of Buttermilk Bay. A part of the runoff from the highway shoulders and the median strip enters the trunkline drainpipe through drop inlets; however, most of the runoff from the shoulders and the median strip, along with snow plowed from the road surface and spray caused by vehicular traffic, percolates through the soil as it does in the open-drainage system at site A. Percolation of salt-laden water through the highway pavement and infiltration of highway runoff and saltspray from the highway shoulders and median strip should result in a uniform line source of road-salt loading to ground water along the highway at site B.

The highway-drainage system at site C combines elements of two distinct designs (fig. 4C). Site C represents a closed-drainage system as described above for site B, but also incorporates an impervious shoulder beneath the eastbound roadway shoulder. An impervious shoulder, also referred to as a snow berm, is a highway shoulder or median strip constructed with a 2-inch-thick layer of bituminous concrete overlain by 3 to 4 ft of well-sorted, permeable sand. The bituminous concrete layer is sprayed with a sealant during construction in an effort to make it 100-percent impervious (L.C. Stevens, Jr., P.E., Massachusetts Department of Public Works, written commun., 1990). A snow berm is channel-shaped, with the deepest area in the center of the shoulder or median strip. The widths of the highway-shoulder snow berms are about 30 ft, with an additional 5 ft underlying the highway. Median-strip snow berms extend the full width of the median strip (typically 100 ft), with an additional 5 ft underlying each roadway. Drop inlets in the center of these channels occur about every 300 ft along the highway and are sealed to the snow berm. Perforated pipes on the snow berm are encased in gravel wrapped with geotechnical cloth that limits the entry of sand. The perforated pipes are connected to the drop inlets just above the snow-berm seal. Highway runoff can enter the drop inlets as overland flow and as percolation through the sand to the snow berm; runoff enters the perforated pipe and flows into the drop inlet at the level of the snow berm. Pipes beneath the snow berm and the roadways connect the drop inlets to the trunkline drainpipe. The drainage system at site C is designed so that highway-surface runoff from both roadways and runoff from the eastbound roadway shoulder, which is constructed with a snow berm, is diverted from the site and is prevented from percolating through the unsaturated zone. Captured highway runoff at site C enters the same trunkline drainpipe that passes through site B and discharges into the sedimentation pool before entering Red Brook. Percolation of salt-laden water through the highway pavement, and infiltration of highway runoff and saltspray from the median strip and westbound roadway shoulder should result in a uniform line source of road-salt loading to ground water along the highway at site C.

Site D is a full-snow-berm drainage system where both highway shoulders and the median strip are underlain by snow berms (fig. 4D). There are no catch basins on the roadway surface. Therefore, highway surface runoff is allowed to flow into the shoulders and the median strip where it either enters drop inlets as overland flow and is channeled directly to the trunkline drainpipe or percolates to the impervious snow berm. Highway-surface runoff captured by the snow berms enters drop inlets from below the land surface through perforated pipe and is then directed to the trunkline drainpipe. This drainpipe is under the median strip of the highway and discharges into the Cape Cod Canal, a coastal waterway connecting Buzzards Bay and Massachusetts Bay (fig. 1). Road-salt loading to ground water is expected to be as a uniform line source along the highway from percolation of salt-laden water through the highway pavement, leaks in the highway drainage system, and from saltspray caused by snowplows and vehicular traffic that is deposited beyond the highway shoulders.

DESCRIPTION OF STUDY AREA

The study area is in southeastern Massachusetts in the seaboard lowland physiographic province of New England (Fenneman, 1946), about 1 to 2 mi from the Atlantic Ocean. Land-surface altitudes in this region range from 0 to about 250 ft above sea level. Land-surface altitudes in the study area range from about 20 to 90 ft above sea level. The study area is in a sand and gravel outwash plain bounded by till and bedrock hills on the north and west, and by the Cape Cod Canal to the south and east. Large areas of the outwash plain have low relief and flat or undulating terrain and slope toward the Atlantic Ocean. The outwash plain is pockmarked with depressions, some of which contain lakes, ponds, and wetlands. Land use in the outwash plain is varied. Sparsely populated woodland and brushland covers an estimated 65 percent of the region. An additional 11 percent is devoted to agricultural use, particularly the production of cranberries. The remaining land is residential (19 percent) or urban-industrial (5 percent) with these areas centered along the coast and around the larger ponds (Hansen and Lapham, 1992). The ponds are used for recreation and as public or private water supplies. Route 25 passes through a woodland area that is vegetated by pine and oak second-growth forest. At the test sites, the surrounding land use is primarily forest, with scattered low-density single-family residences and regional gas and powerlines.

The climate in the area is humid and temperate (Ruffner, 1985), and is influenced by its proximity to the Atlantic Ocean. Summer and winter temperatures are modified by sea breezes, which also bring increased moisture to the area. The mean annual temperature is 49.4°F. The average long-term precipitation is 48.4 in/yr. The average annual runoff has been estimated to be from 20 to 24 in. (Gebert and others, 1985). Although precipitation is relatively constant throughout the year, there is some variation between seasons. In the drier months of June and July, precipitation is commonly less than 3 in. In the wetter months of November and December, precipitation commonly exceeds 4.5 in. (National Oceanic and Atmospheric Administration, 1981-1987). Annual recharge to the unconfined aquifer at a site near the study area was determined to be about 24 in. (Weiskel and Howes, 1991).

Geology

The aquifer in the study area is underlain by crystalline bedrock that is predominately granitic in composition and varies in texture from plutonic granite to granitic gneiss. Some felsic schists also are present. The bedrock is heavily fractured in most areas. The surface altitude of the bedrock in the study area ranges from 50 to 100 ft below sea level (Williams and Tasker, 1974). Bedrock altitude is estimated to range from about 50 ft below sea level at sites A and D, to 75 ft below sea level at sites B and C based on these data. These altitudes represent depths to bedrock of about 150 ft below land surface at both locations.

The aquifer is primarily composed of glacial sand and gravel deposits that overlay the crystalline bedrock. In general, the hydrogeologic setting is similar to many other sites in eastern Massachusetts, New England, and glaciated areas of the United States, Canada, and Europe, where road salt is used as a deicer. The test sites are underlain by a layer of fine to coarse sand with gravel, as shown in the geologic sections (figs. 5 and 6) oriented nearly perpendicular to the highway (figs. 7 and 8). This upper deposit ranges in thickness from about 90 ft at site C to about 15 ft at side D. The sand and gravel is underlain by sand and gravel with silt at site A, fine sand with silt at sites B and C, and fine to coarse sand with gravel and silt at site D. Considerable small-scale vertical and lateral variation in grain-size distribution, typical of sand and gravel deposits, is present in the upper and lower deposits. Scattered boulders are present in these deposits and on the land surface at sites A and D. Boulders have not been identified in the deposits at sites B and C, although they are commonly seen lying on the land surface.

Grain-size analyses were done on selected samples taken during installation of wells at the test sites. Sample materials were separated by size using a standard set of sieves having screen openings from 0.625 to 0.0025 in. Finer materials were retained. Some samples underwent a full analysis including sieve separation and pipet analysis of fine material at the USGS Sediment Laboratory in Pennsylvania. Sand/gravel indicates all material with a particle diameter greater than or equal to 0.0025 in. Silt/clay indicates all material with particle diameter less than 0.0025 in. Ranges and averages from these analyses are presented in table 1 as percentage by weight. The results of these tests indicate that the aquifer materials at the test sites are dominated by sand and gravel.

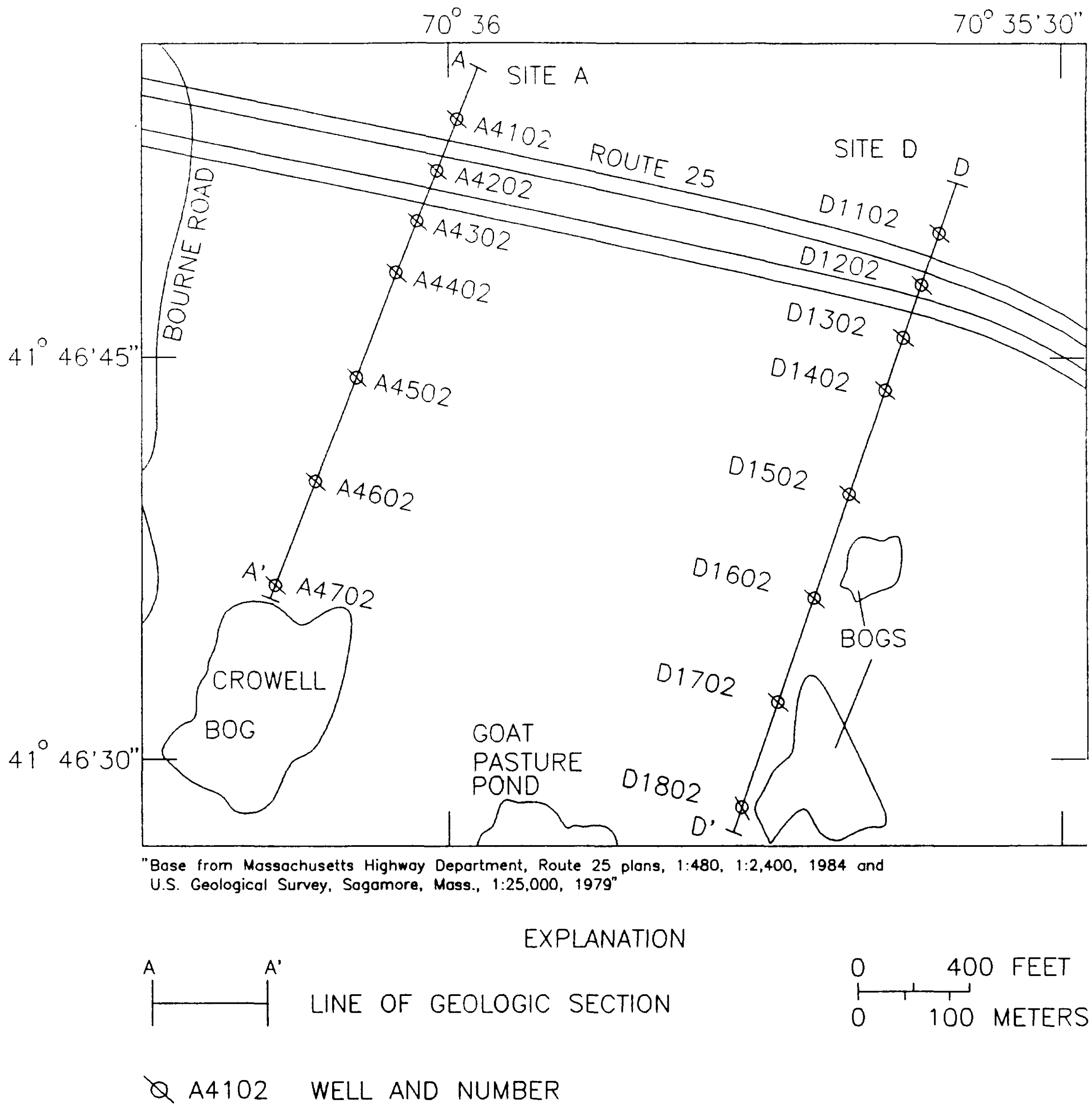
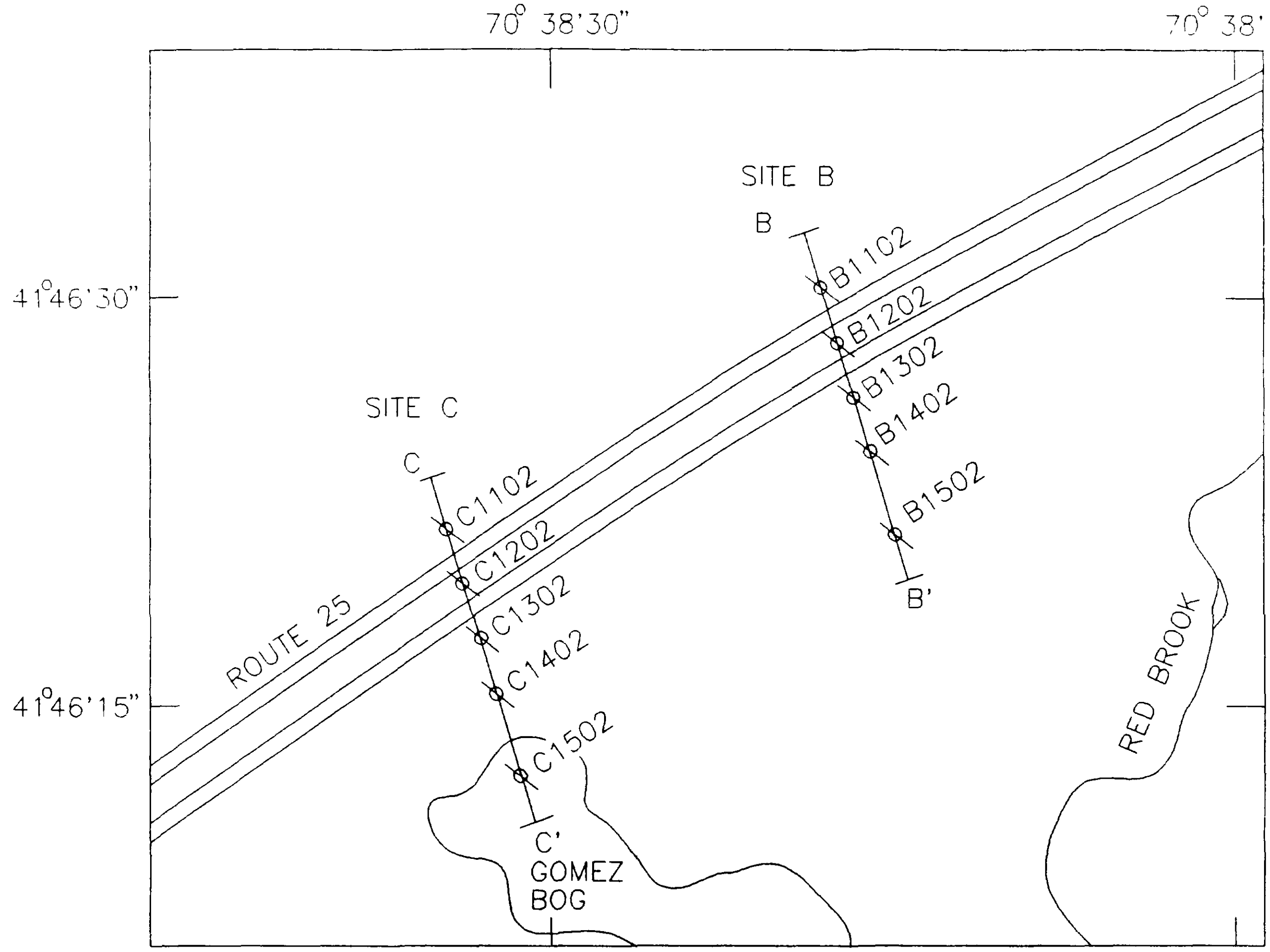


Figure 5. Location of geologic sections *A-A'* and *D-D'* at sites A and D, near Route 25, southeastern Massachusetts.



"Base from Massachusetts Highway Department, Route 25 plans, 1:480, 1:2,400, 1979 and U.S. Geological Survey, Wareham, Mass., 1:25,000, 1972"

EXPLANATION

C — C' LINE OF GEOLOGIC SECTION

C1102 WELL AND NUMBER

0 400 FEET
0 100 METERS

Figure 6. Location of geologic sections *B-B'* and *C-C'* at sites B and C near Route 25, southeastern Massachusetts.

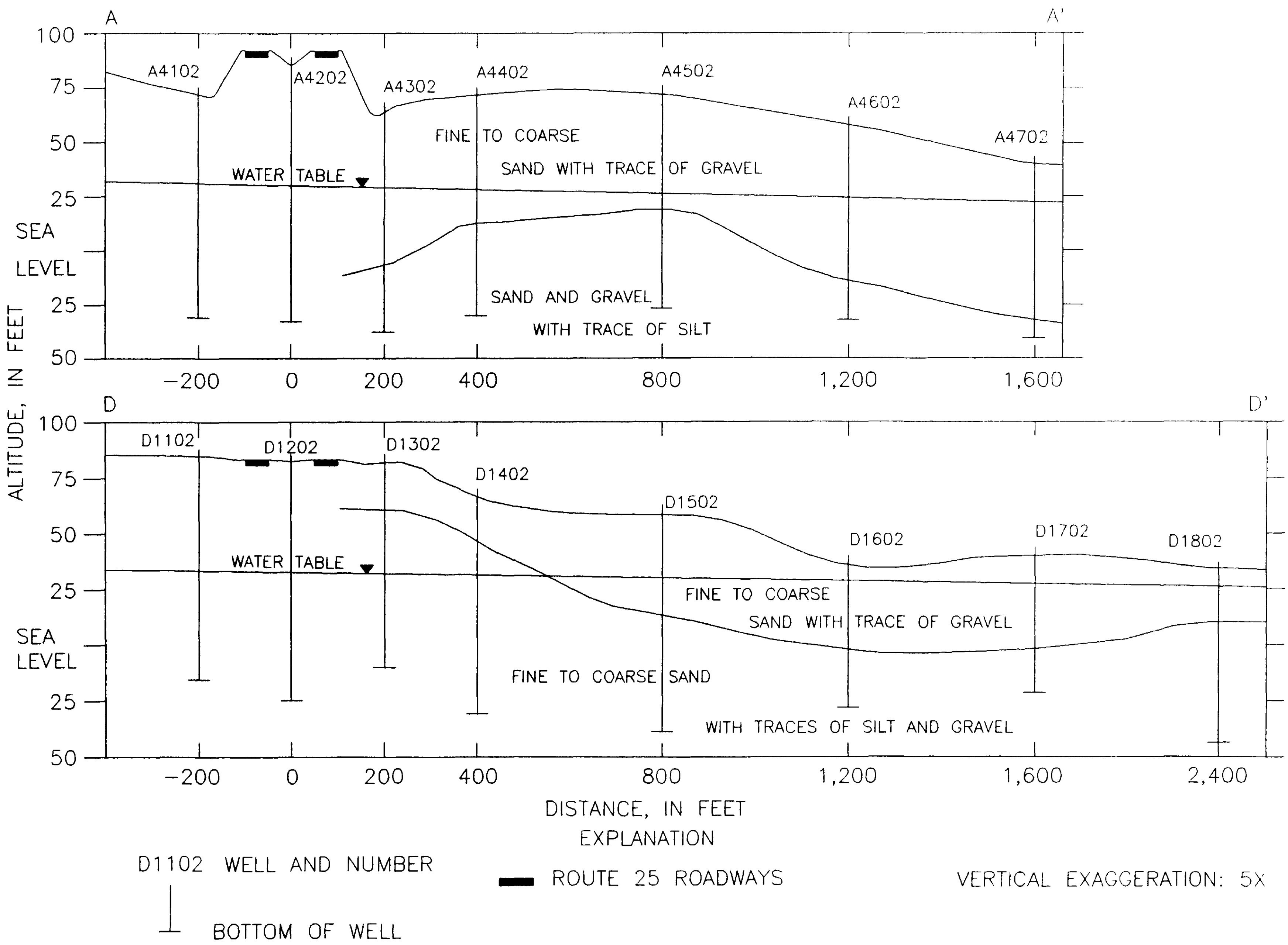


Figure 7. Geologic sections along lines *A-A'* and *D-D'* at sites A and D, near Route 25, southeastern Massachusetts. Line of geologic section shown in figure 5.

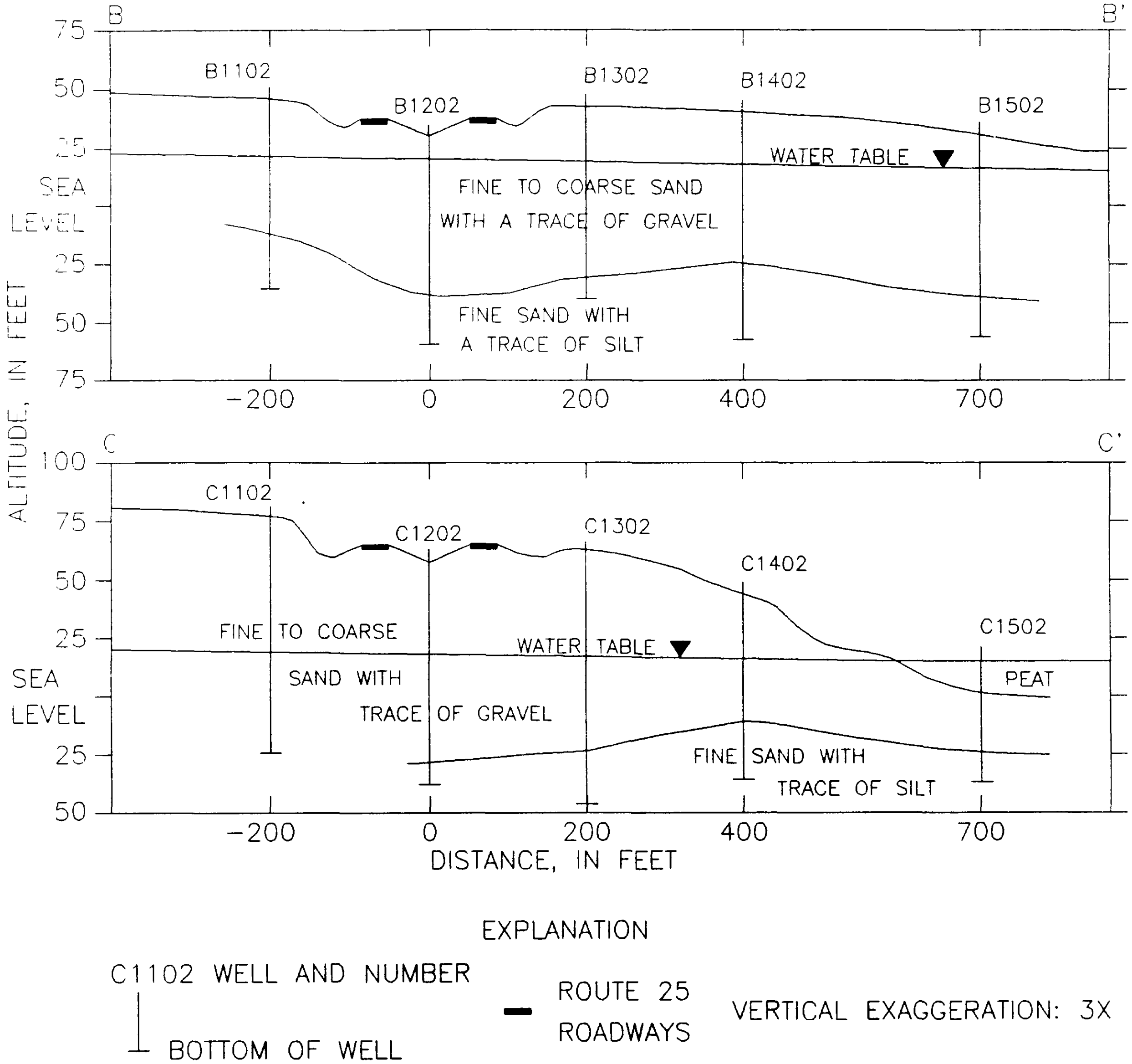


Figure 8. Geologic sections along lines *B-B'* and *C-C'* at sites B and C, near Route 25, southeastern Massachusetts. Line of geologic section shown in figure 6.

Table 1. Ranges and averages of grain-size distributions for test sites A, B, C, and D near Route 25, southeastern Massachusetts

[Sand/gravel indicates all material with particle diameter ≥0.0025 in. Silt/clay indicates all material with particle diameter <0.0025 in.]

Test site	Range of grain sizes (percent by weight)		Average grain sizes (percent by weight)	
	Sand/gravel	Silt/clay	Sand/gravel	Silt/clay
A	99.78-69.18	0.22-30.82	97.37	2.63
B	99.22-68.62	0.78-31.38	94.15	5.85
C	100-23.28	0-76.72	75.65	24.35
D	99.29-78.88	0.71-21.12	93.66	6.34
Overall			91.65	8.35

Ground-Water Hydrology

The shallow unconfined aquifer in the study area comprises the southern parts of the Plymouth-Carver aquifer—a regional aquifer that underlies a 140-square-mile area in southeastern Massachusetts. The storage capacity of the aquifer is estimated to be 500 to 540 billion gallons of water (Williams and Tasker, 1974). Precipitation is the largest source of recharge to the aquifer, contributing about 1.15 million (gal/d)/mi^2. This input, combined with recharge from other sources produces a total annual recharge estimated to average 120 million gal/d. Infiltration through the permeable soils is rapid when the soils are free of frost, resulting in recharge to highly transmissive surficial aquifers that are hydraulically connected to streams and ponds. Water is discharged from the aquifer by pumping, evapotranspiration, direct evaporation, and seepage from the aquifer into streams, lakes, ponds, and wetlands.

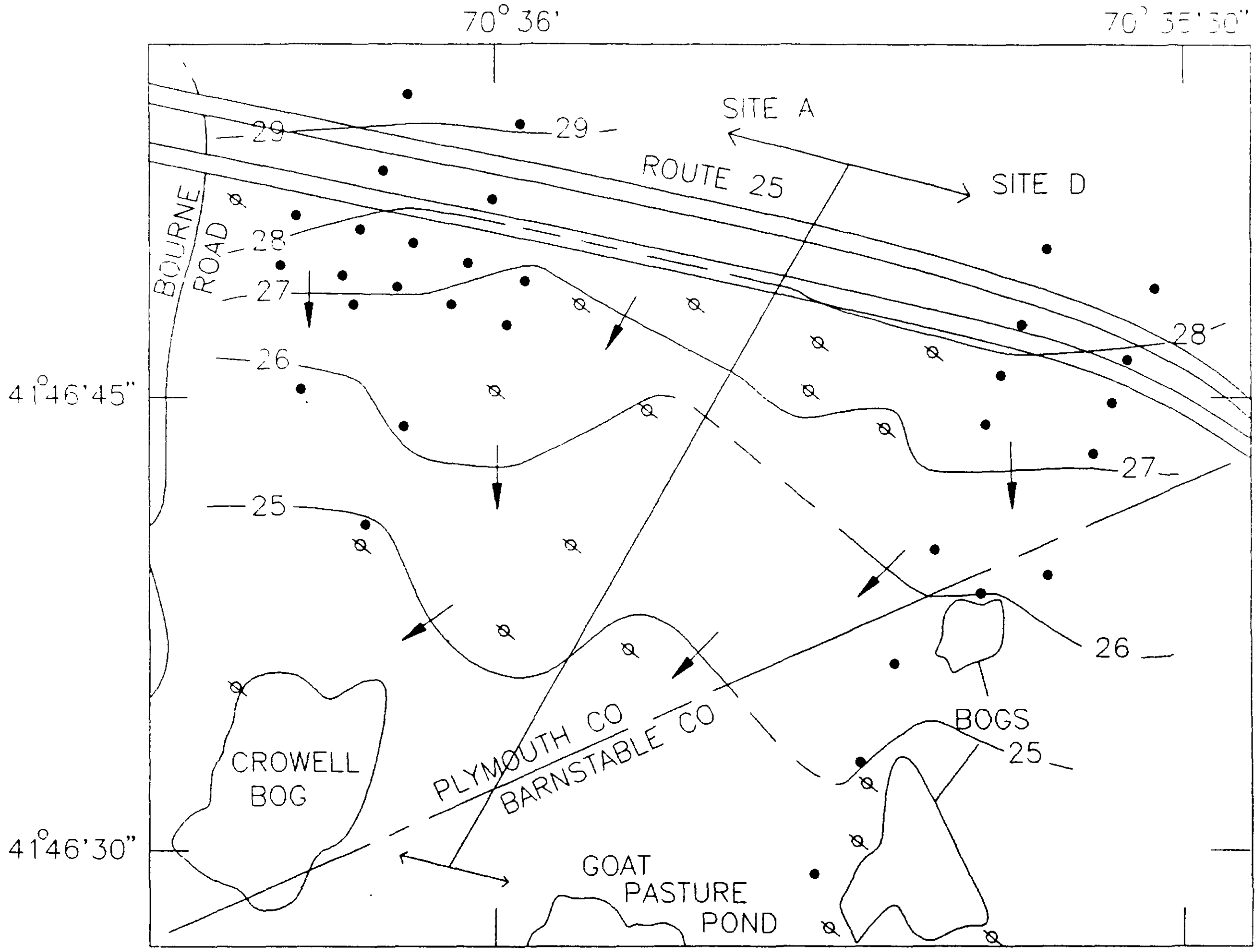
The water table in the study area ranges in depth from 15 to 60 ft below land surface. Compared to land-surface topography, the water table is relatively flat. Thickness of the saturated zone is greater than 50 ft at all test sites. Water-table altitudes fluctuate from year to year in response to precipitation typically within a range of about 1.5 to 2 ft. Water-table gradients range on an annual basis from 0.001-0.004 at sites A and D, and from 0.004 to 0.006 at sites B and C. Depth to the water table below the highway ranges from 15 ft at site B to 60 ft at site A. Water-table maps constructed from water-level data collected on August 1, 1989, are shown in figures 9 and 10. Ground water generally flows to the south, but bears slightly to the west at sites A and D and slightly to the east at sites B and C, nearly perpendicular to the highway at each test site. Although ground-water levels fluctuate seasonally and annually, the direction of ground-water flow varies little.

Hydraulic conductivity of the upper sand and gravel deposit in the study area was estimated from grain-size analyses and ranges from 90 to 150 ft/d (Hansen and Lapham, 1992). The lower deposit of sand with silt was estimated to have hydraulic conductivities ranging from 10 to 100 ft/d (Williams and Tasker, 1974). Hydraulic conductivities of the upper 25 ft of the saturated zone estimated from grain-size analyses (Warren and others, 1996) are about 195, 75, 100, and 80 ft/d at test sites A,B,C, and D, respectively. Effective porosity of the aquifer material is estimated to be 35 percent based on porosity determinations made at a nearby study site having a similar geology (LeBlanc and others, 1987).

Surface-Water Hydrology

Surface water in the study area drains through a chain of seasonally connected ponds in the eastern part of the study area (sites A and D, fig. 2), and by Red Brook in the western part of the study area (sites B and C, fig. 3). The headwaters for surface-water drainage in the eastern part of the study area are from wetlands and kettle ponds that drain to Goat Pasture Pond. Discharge from Goat Pasture Pond is through ground water recharge and evapotranspiration, except during periods of high surface-water flow when there is minor surficial drainage through overflow channels that connect Goat Pasture Pond with other ponds and from there to a coastal marsh and Buttermilk Bay (Federal Highway Administration, 1978, 1983). The headwaters of Red Brook are from a complex of wetlands, kettle ponds, and cranberry bogs. Several kettle ponds and wetlands are just upgradient and downgradient of Route 25 in the study area (fig. 1).

Streamflows in the study area, including Red Brook, are controlled primarily by ground-water contribution and secondarily by pumping of public and private water-supply wells and artificial retention and



"Base from Massachusetts Highway Department, Route 25 plans, 1:480, 1:2,400, 1984 and U.S. Geological Survey, Sagamore, Mass., 1:25,000, 1979"

EXPLANATION

— 25 – – WATER–TABLE CONTOURS–Shows altitude of water table. Dashed where approximately located. Contour interval, 1 foot. Datum is sea level

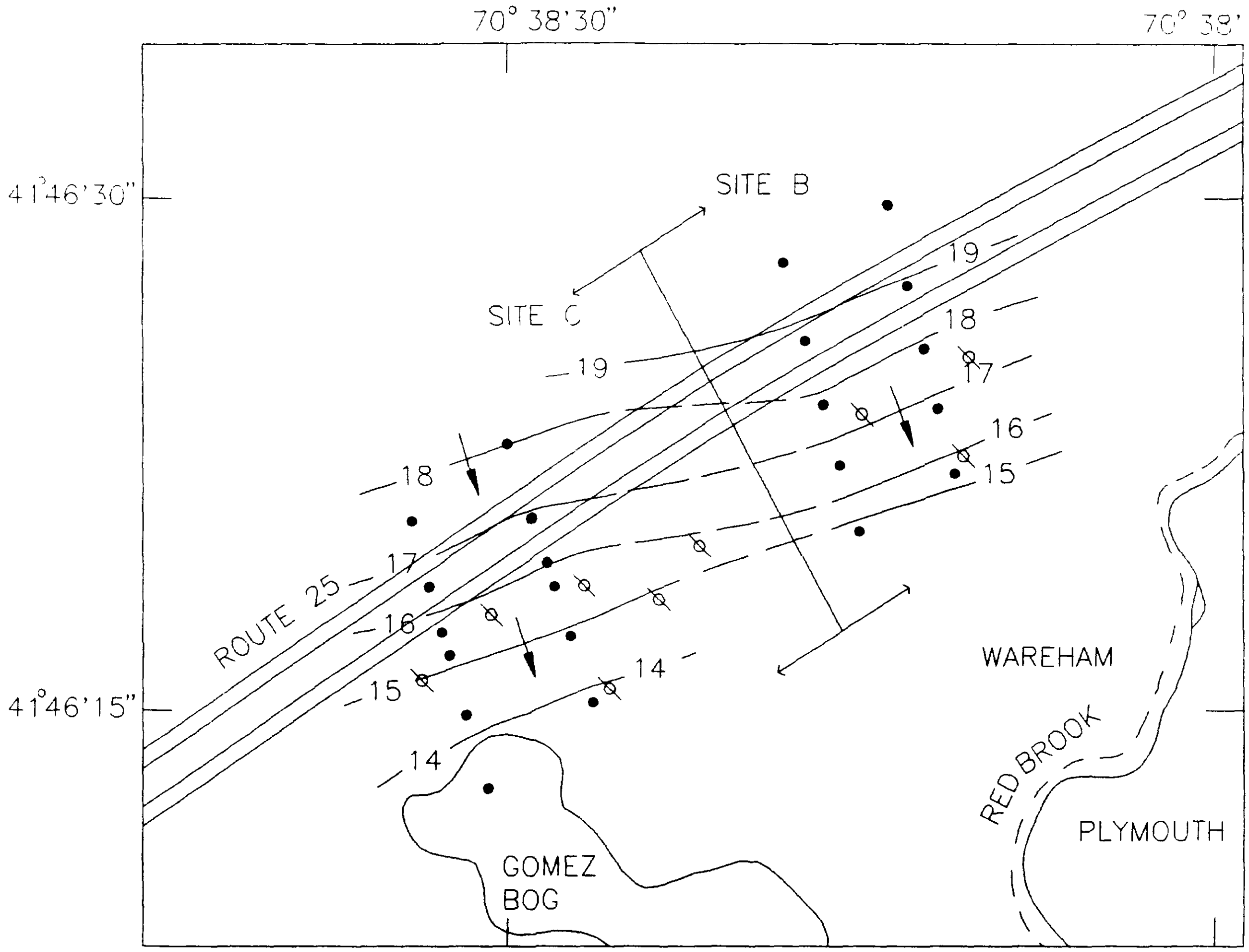
0 400 FEET
0 100 METEPS

→ DIRECTION OF GROUNDOWATER FLOW

• LONG–SCREEN MONITORING WELL

⊗ OBSERVATION WELL

Figure 9. Altitude of the water table on August 1, 1989, at sites A and D, near Route 25, southeastern Massachusetts.



"Base from Massachsetts Highway Department, Route 25 plans, 1:480, 1:2,400,1979 and U.S. Geological Survey, Wareham, Mass., 1:25,000, 1972"

EXPLANATION

—17— — WATER-TABLE CONTOUR—Shows altitude of water table. Dashed where approximately located. Contour interval, 1 foot. Datum is sea level

0 400 FEET

0 100 METERS

→ DIRECTION OF GROUND-WATER FLOW

• LONG-SCREEN MONITORING WELL

⊗ OBSERVATION WELL

Figure 10. Altitude of the water table on August 1, 1989, at sites B and C, near Route 25, southeastern Massachusetts.

release of water from upstream cranberry bogs. Streams were diverted to flow through cranberry bogs and dams were built on streams and ponds for water storage. Base flow of streams in the area is dominated by ground-water discharge (Moog, 1987). Maximum flows occur in the spring because of combined rainfall and snowmelt.

The drainage area for Red Brook above the streamflow-gaging station at Route 25 (USGS station No. 01105884) is about 9.81 mi^2. Red Brook receives discharge from the Route 25 highway-drainage systems at sites B and C. Highway runoff is attenuated in a sedimentation pool before entering Red Brook. Mean annual discharge at the Red Brook gaging station just downstream from Route 25 (USGS Station No. 01105885) for water years 1982-86 was 6.4 ft^3/s. Monthly minimum, mean, and maximum discharges and mean monthly specific conductance for the same period are shown in figure 11. Minimum and maximum discharges recorded for this period are 1.2 and 43 ft^3/s, respectively. High flows are typically the result of releases from upstream cranberry bogs. Daily discharge for Red Brook for calendar years 1981-86 is shown in figure 12.

Background Water Quality

The chemical constituents of interest in this study are dissolved chloride, sodium, and calcium because they are the primary constituents of road salt applied to the highway. Background concentrations of these constituents are affected by the proximity of the study area to the coast. On a microequivalent basis, coastal precipitation is four times more concentrated than inland precipitation, particularly for the anions chloride and sulfate and the cations sodium, magnesium, calcium, and potassium (Gay and Melching, 1995). Although a high percentage of the concentration of these constituents in precipitation can be attributable to seawater, nonoceanic or anthropogenic inputs likely account for some part of the total background concentrations of these constituents, particularly for precipitation from storms tracking from the west (Gay and Melching, 1995).

Dissolved chloride, sodium, and calcium and specific conductance were measured in ground water and surface water before construction of the highway to establish background concentrations (fig. 13). During 1983-85, typical background concentrations at sites A, B, and D ranged from 5 to 20 mg/L for chloride, 5 to 10 mg/L for sodium, and 1 to 5 mg/L for calcium. Background concentrations of these constituents generally were higher at site C than at sites A, B, and D. Concentrations at site C ranged from 10 to 30 mg/L for chloride, 5 to 20 mg/L for sodium, and 3 to 15 mg/L for calcium. Background specific conductance ranged from 40 to 70 µS/cm at sites A, B, and D. At site C, specific conductance ranged from 50 to 250 µS/cm. In summer 1987, just before the opening of the highway, average concentrations of dissolved chloride, sodium, and calcium from all wells at sites A, B, and D were 9.4, 6.1, and 1.7 mg/L, respectively. Average specific conductance for these three sites was 69 µS/cm. Average concentrations of dissolved chloride, sodium, and calcium in samples from all wells at site C were 20.2, 9.6, and 5.4 mg/L, respectively, and average specific conductance was 125 µS/cm. Background concentrations at site C may be higher than at the other test sites because of an unpaved lot about 0.5 mi upgradient from the test site where many used buses were stored, and a former pig farm at the same location. Further investigation indicated that a separate plume originating upgradient of the highway but deeper than the road salt plume existed at site C.

Background concentrations of dissolved chloride, sodium, and calcium in Red Brook and Goat Pasture Pond were similar to background concentrations in ground water at sites A, B, and D (fig. 13). The similarity between the quality of surface water and ground water in the study area and the close correspondence between surface-water and ground-water altitudes near Red Brook and Goat Pasture Pond indicates that surface-water bodies in the study area interact with the local ground-water system. Average concentrations of dissolved chloride, sodium, and calcium from all samples collected during water years 1982 through 1986 from Red Brook were 11.3, 5.4, and 2.1 mg/L, respectively. Average specific conductance for the same period was 48 µS/cm. Mean monthly specific conductances for water years 1982-86 are shown in figure 11.

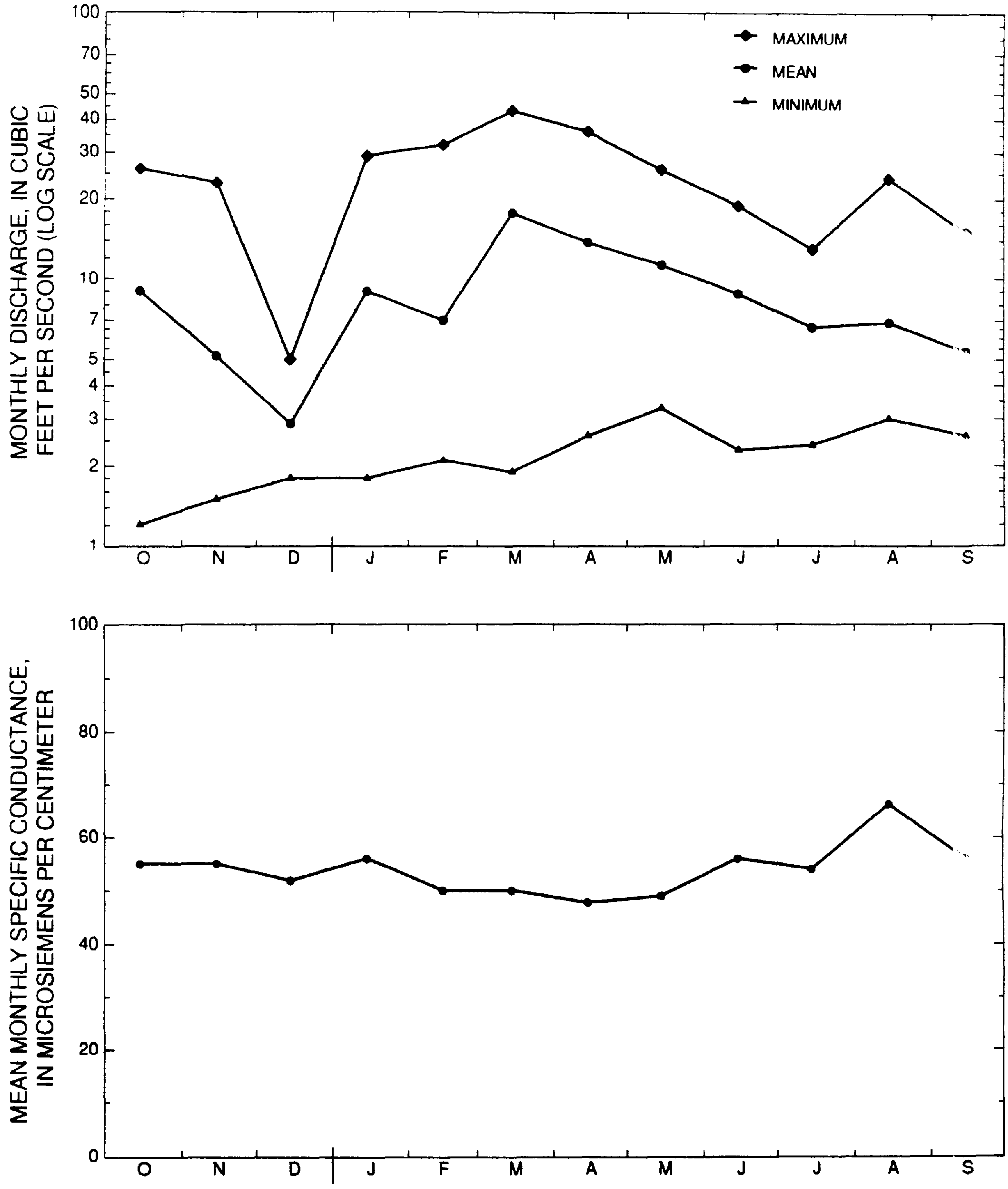


Figure 11. Discharge and specific conductance at Red Brook (U.S. Geological Survey streamflow-gaging station 01105885), southeastern Massachusetts, water years 1982-86.

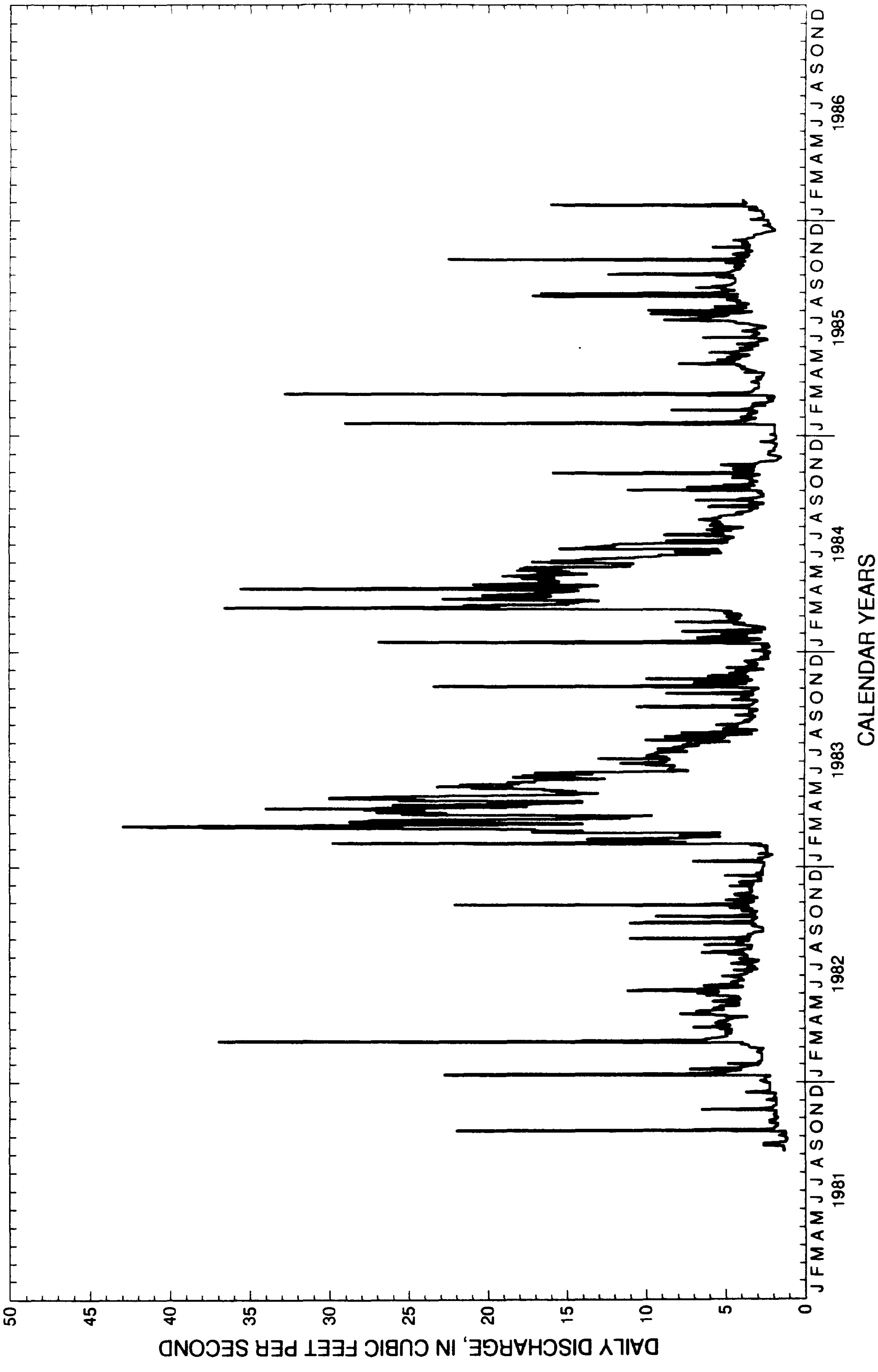


Figure 12. Daily discharge at Red Brook (U.S. Geological Survey streamflow-gaging station 01105885), southeastern Massachusetts, calendar years 1981-86.

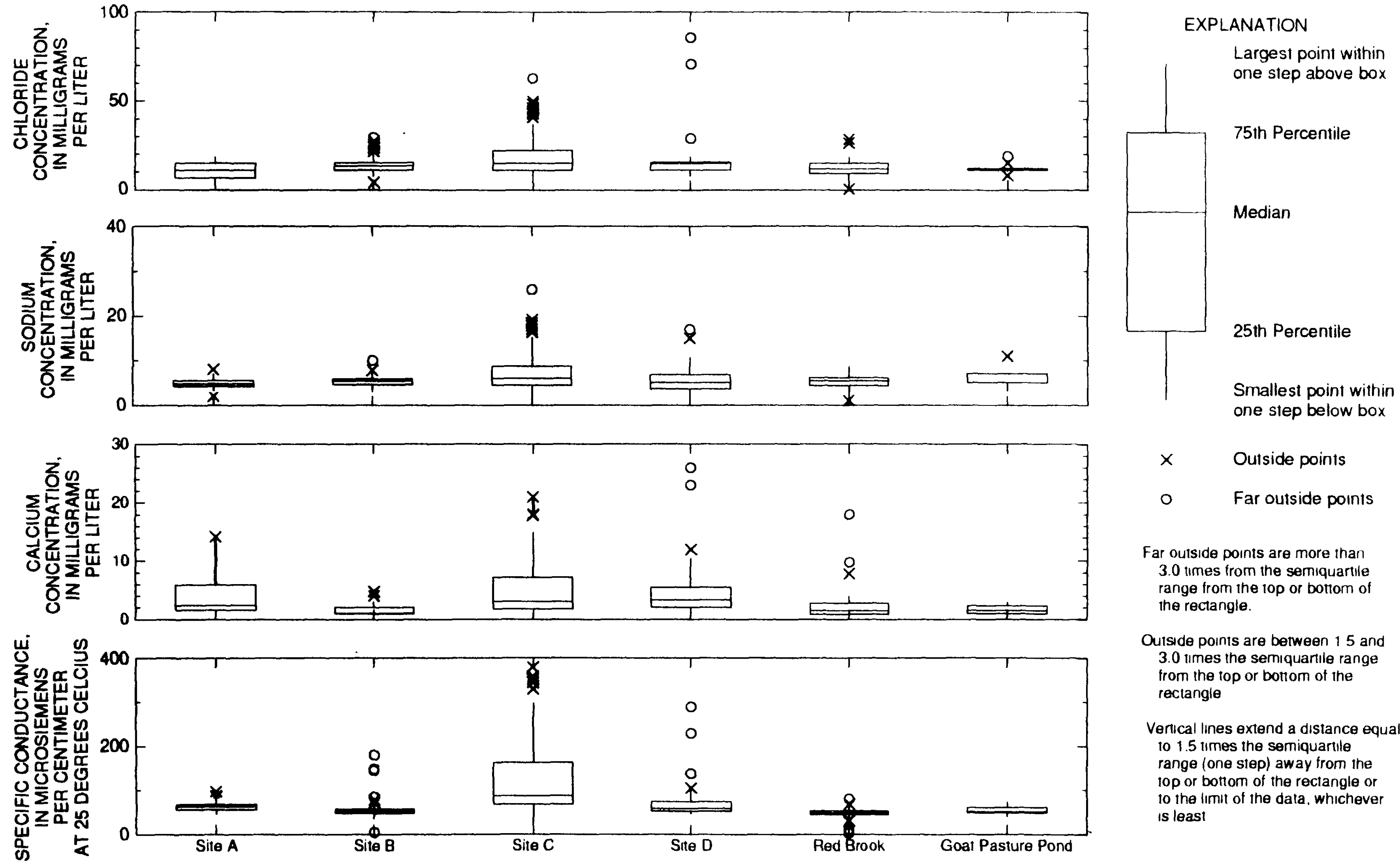


Figure 13. Quality of ground water at sites A, B, C, and D, and of surface water in Red Brook and Goat Pasture Pond in 1979-August 1987, before Route 25 was completed, southeastern Massachusetts.

DATA-COLLECTION PROGRAMS

Data-collection programs were developed for this study to determine the relative effectiveness of the highway-drainage systems on Route 25 in preventing contamination of ground water by road salt. These programs were designed to monitor the application of road salt to the highway, and the quantity of road salt entering the local ground-water system, the highway-drainage systems, and a local stream, Red Brook. These data-collection programs vary considerably in scope and were implemented at different times during 1979 to 1995. The years in which each data collection program was active are shown in table 2.

Table 2. Summary of data-collection programs, Route 25, southeastern Massachusetts, 1979-95

	Calendar Year																
Data-Collection Program	**1979**	**80**	**81**	**82**	**83**	**84**	**85**	**86**	**87**	**88**	**89**	**90**	**91**	**92**	**93**	**94**	**95**
MASSACHUSETTS STATE ROUTE 25																	
Highway completion				X	(in Wareham)				X	(in Plymouth and Bourne)							
ROAD-SALT APPLICATION									X	X	X	X	X	X	X	X	X
GROUND-WATER																	
Collection of water-level data for selection of test sites	X	X	X	X													
Installation of long-screen wells at selected sites				X	X	X	X	X	X	X							
Intermittent collection of water-level and water-quality data				X	X	X	X	X	X	X	X	X					
Evaluation of effectiveness of long-screen wells											X	X					
Installation of short-screen well clusters												X					
Monthly collection of water-level and water-quality data												X	X	X	X	X	X
HIGHWAY DRAINAGE																	
Installation of monitoring stations									X								
Continuous collection of stage and specific conductance data										X	X	X	X	X	X	X	X
RED BROOK																	
Continuous collection of stage and specific conductance data				X	X	X	X	X									
Intermittent collection of stage and specific conductance data									X	X	X	X	X				

Road-Salt Application

The MHD maintains records of road salt applied to Route 25 and forwards these records to the USGS. These records include date, time, and quantity of road salt and sand applied over a given spreader route. The term road salt can refer to salt (sodium chloride) or premix (a mixture of 80-percent sodium chloride and 20-percent calcium chloride, by weight). All road salt applied to Route 25 is purchased to standards that specify chemical purity. Sodium chloride conforms to the standard ASTM D632-84, which specifies that all samples tested must be at a minimum of 95-percent pure sodium chloride and all calcium chloride must be at a minimum of 90-percent pure as specified by the standard ASTM D98-93. Since 1990, each year's supply of road salt has been analyzed for chemical composition at the NWQL. This analysis revealed that the chemical composition of the road salt has been relatively constant since 1990. The largest "contaminants" in the sodium chloride and calcium chloride salts are calcium chloride (about 1 percent of sodium by mass) and sodium chloride (about 7 percent calcium by mass), respectively. These are followed by sodium, calcium, and magnesium sulfates, which comprise less than 1 percent of the remaining salts by weight. Salt-application records are a useful indication of the total amount of salt spread along the highway, and are used as a check against road-salt loads computed from water-quality data from ground-water and from highway drainage. Typical spreading rates from trucks with calibrated spreaders are about 300 lb per lane-mile. However, the values reported may vary from what was actually applied by ±20 percent (Samuel Pollock, Massachusetts Highway Department, personal commun., March 1994). The total amount of salt applied to the highway varies from storm to storm and year to year. Monthly totals of the amounts of road salt and premix applied to the 7-mile section of Route 25 from 1990 to 1994 are illustrated in figure 14.

Ground Water

The ground-water data-collection program was originally designed in two phases—installation of observation wells for collection of water-level data for selection of representative test sites along Route 25, and installation of long-screen wells for collection of water-level and water-quality data at the selected test sites to monitor background water quality upgradient from the highway and ground water potentially contaminated by road salt downgradient from the highway. Two additional phases of ground-water data collection were designed and implemented as new technology for the use of long-screen wells for collection of water-quality data became available—installation of short-screen wells for collection of water-level, water quality, and geophysical data to determine if water-quality samples from the long-screen wells were representative of the water-quality of the aquifer, and installation of clusters of short-screen wells for collection of water-level, water quality, and geophysical data at the test sites to monitor background water quality upgradient from the highway and ground water contaminated by road salt downgradient from the highway. Analyses of water-quality samples collected from short-screen well are used in the evaluation of the relative effectiveness of the highway-drainage systems in preventing road-salt contamination of ground water.

Installation of wells was a major part of the four phases of ground-water-data collection and the methods for drilling and installing these wells were the same for each phase. In general, boreholes in which wells were installed were drilled by drive-and-wash or auger methods. Where boulders were encountered at depth in boreholes at sites A and D, rock drilling and coring methods were used. Drill casing was advanced through the boulder(s) for continuing the hole with drive-and-wash or spin casing methods. After boreholes were drilled to the desired depths, well screen and casing were lowered inside the drill casing or augers. Drill casing or auger were then withdraw, and the aquifer materials were allowed to collapse against the well screen and casing. Cement or bentonite grout was not used to avoid contamination of ground-water samples. Wells installed in the various data-collection phases differ in materials, diameter, length of screen, and depth of screen below the water table. With the exception of the wells made of galvanized steel pipe in the site selection phase, all wells were constructed of schedule 40, polyvinyl chloride casing and screen with screen slot widths of 0.01 in. Well and pipe diameters referred to in this report are inside diameters.

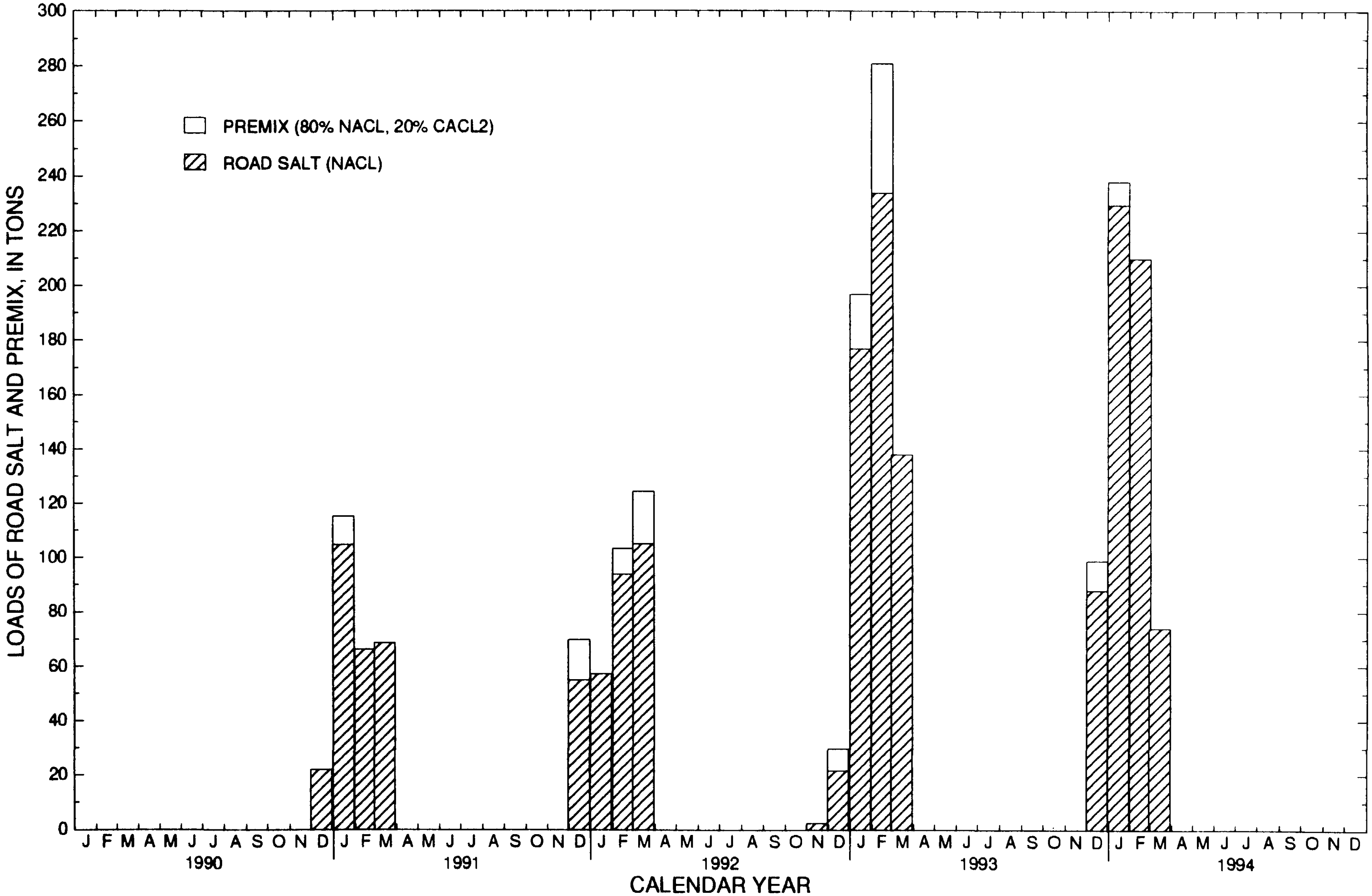


Figure 14. Monthly application of road salt and premix to Route 25, southeastern Massachusetts, 1990 through 1994.

Selection of Test Sites

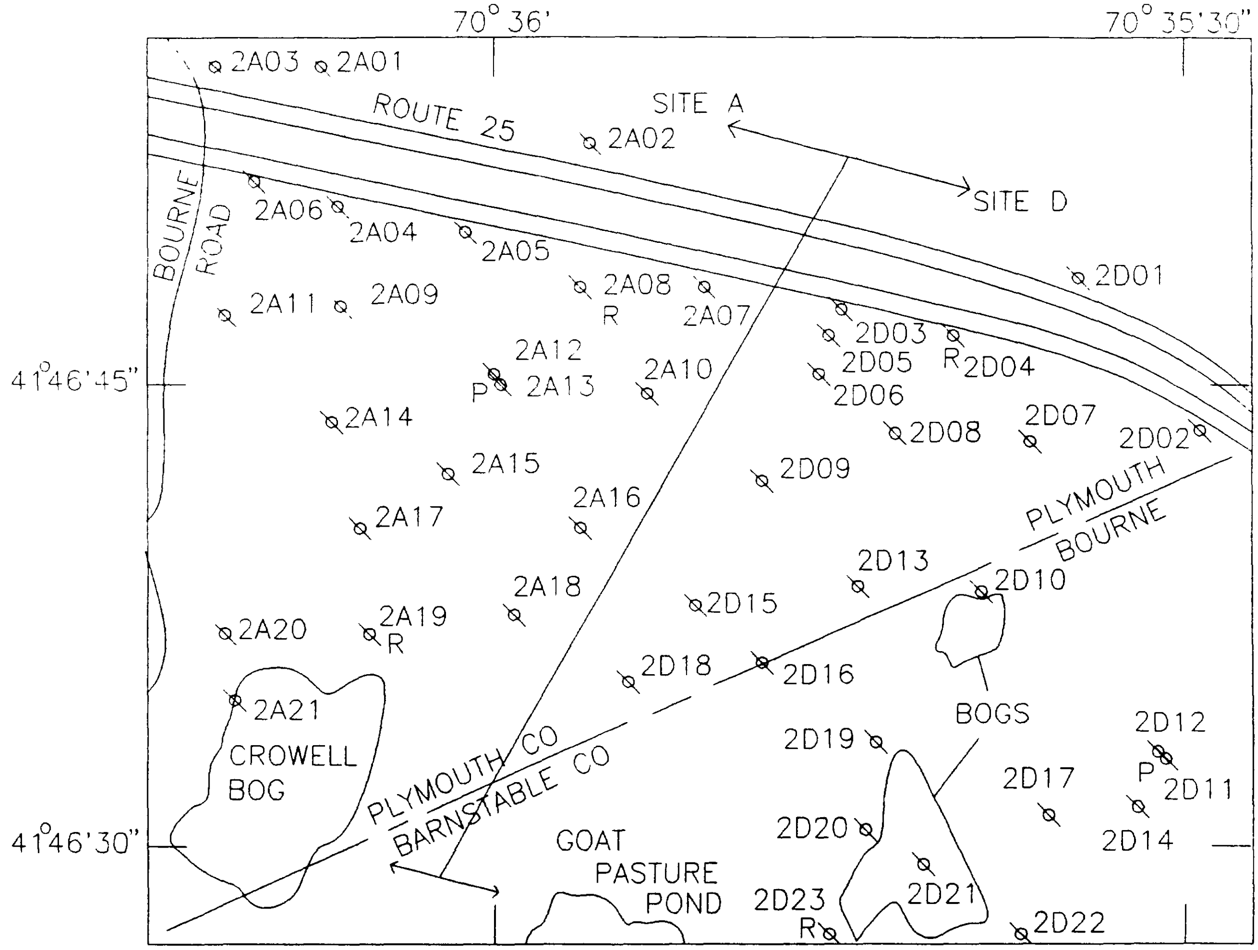
The first phase of ground-water-data collection was the installation of observation wells and collection water-level data along proposed alignments of Route 25 where specific types of drainage systems would potentially be constructed. After highway alignments and drainage systems were selected by the State of Massachusetts, water-level data were used to select test sites representing four drainage systems where ground-water-flow direction was nearly perpendicular to the highway. Installation of these wells began in 1979 and was complete in 1983 (Pollock, 1984). Locations of these observation wells at the selected test sites are shown in figures 15 and 16 and are listed along with associated construction data in table 3. Observation wells are constructed of 1.25-inch galvanized steel pipe with 2- to 3-foot screens placed about 10 ft below the water table. Continuous ground-water-level recorders were installed on one observation well downgradient from the highway at each test site during the period 1982 through 1984. An additional recorder was installed downgradient of the highway at each test site in 1987 (figs. 15 and 16). Water-levels recorded from these wells are shown in figure 17.

Monitoring Road-Salt Contamination by Use of Long-Screen Wells

In the second phase of ground-water-data collection, networks of wells with long screens were installed for collection of water-level and water-quality data at each test site (Pollock, 1984). These wells are referred to as long-screen wells because a typical well-screen length is 30 to 40 ft. Long-screen wells were installed in groups (well sites) arranged along two lines parallel to ground-water flow and extending upgradient from the highway to downgradient from the highway. Three additional lines of long-screen well sites, each downgradient from the highway, were installed at site A because of the expected nonuniform distribution of highway runoff along the highway. Locations of the long-screen well sites and the highway-drainage features are shown for each test site in figures 18 through 21. A listing of these long-screen wells along with associated construction data is provided in table 4. Number, depth, diameter, and screen length of sampling wells differ among test sites. A minimum of two wells, one well screened through upper sand with gravel unit and the other through the lower sand with silt unit, were installed at each well site. At locations where the lithology is more homogeneous than in the afore-mentioned units, one well was screened through about the upper half of the aquifer and the other through about the lower half. The deep-well screens at each long-screen well site typically extend 80 to 100 ft below land surface. Two additional pairs of long-screen wells were installed through the snow berm at site C; one on each line of well sites. Split-spooned samples were taken at approximate 5-foot intervals from the deeper of the two bore holes at about 75 percent of the long-screen well sites.

The long-screen wells sites were labeled by test site (A, B, C, or D), line of wells parallel to ground-water flow direction, and row of wells perpendicular to ground-water flow direction. For example, well site A23 is located at site A in the second line (2) of well sites from west to east and in the third row (3) of wells from north to south (fig. 18). Individual wells are labeled by well site and location of screen in the aquifer. For example, wells A2301and A2302 are located at well site A23 and are screened through the upper part of the aquifer (01) and the lower part of the aquifer (02), respectively. The long-screen wells penetrating through the snow berm at site C were labeled C1S01 and C1S02 on the western line of long-screen well sites, and C2S01 and C2S02 on the eastern line.

Installation of the long-screen wells began in 1982 at sites B and C. Wells installed from 1982 to autumn 1984 (most of the long-screen wells at sites B and C) are 1.5 in. in diameter. All sampling wells installed after the autumn of 1984 (the remaining site B and C wells and the site A and D wells) are 2 in. in diameter. The change in well diameter from 1.5 to 2 in. was to allow for use of submersible pumps and geophysical logging probes. In autumn 1987, an additional long-screen well was installed at every well site with 1.5-inch-diameter wells. These additional wells, which were fully screened to the depth of the deepest 1.5-inch-diameter well at each well site, are identified by well-site name and the suffix "03" (table 4). Installation of long-screen wells was completed at sites B and C in 1987 and at sites A and D in 1988. Lithologic data from boreholes where split-spooned soil samples were collected are presented in table 5.



"Base from Massachusetts Highway Department, Route 25 plans, 1:480, 1:2,400, 1984 and U.S. Geological Survey, Sagamore, Mass., 1:25,000, 1979"

EXPLANATION

2D17 OBSERVATION WELL AND NUMBER—
R, indicates well equipped with a water-level recorder.
P, indicates paired wells

0 400 FEET
0 100 METERS

Figure 15. Location of observation wells used for mapping the water table and for test site selection at sites A and D, near Route 25, southeastern Massachusetts.

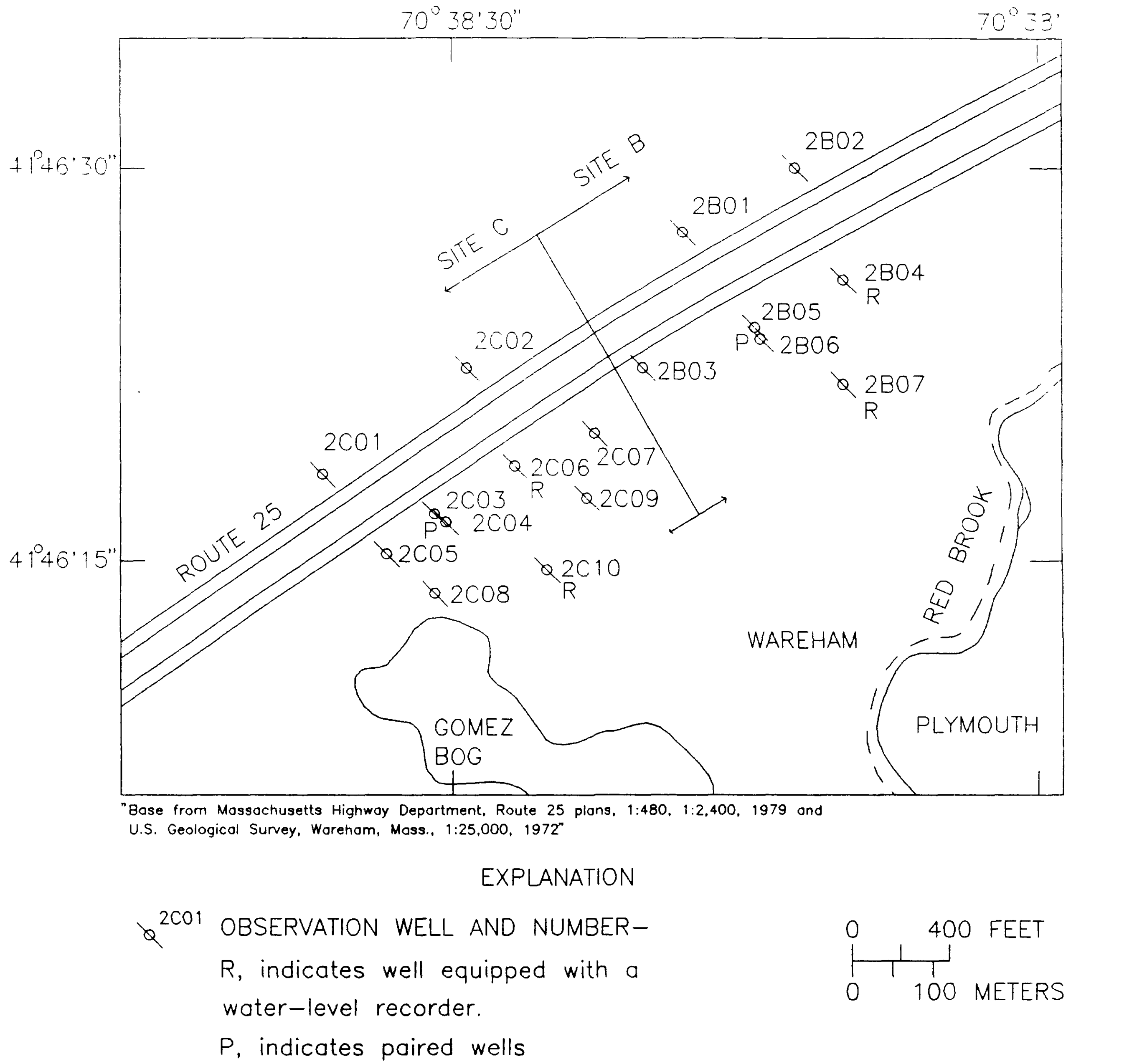


Figure 16. Location of observation wells used for mapping the water table and for test site selection at sites B and C, near Route 25, southeastern Massachusetts.

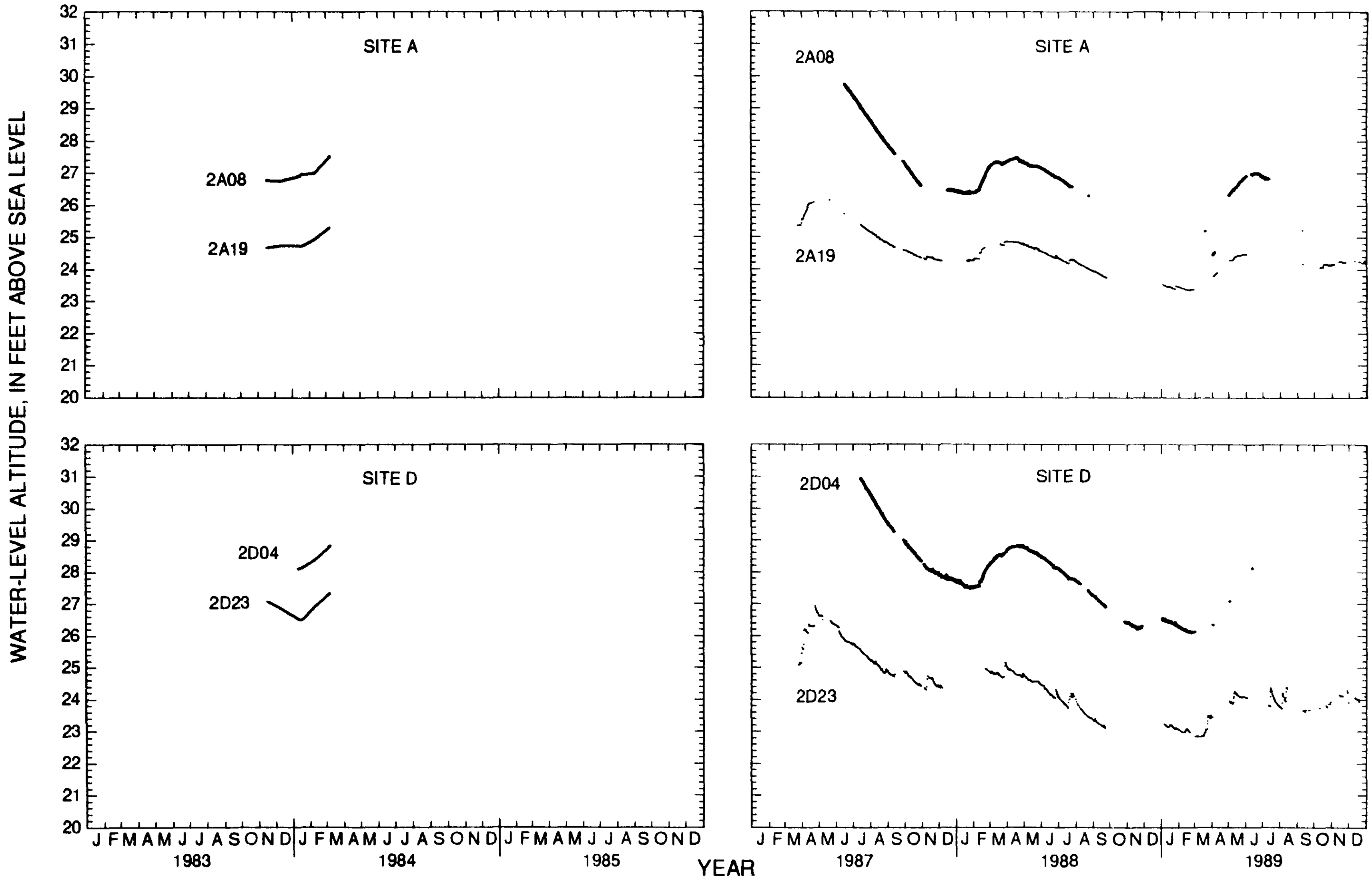


Figure 17. Water-level fluctuations for observation wells, near Route 25, in southeastern Massachusetts for (*A*) sites A and D 1983-85, and 1987-89; (*B*) sites B and C for 1979-81, and 1987-89.

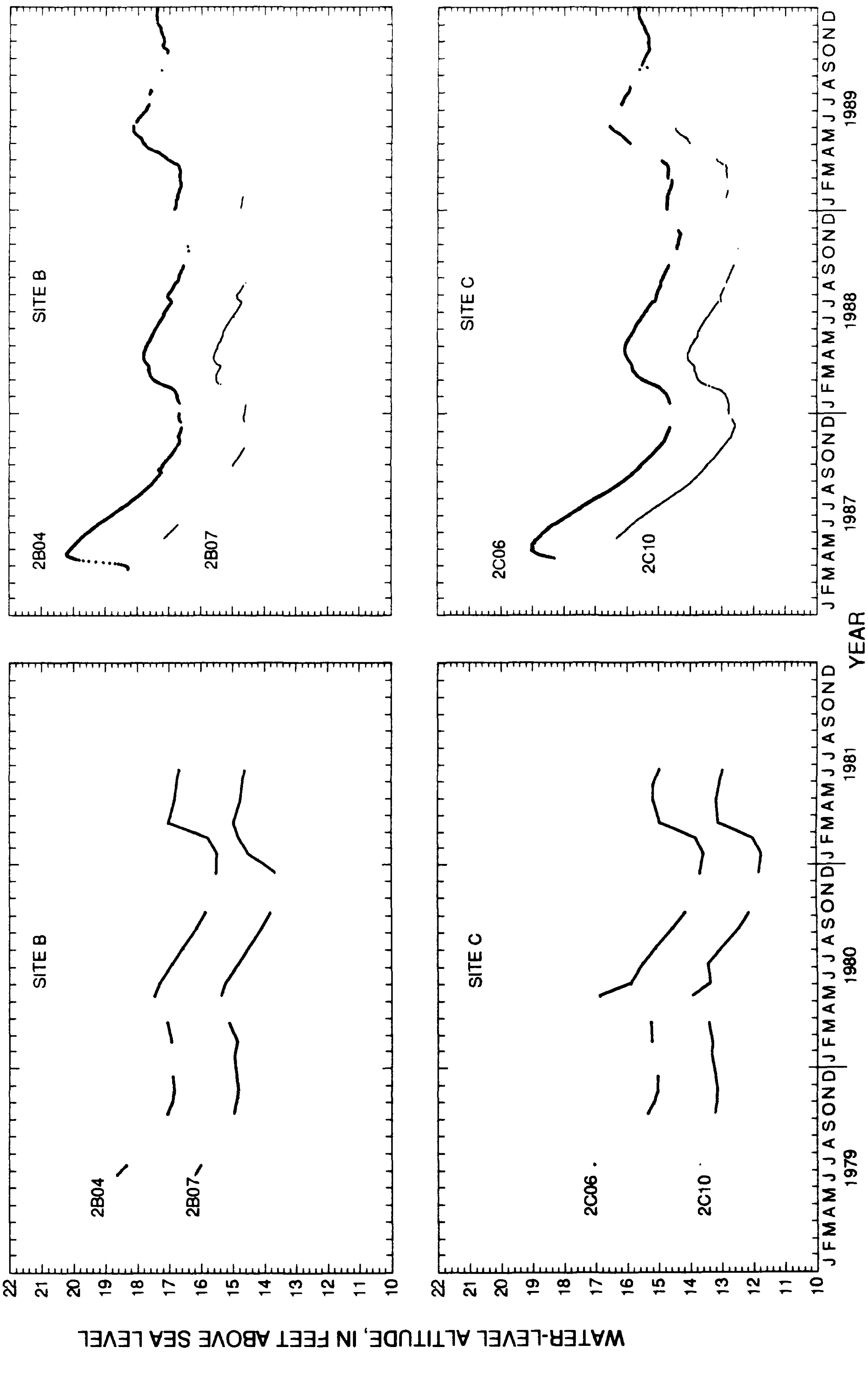


Figure 17. Water-level fluctuations for observation wells, near Route 25, in southeastern Massachusetts for (*A*) sites A and D 1983-85, and 1987-89; (*B*) sites B and C for 1979-81, and 1987-89—*Continued*

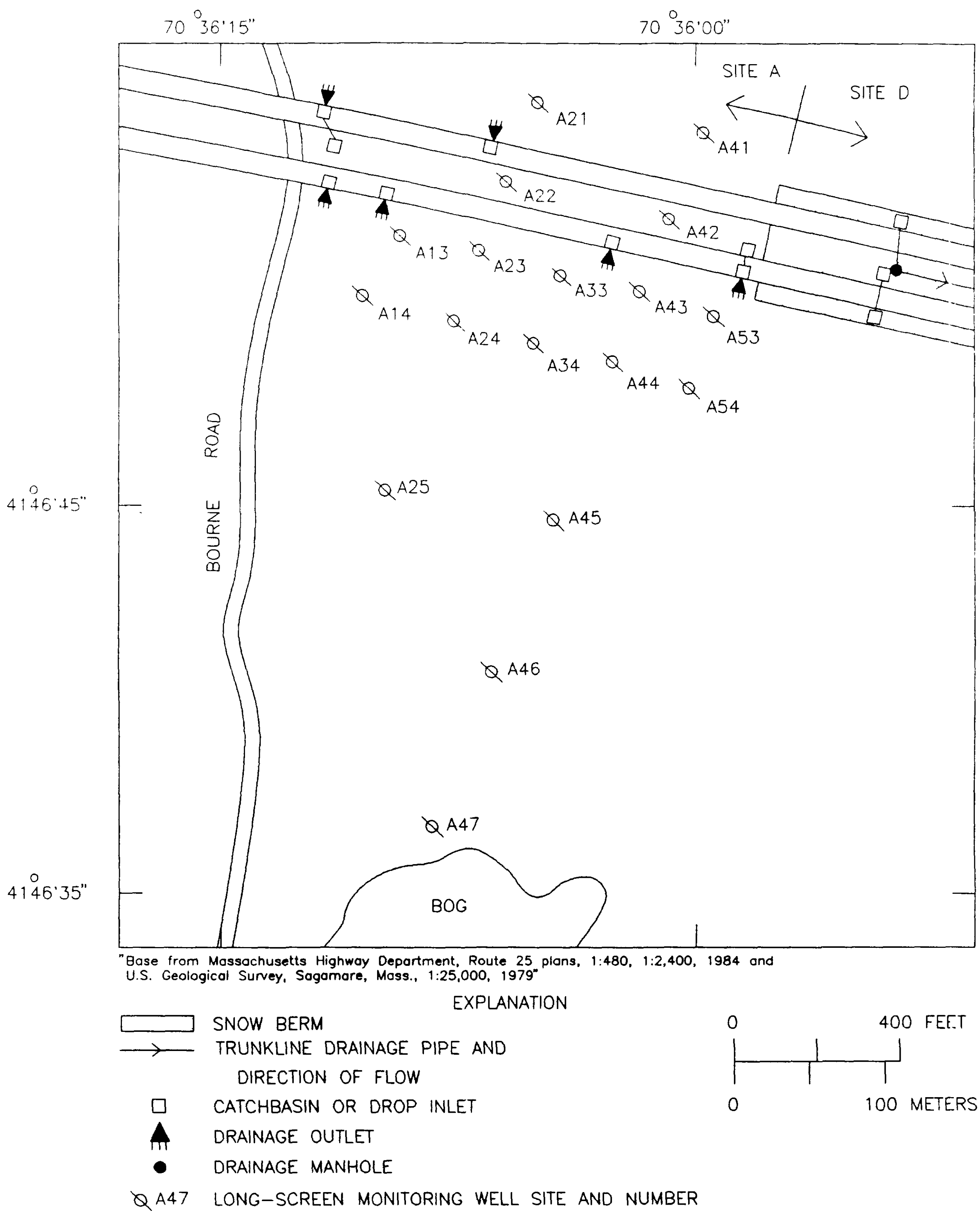


Figure 18. Location of long-screen monitoring well sites and highway-drainage features at site A, near Route 25, southeastern Massachusetts.

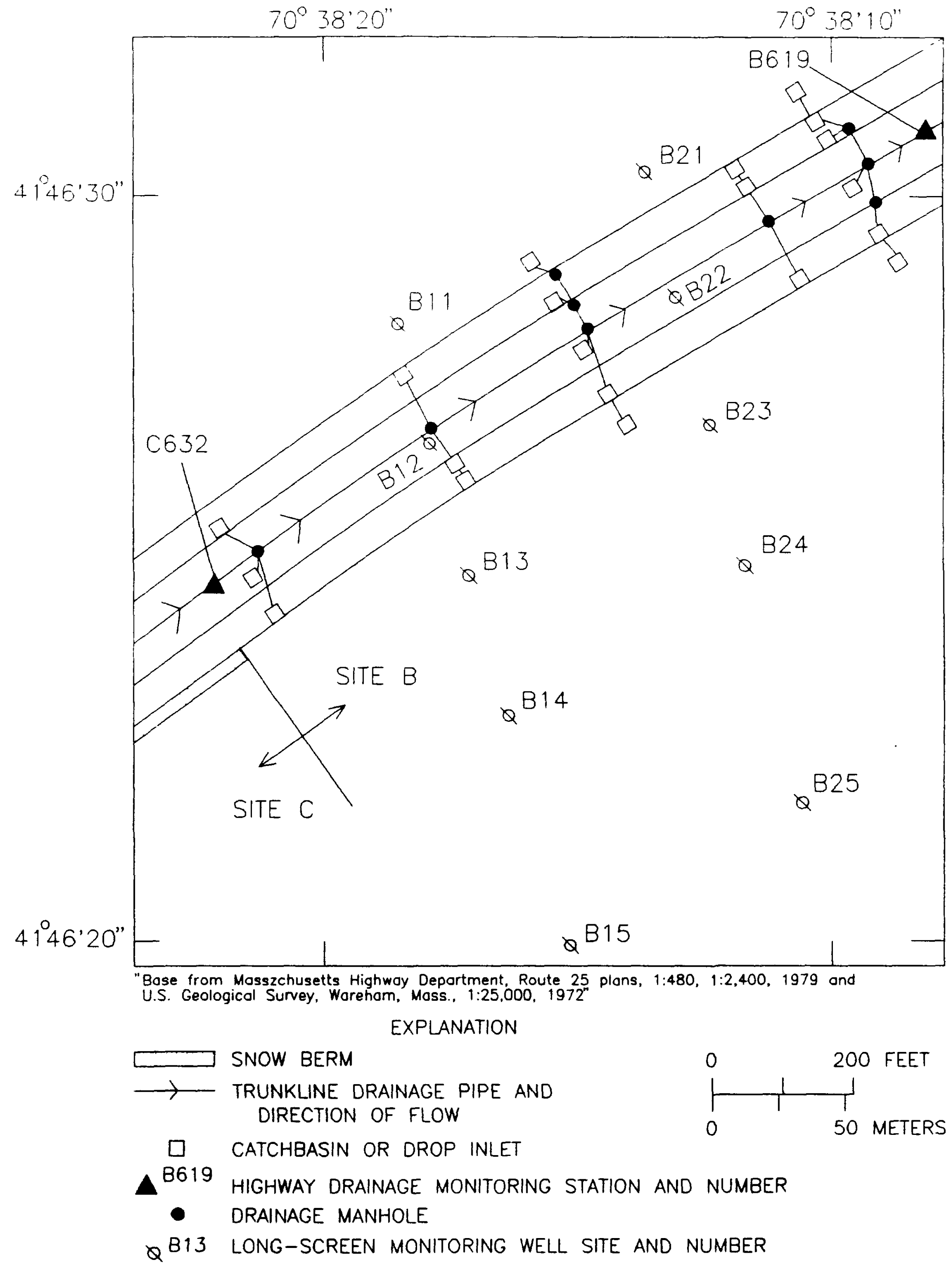


Figure 19. Location of long-screen monitoring well sites and highway-drainage features at site B, near Route 25, southeastern Massachusetts.

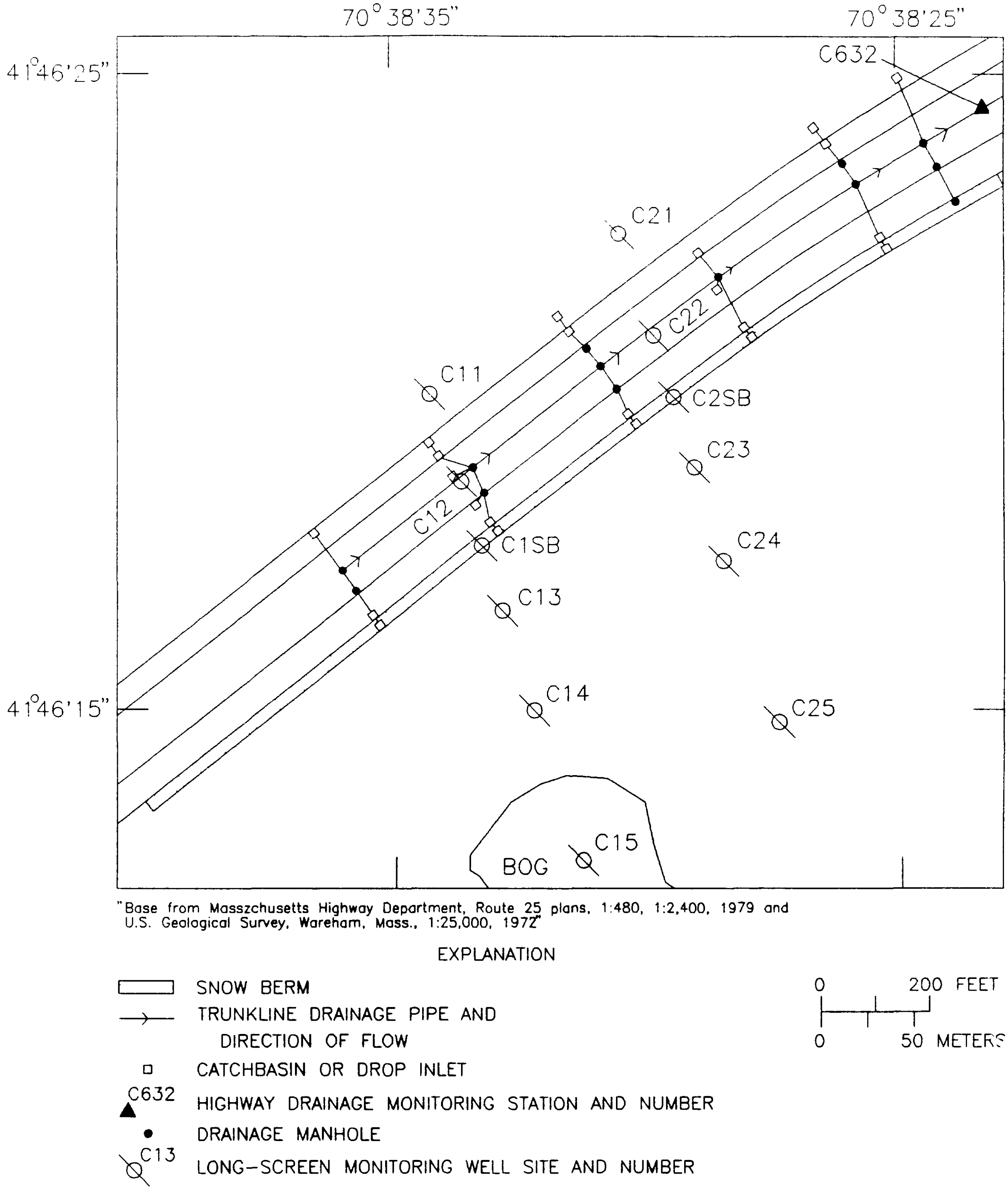


Figure 20. Location of long-screen monitoring well sites and highway-drainage features at site C, near Route 25, southeastern Massachusetts.

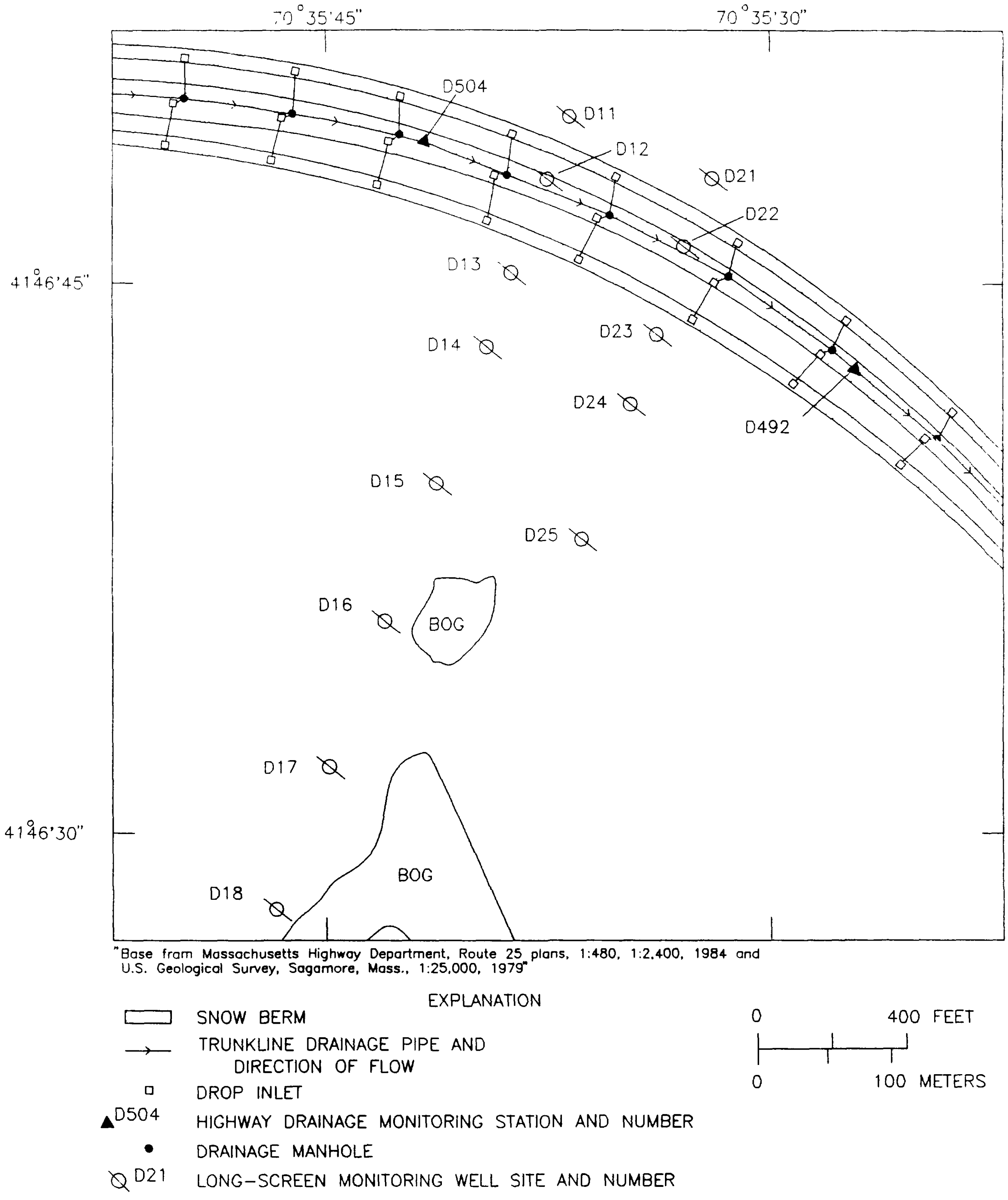


Figure 21. Location of long-screen monitoring well sites and highway-drainage features at site D, near Route 25, southeastern Massachusetts.

Table 3. Characteristics of observation wells used for collection of water-level data and test-site selection, near Route 25, southeastern Massachusetts

[Locations shown in figures 15 and 16. Diameter of screen for wells is 1.25 inches. **Well No.:** see explanation in text on well-numbering convention. **Site identification No.:** Unique number for each site based on the latitude and longitude of the site. First six digits are latitude. Next seven digits are longitude and final two digits are a sequence number to uniquely identify each well. ft, foot; R, observation well equipped with water-level recorder]

Well No.	Site identification No.	Date well constructed	Altitude of land surface (ft above sea level)	Height of measuring point (ft above land surface)	Depth to top of screen (ft below land surface)	Depth to bottom of screen (ft below land surface)
			SITE A			
2A01	414655070360701	5-02-83	59.9	2.0	45	47
2A02	414652070355601	11-10-83	71.9	2.0	66	69
2A03	414655070361201	5-03-83	60.6	1.5	50	52.5
2A04	414653070360601	5-06-80	50.1	3.0	40	43
2A05	414650070360101	8-02-79	60.4	2.5	43	47.5
2A06	414651070361001	5-09-83	72.5	2.0	61	63.5
2A07	414649070355301	1-21-80	73.2	3.2	52	56
2A08R	414648070355601	1-22-80	74.8	3.0	58	61
2A09	414648070360901	1-23-80	71.0	2.0	52	56
2A10	414645070355501	8-02-79	61.4	2.5	39	42.5
2A11	414647070361101	5-12-83	79.2	2.0	63	65.5
2A12	414644070360101	7-24-79	73.1	3.5	53	57
2A13	414644070360102	7-30-79	73.7	2.5	73	77
2A14	414650070360701	7-26-79	62.7	3.0	49	52.5
2A15	414642070360201	7-26-79	62.2	3.0	48	52
2A16	414640070355801	7-24-79	67.3	3.5	53	57
2A17	414640070360601	5-25-83	55.3	1.0	40	43.5
2A18	414637070360001	9-14-83	35.1	2.0	22	25
2A19R	414637070360601	7-25-79	34.5	3.0	21	24.5
2A20	414636070361201	5-24-83	72.7	1.5	61	64.5
2A21	414635070361201	9-07-83	28.5	2.0	22	25
			SITE B			
2B01	414627070381801	6-12-79	44.9	2.5	28	32
2B02	414630070381201	6-13-79	58.0	2.0	39	42.5
2B03	414622070381901	6-19-79	35.6	3.5	38	42
2B04R	414625070381001	6-14-79	53.4	2.0	40	43.5
2B05	414623070381401	6-05-79	45.6	2.0	91	95
2B06	414623070381402	6-11-79	45.4	2.0	37	41
2B07R	414620070381001	6-12-79	34.2	3.5	28	31.5
			SITE C			
2C01	414619070383801	7-16-79	69.5	3.3	59	63
2C02	414623070383002	7-17-79	56.4	3.5	64	68
2C03	414618070383101	6-26-79	50.4	3.0	39	42.5
2C04	414618070383102	7-09-79	49.8	2.5	81	84.5
2C05	414615070383401	9-16-79	55.4	2.5	44	47.5

Table 3. Characteristics of observation wells used for collection of water-level data and test-site selection, near Route 25, southeastern Massachusetts—*Continued*

Well No.	Site identification No.	Date well constructed	Altitude of land surface (ft above sea level)	Height of measuring point (ft above land surface)	Depth to top of screen (ft below land surface)	Depth to bottom of screen (ft below land surface)
			SITE C—*Continued*			
2C06R	414619070382901	6-25-79	51.4	2.0	49	52
2C07	414622070382301	6-20-79	44.4	3.0	39	42.5
2C08	414615070383101	7-17-79	20.4	3.0	18	21.5
2C09	414618070382401	6-20-79	50.6	3.0	39	42.5
2C10R	414616070382701	6-21-79	44.5	3.5	59	62.5
2D01	414648070353501	5-11-83	78.9	2.0	61	63.5
2D02	414643070352901	4-27-83	48.7	3.0	38	41
2D03	414647070354501	11-21-83	83.7	3.0	81	83.5
2D04R	414646070354001	11-14-83	81.2	2.0	67	70.5
2D05	414646070354601	9-28-83	78.7	2.0	61	63
2D06	414645070354601	6-01-83	78.6	1.0	64	67
2D07	414642070353701	9-26-83	60.0	2.0	63	65
2D08	414642070354301	5-31-83	70.7	2.0	51	54
2D09	414641070354901	5-18-83	79.6	1.0	62	65
2D10	414637070353801	3-10-81	30.1	2.0	24	27
2D11	414632070353101	5-01-80	35.8	2.0	24	26.5
2D12	414632070353102	5-02-80	35.1	2.0	36	38.5
2D13	414637070354401	5-17-83	38.0	1.5	34	37
2D14	414631070353301	5-08-80	27.2	2.0	17	20
2D15	414637070355201	5-26-83	56.0	1.5	39	42.5
2D16	414635070354801	5-24-83	45.9	1.5	29	32.5
2D17	414630070353701	3-11-81	26.8	2.0	23	26
2D18	414635070355401	9-19-83	31.3	2.0	22	25
2D19	414632070354301	3-09-81	31.1	2.0	24	27
2D20	414630070354301	3-09-81	30.3	2.0	24	27
2D21	414629070354101	3-10-81	26.1	2.0	24	27
2D22	414627070353901	6-02-80	31.6	2.0	19	21.5
2D23R	414627070354601	3-09-81	30.6	2.0	24	27

Table 4. Characteristics of long-screen monitoring wells installed for collection of water-level and water-quality data, near Route 25, southeastern Massachusetts

[Well site locations shown in figures 18, 19, 20, and 21. Diameter of screen is 2.0 inches unless otherwise noted. **Well No.:** see explanation in text on well-numbering convention. **Site identification No.:** Unique number for each site based on the latitude and longitude of the site. First six digits are latitude. Next seven digits are longitude and final two digits are a sequence number to uniquely identify each well. ft, foot]

Well No.	Site identification No.	Date well constructed	Altitude of land surface (ft above sea level)	Height of measuring point (ft above land surface)	Depth to top of screen (ft below land surface)	Depth to bottom of screen (ft below land surface)
		SITE A				
A1301	414650070360901	4-29-87	71.53	1.9	29	65
A1302	414650070360902	4-14-87	71.32	1.5	64	101
A1401	414649070361001	5-21-87	79.50	1.9	36	56
A1402	414649070361002	4-30-87	79.44	1.5	61	101
A2101	414654070360402	12-13-85	61.32	2.0	21	61
A2102	414654070360401	12-10-85	60.54	2.0	61	86
A2201	414652070360501	9-11-87	86.09	1.3	46	89
A2202	414652070360502	4-21-88	86.33	1.7	86	131
A2301	414650070360602	3-21-86	66.64	1.9	30	68
A2302	414650070360601	2-20-86	65.79	1.5	66	101
A2401	414648070360702	8-30-85	72.53	1.9	46	66
A2402	414648070360701	2-24-86	72.29	1.8	67	106
A2501	414645070360902	9-12-85	71.54	1.6	41	69
A2502	414645070360901	9-09-85	71.11	1.9	67	87
A3301	414650070360301	6-10-87	63.58	2.0	26	61
A3302	414650070360302	5-27-87	64.32	1.7	62	102
A3401	414648070360401	9-08-87	71.81	1.5	29	59
A3402	414648070360402	8-24-87	71.30	1.9	65	106
A4101	414653070355901	9-07-88	74.64	1.9	37	72
A4102	414653070355902	8-11-88	74.78	2.0	72	102
A4201	414651070360001	10-17-87	85.14	2.2	41	81
A4202	414651070360002	10-06-87	85.36	1.8	82	112
A4301	414649070360101	12-02-85	63.25	2.5	24	62
A4302	414649070360102	4-01-86	63.79	1.8	66	101
A4401	414647070360201	3-26-85	71.45	1.7	39	61
A4402	414647070360202	11-19-85	71.24	2.1	61	101
A4501	414644070360402	9-19-85	73.74	2.1	40	65
A4502	414644070360401	9-16-85	74.02	1.5	66	101
A4601	414640070360602	11-28-84	58.15	1.8	21	61
A4602	414640070360603	11-21-84	57.96	1.6	60	90
A4701	414636070360802	11-16-84	40.00[1]	2.0	6	41
A4702	414636070360801	11-06-84	40.00[1]	2.0	41	91
A5301	414649070355801	7-30-87	73.44	2.1	27	60
A5302	414649070355802	6-22-87	73.19	1.5	60	100
A5401	414647070355901	12-31-86	74.08	1.9	38	66
A5402	414647070355902	12-01-86	73.98	2.2	61	102

Table 4. Characteristics of long-screen monitoring wells installed for collection of water-level and water-quality data, near Route 25, southeastern Massachusetts—*Continued*

Well No.	Site identification No.	Date well constructed	Altitude of land surface (ft above sea level)	Height of measuring point (ft above land surface)	Depth to top of screen (ft below land surface)	Depth to bottom of screen (ft below land surface)
			SITE B			
B1101[2]	414628070381701	10-20-83	45.20	2.0	19	61
B1102[2]	414628070381702	10-20-83	45.70	1.7	61	81
B1103	414628070381703	9-16-87	45.23	1.6	20	100
B1201[2]	414626070381702	8-27-82	32.92	2.0	9	50
B1202[2]	414626070381701	8-23-82	31.12	2.0	50	70
B1203	414626070381703	9-16-87	32.22	2.0	10	100
B1301[2]	414624070381602	11-10-82	40.98	2.0	15	60
B1302[2]	414624070381601	11-03-82	41.76	2.0	61	81
B1303	414624070381603	9-22-87	41.90	1.3	21	101
B1401[2]	414622070381501	5-19-82	41.51	1.0	21	66
B1402[2]	414622070381502	4-12-82	39.84	2.0	60	97
B1403	414622070381503	9-17-87	40.36	1.5	20	80
B1501[2]	414619070381402	11-22-82	30.84	2.0	10	60
B1502[2]	414619070381401	11-16-82	30.19	1.0	59	86
B1503	414619070381403	9-24-87	41.04	1.5	18	118
B2101	414630070381203	1-30-86	54.91	2.0	28	68
B2102	414630070381202	1-22-86	55.38	1.0	94	102
B2201[2]	414628070381202	10-13-82	30.62	2.0	5	50
B2202[2]	414628070381203	10-18-82	31.14	2.0	50	85
B2203	414628070381204	9-17-87	30.95	1.3	11	101
B2301[2]	414626070381102	11-02-82	46.51	2.0	21	76
B2302[2]	414626070381101	10-25-82	46.69	1.5	76	86
B2303	414626070381103	9-25-87	46.20	2.0	28	98
B2401[2]	414624070381101	5-23-82	44.07	1.0	16	61
B2402[2]	414624070381102	5-23-82	43.46	2.0	58	78
B2403	414624070381103	9-18-87	43.64	2.3	30	100
B2501[2]	414621070381002	4-30-82	33.01	1.0	15	65
B2502[2]	414621070381001	4-26-82	32.69	1.0	60	70
B2503	414621070381003	9-24-87	33.23	1.6	10	87
			SITE C			
C1101[2]	414620070383403	10-28-83	78.13	2.0	47	72
C1102[2]	414620070383402	10-25-83	77.93	2.0	72	102
C1103	414620070383405	9-14-87	78.41	1.5	55	115
C1201[2]	414618070383302	9-22-82	59.03	2.0	30	45
C1202[2]	414618070383301	9-21-82	58.42	2.0	45	95
C1203	414618070383303	9-16-87	59.09	1.7	40	120

Table 4. Characteristics of long-screen monitoring wells installed for collection of water-level and water-quality data, near Route 25, southeastern Massachusetts—*Continued*

Well No.	Site identification No.	Date well constructed	Altitude of land surface (ft above sea level)	Height of measuring point (ft above land surface)	Depth to top of screen (ft below land surface)	Depth to bottom of screen (ft below land surface)
			SITE C—*Continued*			
C1S01[2]	414617070383301	8-06-84	62.63	2.5	5	80
C1S02[2]	414617070383302	7-25-84	62.06	2.0	75	91
C1301[2]	414616070383302	3-23-83	54.62	2.0	30	50
C1302[2]	414616070383301	3-08-83	55.39	1.5	50	80
C1303	414616070383303	9-14-87	56.44	1.6	30	100
C1401[2]	414614070383201	3-30-83	38.15	2.0	9	45
C1402[2]	414614070383202	3-24-83	36.78	2.0	45	60
C1403	414614070383203	9-23-87	50.31	1.6	30	110
C1501[2]	414611070383101	4-25-83	14.50	2.0	14	42
C1502[2]	414611070383102	4-20-83	14.39	3.0	39	50
C1503	414611070383103	9-22-87	19.41	2.0	0	100
C2101	414622070382901	2-14-86	77.09	2.5	45	60
C2102	414622070382902	2-04-86	77.23	2.0	98	103
C2201[2]	414620070382902	10-12-82	50.65	2.0	30	55
C2202[2]	414620070382901	10-04-82	50.50	2.0	55	80
C2203	414620070382905	9-16-87	49.41	2.0	30	86
C2S01	414620070382903	1-04-85	54.33	1.5	16	51
C2S02	414620070382904	12-20-84	54.02	2.0	50	81
C2301[2]	414618070382802	12-07-82	58.33	2.0	36	74
C2302[2]	414618070382801	11-30-82	57.80	2.0	73	91
C2303	414618070382803	9-23-87	58.86	1.7	40	120
C2401[2]	414617070382701	4-05-83	46.69	2.0	20	55
C2402[2]	414617070382702	3-31-83	46.60	2.0	55	70
C2403	414617070382703	9-23-87	47.16	1.5	30	100
C2501[2]	414614070382601	4-12-83	44.19	2.0	21	51
C2502[2]	414614070382602	4-06-83	44.14	1.0	51	61
C2503	414614070382603	9-24-87	44.53	1.3	21	116
			SITE D			
D1101	414649070353601	8-02-88	84.55	1.0	49	79
D1102	414649070353602	7-07-88	84.40	1.5	79	104
D1201	414647070353701	12-15-87	81.57	1.5	48	78
D1202	414647070353702	11-18-87	81.83	1.4	76	111
D1301	414645070353701	6-05-86	81.35	1.9	43	78
D1302	414645070353702	5-21-86	81.56	2.2	79	95
D1401	414643070353801	5-13-86	65.99	2.0	26	66
D1402	414643070353802	4-25-86	64.83	2.0	66	101

Table 4. Characteristics of long-screen monitoring wells installed for collection of water-level and water-quality data, near Route 25, southeastern Massachusetts—*Continued*

Well No.	Site identification No.	Date of construction	Altitude of land surface (ft)	Height of measuring point above land surface (ft)	Depth to top of screen below land surface (ft)	Depth to bottom of screen below land surface (ft)
			SITE D—*Continued*			
D1501	414639070354001	4-24-86	58.05	2.0	21	71
D1502	414639070354002	4-15-86	56.89	2.5	71	101
D1601	414636070354201	8-02-85	32.72	1.5	3	40
D1602	414636070354202	7-10-85	32.52	2.0	41	64
D1701	414632070354401	11-05-84	37.23	2.3	5	40
D1702	414632070354402	10-22-84	37.32	2.2	40	63
D1801	414628070354501	10-18-84	35.69	1.8	5	40
D1802	414628070354502	10-09-84	35.48	1.5	40	84
D2101	414647070353101	6-21-88	67.49	1.9	28	78
D2102	414647070353102	5-17-88	67.74	1.7	82	102
D2201	414645070353201	4-06-88	79.88	2.5	37	87
D2202	414645070353202	3-23-88	79.83	2.4	88	128
D2301	414644070353301	11-18-86	51.41	2.0	17	62
D2302	414644070353302	10-28-86	51.51	2.7	61	101
D2401	414642070353402	10-09-86	46.95	2.2	12	69
D2402	414642070353401	9-22-86	47.34	1.8	69	96
D2501	414638070353701	4-25-85	33.75	2.2	6	41
D2502	414638070353702	4-22-85	33.61	2.4	42	69

[1] Estimated from Route 25 construction plans.
[2] Diameter of screen is 1.5 inches.

Table 5. Lithologic data from long-screen wells, near Route 25, southeastern Massachusetts

[Well site locations shown in figures 18, 19, 20, and 21. Site identification numbers given in table 4. Well identification numbers ending in 01 are screened in upper part of aquifer; well identifications numbers ending in 02 are screened in lower part of aquifer. All altitudes are land surface. All depths relative to land surface. ft, feet]

Description	Depth to top of unit (ft)	Depth to bottom of unit (ft)
A1302 Altitude, 71.32 ft Depth of hole, 101 ft		
Sand, fine to coarse; gravel, trace	0	63
Boulder(s)	63	70
Sand, fine to coarse; gravel; silt, trace	70	--
A1402 Altitude, 79.44 ft Depth of hole, 101 ft		
Sand, fine to coarse; gravel, trace	0	47
Boulder(s)	47	60
Sand; gravel some; silt, trace	60	--
A2102 Altitude, 60.54 ft Depth of hole, 86 ft		
Sand, fine; gravel, trace; silt, trace	0	8
Sand, fine; gravel, trace	8	68
Sand, fine to coarse; gravel, some; silt, trace	68	78
Sand, fine; gravel; silt, trace	78	--
A2201 Altitude, 86.09 ft Depth of hole, 93 ft		
Sand, fine to coarse; gravel, trace	0	--
A2302 Altitude, 65.79 ft Depth of hole, 101 ft		
Sand, fine to coarse; gravel, some	0	65
Sand, coarse; gravel, some; silt, trace	65	--
A2401 Altitude, 72.53 ft Depth of hole, 71 ft		
Sand, fine to coarse; gravel, trace	0	56
Sand, fine to coarse; gravel, trace; silt, trace	56	--
A2402 Altitude, 72.29 ft Depth of hole, 106 ft		
Sand; gravel, some; silt, trace	0	--
A2502 Altitude, 71.11 ft Depth of hole, 87 ft		
Sand, fine to coarse; gravel, some	0	18
Sand, coarse; gravel	18	33
Sand, fine to coarse; gravel	33	43
Sand, coarse	43	67
Boulder(s)	67	68
Sand, fine to coarse; gravel; silt, trace	68	--
A3302 Altitude, 64.32 ft Depth of hole, 102 ft		
Sand, fine to coarse	0	40
Sand, coarse; gravel, some	40	60
Sand; gravel; silt, trace	60	--
A3402 Altitude, 71.30 ft Depth of hole, 106 ft		
Sand, fine to coarse; gravel, trace	0	53
Sand, coarse; gravel	53	60
Sand, fine; gravel, trace; silt, trace	60	--
A4302 Altitude, 63.79 ft Depth of hole, 101 ft		
Sand, fine to coarse; gravel, trace	0	63
Sand, coarse; gravel; silt, trace	63	67
Boulder(s)	67	69
Sand, coarse; gravel; silt, trace	69	--
A4401 Altitude, 71.45 ft Depth of hole, 61 ft		
Sand, fine; gravel, trace	0	23
Sand, fine	23	43
Sand, fine; gravel, trace	43	58
Sand, fine to coarse; gravel, trace; silt, trace	58	--
A4402 Altitude, 71.24 ft Depth of hole, 101 ft		
Sand, coarse	50	58
Sand, fine; gravel, some; silt, trace	58	85
Boulder(s)	85	86
Sand, fine to coarse; gravel, trace; silt, trace	86	--
A4502 Altitude, 74.02 ft Depth of hole, 101 ft		
Sand, fine to coarse; gravel, trace	0	55
Sand, fine to coarse; gravel, some; silt, trace	55	--
A4602 Altitude, 57.96 ft Depth of hole, 90 ft		
Sand, medium to coarse; gravel, some	0	3
Sand, fine; silt, trace;	3	6
Boulder(s)	6	8
Sand, medium to coarse	8	13
Sand, fine to coarse; gravel, trace	13	65
Boulder(s)	65	72
Sand, fine to coarse; gravel; silt, trace	72	--
A4702 Altitude, 40.00[1] ft Depth of hole, 91 ft		
Sand, medium to coarse; gravel, some	0	18
Sand, fine	18	28
Sand, medium to coarse; gravel	28	32
Sand, fine to coarse	32	58
Sand, fine to coarse; gravel	58	72
Sand, fine; gravel, some; silt, trace	72	78
Sand, fine; gravel; silt, trace	78	--
A5302 Altitude, 73.19 ft Depth of hole, 100 ft		
Sand, fine to coarse; gravel, trace	0	55
Sand; gravel; silt, trace	55	87
Boulder(s)	87	99
Sand; gravel; silt, trace	99	--
A5401 Altitude, 74.08 ft Depth of hole, 66 ft		
Sand, fine to coarse; gravel, some	0	65
Sand; gravel; silt, trace	65	--
A5402 Altitude, 73.98 ft Depth of hole, 102 ft		
Sand, fine to coarse; gravel, some	0	65
Sand; gravel; silt, trace	65	95
gravel; cobbles, some	95	--
B1102 Altitude, 45.70 ft Depth of hole, 81 ft		
Sand, fine	0	12
Sand, coarse; gravel, trace	12	33

Table 5. Lithologic data from long-screen wells, near Route 25, southeastern Massachusetts—*Continued*

Description	Depth to top of unit (ft)	Depth to bottom of unit (ft)
Sand, fine	33	48
Sand, fine; silt, trace	48	53
Sand, fine; gravel, trace	53	59
Sand, fine; silt, some	59	--
B1202 Altitude, 31.12 ft Depth of hole, 90 ft		
Sand, fine to coarse; gravel, trace	0	28
Sand, fine	28	50
Sand, coarse; gravel	50	70
Sand, fine; silt, trace	70	--
B1302 Altitude, 41.76 ft Depth of hole, 81 ft		
Sand, medium to coarse; gravel; cobbles, trace	0	12
Sand, fine to coarse; gravel, trace	12	55
Sand, fine to coarse; silt, trace	55	70
Sand, fine; silt, trace	70	--
B1402 Altitude, 39.84 ft Depth of hole, 97 ft		
Sand, fine; gravel, trace	0	18
Sand, coarse	18	63
Sand, fine; silt, some	63	--
B1502 Altitude, 30.19 ft Depth of hole, 87 ft		
Sand, coarse; gravel, some	0	28
Sand, fine to coarse; gravel, trace	28	48
Sand, fine to coarse; silt, trace	48	68
Sand, fine; silt, some	68	--
B2102 Altitude, 55.38 ft Depth of hole, 102 ft		
Sand, fine to coarse	0	18
Sand, coarse; gravel, trace	18	38
Sand, coarse	38	58
Sand, coarse; gravel, some	58	93
Sand, fine; silt, some	93	--
B2202 Altitude, 31.14 ft Depth of hole, 87 ft		
Sand, fine to coarse	0	35
Sand, medium to coarse; gravel, some	35	53
Sand, fine to coarse; silt, trace	53	73
Sand, fine to coarse; silt, some	73	--
B2302 Altitude, 46.69 ft Depth of hole, 87 ft		
Sand, fine; gravel, some	0	18
Sand, fine to coarse	18	48
Sand, coarse; gravel, some	48	73
Sand, fine; silt, some	73	--
B2402 Altitude, 43.46 ft Depth of hole, 96 ft		
Sand, fine to coarse; gravel, trace	0	43
Sand, fine; gravel, trace; silt, trace	43	78
Sand, fine; silt, trace	78	--
B2502 Altitude, 32.69 ft Depth of hole, 77 ft		
Sand, coarse; gravel, trace	0	38
Sand, fine to medium; gravel, trace	38	53
Sand, fine to coarse; silt, trace	53	68
Silt	68	--
C1102 Altitude, 77.93 ft Depth of hole, 102 ft		
Sand, fine to medium; gravel, trace	0	28
Sand, fine	28	43
Sand, fine; silt, trace	43	53
Sand, coarse; gravel, trace	53	78
Sand, fine to medium; gravel, trace	78	--
C1202 Altitude, 58.42 ft Depth of hole, 96 ft		
Sand, medium to coarse; gravel, trace	0	43
Sand, fine	43	71
Sand, fine to coarse; gravel, trace	71	88
Sand, fine; silt, some; gravel, trace	88	--
C1302 Altitude, 55.39 ft Depth of hole, 102 ft		
Sand, fine; gravel, trace	0	48
Sand, coarse; gravel, trace	48	68
Sand, fine to coarse; silt, trace; gravel, trace	68	78
Sand, fine; silt, some	78	--
C1402 Altitude, 36.78 ft Depth of hole, 72 ft		
Sand, fine to medium; gravel, trace	0	48
Sand, fine; silt, trace	48	--
C1502 Altitude, 14.39 ft Depth of hole, 51ft		
peat; sand, some	0	13
Sand, fine	13	28
Sand, medium to coarse; gravel, trace	28	38
Sand, coarse; gravel; silt, trace	38	--
C2102 Altitude, 77.23 ft Depth of hole, 103 ft		
Sand, fine	0	38
Sand, fine to coarse; gravel, trace	38	65
Sand, fine; silt, trace	65	--
C2202 Altitude, 50.50 ft Depth of hole, 81 ft		
Sand, medium to coarse; gravel, trace	0	43
Sand, fine; gravel, trace	43	58
Sand, fine; silt, trace	58	73
Sand, fine; silt, some	73	--
C2302 Altitude, 57.80 ft Depth of hole, 91 ft		
Sand, fine to coarse; gravel, some	0	73
Sand, fine; silt, trace	73	--
C2402 Altitude, 46.60 ft Depth of hole, 82 ft		
Sand, medium; gravel, trace	0	35

Table 5. Lithologic data from monitoring wells, near Route 25, southeastern Massachusetts—*Continued*

Description	Depth to top of unit (ft)	Depth to bottom of unit (ft)
Sand, fine; gravel, trace	35	45
Sand, fine to coarse; gravel, trace	45	60
Sand, fine; silt, trace	60	--
C2502 Altitude, 44.14 ft Depth of hole, 72 ft		
Sand, medium to coarse	0	48
Sand, fine; silt, trace	48	--
D1302 Altitude, 81.56 ft Depth of hole, 95 ft		
Sand, coarse; gravel, some	0	13
Sand, fine; gravel, trace; silt, trace	13	23
Sand, fine to coarse; gravel; silt, trace	23	48
Sand, fine to coarse; gravel, some; silt, trace	48	58
Sand, fine to coarse; gravel; silt, trace	58	78
Sand, fine to coarse; gravel, some; silt, trace	78	--
D1402 Altitude, 64.83 ft Depth of hole, 101 ft		
Sand, coarse; gravel, some	0	23
Boulder(s)	23	24
Sand; coarse; gravel, some	24	28
Sand, fine to coarse; gravel, some; silt, trace	28	38
Sand, coarse; gravel, trace	38	53
Sand, fine to coarse;gravel; silt, trace	53	83
Sand, fine to coarse; gravel, some; silt, some	83	93
Sand, fine to coarse; gravel; silt, some	93	--
D1502 Altitude, 56.89 ft Depth of hole, 101 ft		
Sand, fine to coarse; gravel, some	0	38
Sand, fine; gravel, some; silt, trace	38	47
Sand, fine to coarse; gravel; silt, trace	47	63
Sand, fine to coarse; gravel, some	63	73
Sand, fine to coarse; gravel, trace; silt, trace	73	--
D1602 Altitude, 32.52 ft Depth of hole, 64 ft		
Sand, fine to coarse	0	30
Sand, fine to coarse; gravel, some	30	32
Sand, fine to coarse	32	38
Sand, coarse; gravel; silt, trace	38	43
Sand, fine; gravel, some; silt, some	43	48
Sand, fine; gravel; silt, some	48	--

Description	Depth to top of unit[1] (ft)	Depth to bottom of unit (ft)
D1702 Altitude, 37.32 ft Depth of hole, 63 ft		
Sand, medium to coarse; gravel, some	0	3
Sand, coarse; gravel	3	43
Sand, coarse; silt, trace	43	58
Sand, coarse; gravel, trace	58	--
D1802 Altitude, 35.48 ft Depth of hole, 84 ft		
Sand, fine to coarse; gravel, trace	0	13
Sand, fine to medium	13	28
Sand, fine to coarse; gravel, trace; silt, trace	28	73
Sand, fine to coarse; silt, trace	73	--
D2302 Altitude, 51.51 ft Depth of hole, 101 ft		
Sand, fine to coarse	0	5
Sand, fine to coarse; gravel	5	15
Boulder(s)	15	16
Sand, coarse; gravel, some; silt, trace	16	22
Sand, coarse; gravel, trace	22	40
Sand, coarse; gravel, some; silt, trace	40	--
D2402 Altitude, 47.34 ft Depth of hole, 96 ft		
Sand, fine to coarse	0	3
Sand, fine to coarse; boulders, some	3	18
Sand, fine to coarse	18	63
Sand, coarse; silt, trace	63	70
Boulder(s)	70	73
Sand, coarse; silt, trace	73	--
D2502 Altitude, 33.61 ft Depth of hole, 69 ft		
Sand, fine to coarse; gravel, some	0	13
Sand, fine to coarse; gravel, some; silt, trace	13	23
Sand, fine to coarse	23	28
Sand, fine to coarse; gravel, trace; silt, trace	28	43
Sand, coarse; gravel; silt, trace	43	48
Sand, fine; silt, trace	48	53
Sand, coarse; gravel; silt, trace	53	66
Boulder(s)	66	--

[1]Estimated from Route 25 construction plans.

Water-quality samples and water-level measurements were collected intermittently from the long-screen wells from the dates they were installed through the autumn of 1990 and water-level measurements and water-quality samples collected prior to August 1987, the date when Route 25 was completed and opened for traffic, were used for determination of ground-water flow direction and background concentrations of chloride, sodium, and calcium and background specific conductance of ground water. Water-quality samples collected upgradient from the highway after August 1987 were assumed to be unaltered by road salt in highway runoff and continue to represent background water quality. Water-quality samples collected downgradient from the highway after August 1987, and particularly during and after the winter of 1987-88, were assumed to represent ground water potentially contaminated by road salt.

Water-Sample Collection Methods

Collection of water samples from the long-screen wells required several different pumping methods. The method used at any particular well depended on the well diameter, depth to water table, depth to the bottom of the well, screen placement, and the amount of sediment suspended in the well-bore water. Depth to the water table in most wells at each test site, particularly those near the highway, are such that pumping methods that rely on suction are ineffective. Pumping methods that require relatively sediment free water also were ineffective. Efforts to fully develop the long-screen wells were only partly successful because the long-screen wells provide large surface areas of slotted screen through which fine sediment enters the well bores. Pumping methods that could potentially work in all wells, such as submersible bladder pumps, deliver water at a maximum rate of only 0.25 gal/min. These pumps commonly fail because sediment suspended in the well water prevents closure of the internal check valves or causes the valves to seize. Air-lift methods that deliver water at rates near 5 gal/min seldom were affected by suspended sediment. However, these high-volume sampling methods were restricted by water-table depths, well bottom depths, and well diameter. As a result, no single pumping method was found that could adequately pump all of the long-screen wells at this study site. Additionally, pumping methods used in individual long-screen wells, particularly the water-table wells, were not always consistent. The most effective method varied throughout the year as the water-level changed.

Pumping methods used to collect ground-water-quality samples from long-screen wells and their primary applications are described below. Some of these methods can be used with or without packers. If packers were not used, the method is described as a bulk method—as water from the entire length of the well is affected. If packers were used, whether singly or in pairs, to seal off a section of the well, the method is referred to as a packer method.

Air Lift

The air lift method uses an air compressor to force air through a hose set near the bottom of the well. Surges of water exit the well as the water is lifted by the rising air. Pumping rates of 5 gal/min can be attained with this method. However, it can only be used if the length of the water column in the well is equal to or exceeds the depth to water table, and if the top of the well screen is set below the water table. This method primarily is used in wells that are screened through the lower part of the aquifer and can be used in wells with diameters as small as 1.5 in.

Modified Air Lift

The modified air-lift method uses an air compressor to force air into the annular space between two hoses secured at the bottom with a check valve and set near the bottom of the well. Water enters the coaxial hoses as they are lowered into the well and fill to the level of the water table. As air pressure is applied the check valve closes and water is forced down the annular space and up the inner hose to the top of the well. When air pressure is released the check value is forced open by the pressure of the surrounding water and the hoses refill. Each cycle of pressurization and release may range from 10 to 20 seconds and pumping rates of 2.5 gal/min can be attained. This method requires the length of the water column in the well to be no less than one fifth the depth to water table, as determined by the ratio of the internal cross-sectional area of the inner hose and the cross-sectional area of the annular space between the hoses. This method primarily was used in wells that are screened through the upper part of the aquifer where the top of the screen is set in the unsaturated zone, and the length of the water column in the well is typically less than the depth to water table. Well diameters of 2 in. or greater are required.

Bailer

A bailer consists of a short pipe fitted with a check valve on the bottom. The bailer is lowered into the well with a plastic rope or monofilament line. As the bailer is retrieved the check valve seats and holds the water inside the bailer. Collection of 0.25 gal/min is possible. The bailer method was used in wells where the length of the water column is less than one-fifth the depth to water table. Bailers can be used in wells with diameters as small as 1.5 in.

Bladder Pump With Packers

Bladder pumps are constructed with a flexible membrane tube covering a perforated steel tube with check valves on both ends, all encased in a stainless steel sleeve. The flexible tube, called the bladder, fills with water as the pump is lowered below the water table. An air compressor is used to squeeze the bladder, force the bottom check value closed, and force the water within the bladder chamber upward through the upper check valve. When the air pressure is released the upper check valve closes, holding the pulse of water just lifted, the bottom check valve opens, and the bladder chamber refills with water. Each cycle may range from 15 to 30 seconds. Bladder pumps for both 1.5 and 2 in.-diameter wells were used and the their maximum pumping rates were about 0.12 and 0.25 gal/min, respectively. These bladder pumps were used with inflatable packers placed above and below the pump inlet to isolate zones within long-screen wells for selective sampling. A single nitrogen tank was used to inflate both packers. Inflation pressures ranged from 150 to 200 lbs/in^2 (pounds per square inch) depending on the depth of the packers below the water table.

Helical-Rotor Pump With Packer

This electrical submersible pump contains an electric motor that turns a helical rotor encased in a semi-rigid rubber gland. As the rotor turns water is forced upward in the spaces between the rotor and the gland. The pump is equipped with an inflatable packer located above the sample inlet that can be used to reduce the volume of water required to evacuate the well before collecting the sample. A nitrogen tank is used to inflate the packer. Inflation pressures range from 40 to 60 lbs/in^2 depending on the depth of the packer below water table. Water was pumped at a rate of 1 gal/min in wells no smaller than 2 inch diameter. This pump is very sensitive to sediment in the well water and had limited success in the long-screen wells.

Water-Sample Processing

The procedure for processing water samples was independent of the type of well or pumping method. A minimum of three well bore volumes of water were evacuated while specific conductance of the evacuated water was monitored to assure that water samples pumped from wells came from the aquifer and not from stagnant water in the well bore. The sample was collected when the minimum volume was pumped and the specific conductance was stable. A minimum of five specific-conductance measurements were collected before physiochemical stability was assumed. Water samples were prepared for laboratory analysis of specific conductance and dissolved chloride, sodium, and calcium concentrations prior to shipment to the U.S. Geological Survey, National Water-Quality Laboratory (NWQL). Samples for analysis of chloride, sodium, and calcium concentrations were filtered in the field using 0.45-µm pore-sized filters. The samples for analysis of sodium and calcium were preserved with nitric acid. Samples for laboratory analysis of specific conductance were shipped unfiltered and unacidified. A part of each water sample collected was retained for analysis of chloride concentration at the laboratory in the USGS Massachusetts Office to allow for preliminary analysis and interpretation of chloride data while waiting for results from the NWQL. Chloride results from both labs are compared to verify the accuracy of the data. These water-sample processing methods also were used for samples collected from short-screen wells and for samples collected from the highway-drainage system and Red Brook.

Evaluation of Effectiveness of Long-Screen Wells

Implicit in the long-screen well design was the assumption that bulk samples (samples obtained from long-screen wells without use of packers to restrict lengths of sampling zones) would provide a composite sample representing average chemical concentrations along the length of the well screen. Additionally, it was assumed that the use of long-screen wells in the aquifer would not cause vertical redistribution of water and chemical constituents within the well bores and the aquifer adjacent to the wells in response to vertical head gradients. During the unanticipated several-year delay in highway construction, when most of the long-screen wells were installed, new information about transport of chemical constituents in ground water and reliability of water-quality data from long-screen wells became available. The findings of LeBlanc and others (1987), from their natural-gradient tracer test done in a sand and gravel aquifer similar to that at the Route 25 study site, showed that contaminants can flow in thin zones with little vertical dispersion. Additional studies have shown that vertical head gradients can cause vertical flow and redistribution of chemical constituents within long-screen wells and the adjacent aquifer (Reilly, and others, 1989 and McIlvride and Rector, 1988). Should this redistribution occur, water samples collected from the long-screen wells, whether by bulk methods or by packer methods that seal off selected zones within the well, may not represent the quality of the water in the aquifer.

Additional data that supported testing of the long-screen wells came from geophysical logs performed in the long-screen wells downgradient from the highway in 1988 and 1989. Fluid conductance logs, vertical profiles of specific conductivity of the water in well bores, indicated that high specific conductivities, compared to background levels, were present throughout the entire depth of many long-screen wells. In contrast, borehole-induction logs, vertical profiles of the electric conductivity of the aquifer fluid and materials in a cylindrical zone outside well bores, showed a thin zone of high conductivity just below the water table in the same wells. These thin zones of high conductivity were interpreted to be the result of road-salt contamination. Although borehole-induction logs are also sensitive to changes in lithology, lithologic logs and natural-gamma logs (Keys 1990) do not show any significant changes in lithology at depths that encompass these thin zones of high conductivity. Borehole-induction logs taken at different times show changes in conductivity in these zones, further indicating that the high conductivity is from the aquifer fluid (Church and Granato, 1996). The discrepancies between the fluid conductance logs and the borehole induction logs prompted the testing of the effectiveness of long-screen wells in yielding water-quality samples representative of the aquifer water quality. Water-quality data collected from long-screen wells by bulk and packer methods were compared with water-quality data collected by bulk methods from nearby clusters of short-screen wells to test the effectiveness of the long-screen wells. Borehole induction logs were used as a standard from which water-quality data from the long- and short-screen wells were compared.

This testing began with the installation of two clusters of short-screen wells in autumn 198?, one at well site B23 and the other at well site C13 (figs. 19 and 20). The short-screen well cluster at each well site is just upgradient from the long-screen well. The short-screen wells are 2 in. in diameter with 10-foot screens. The long-screen well at site B23, B2303, was constructed with 70 ft of screen, extending from just above the water table at about 30 ft to about 100 ft below land surface. Seven short-screen wells were installed at 10 ft depth increments from the water table to the depth of the bottom of the long-screen well (fig. 22). These short-screen wells were designated B2304 for the shallowest well through B2310 for the deepest well. Similarly, the long-screen well at site C13, C1303, was constructed with 60 ft of screen, extending from just above the water table at about 40 ft to about 100 ft below land surface. Six short-screen wells were installed at 10 ft depth increments from the water table to the depth of the bottom of the long-screen well (fig. 23). These wells were designated C1304 for the shallowest well through C130? for the deepest well. Short-screen well locations and depths were staggered to reduce the potential for cross flow between wells. A listing of these short-screen wells along with associated construction data is provided in table 6.

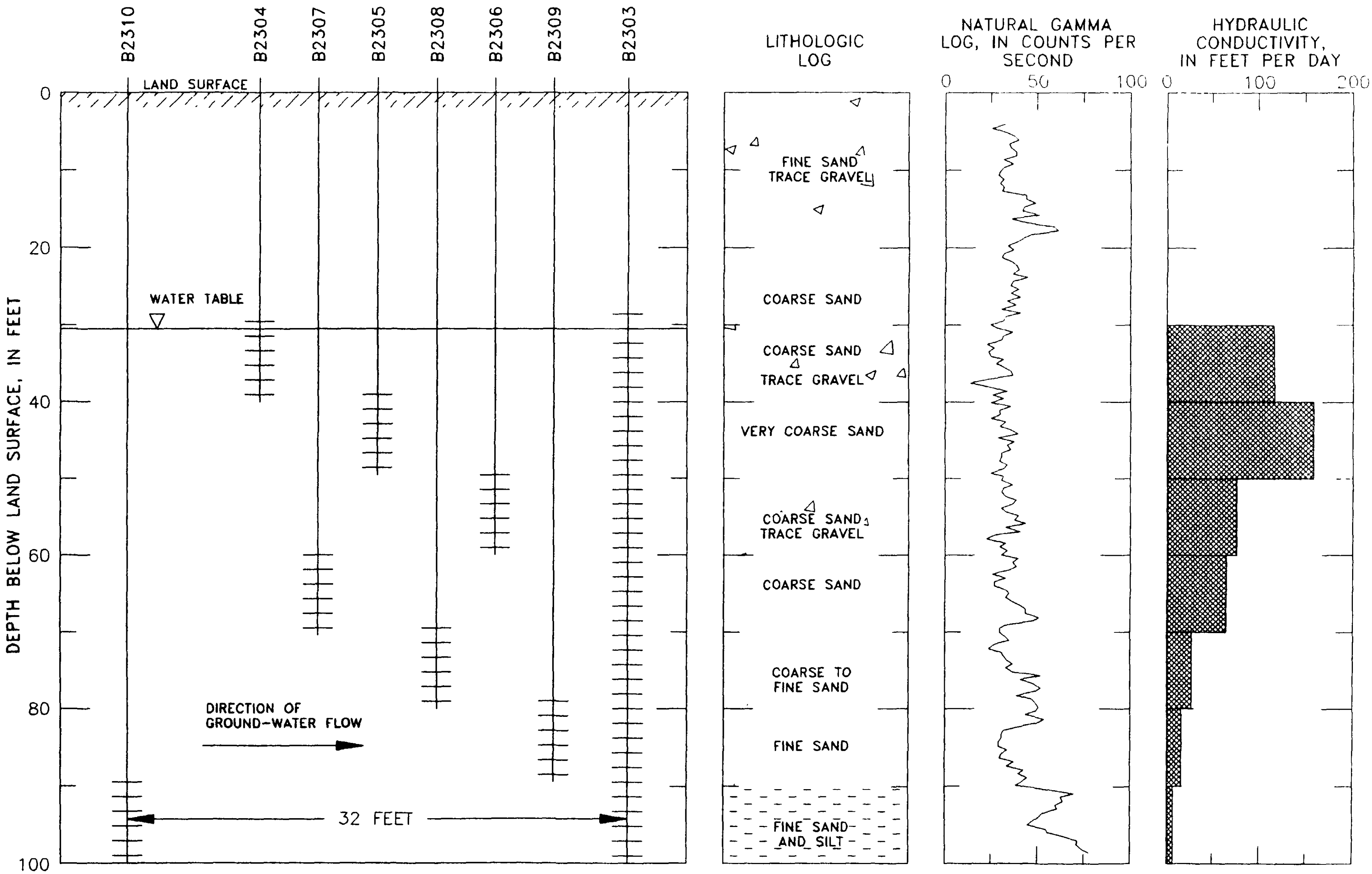


Figure 22. Lithologic logs, gamma logs, and hydraulic conductivity profiles for site B23, near Route 25, southeastern Massachusetts.

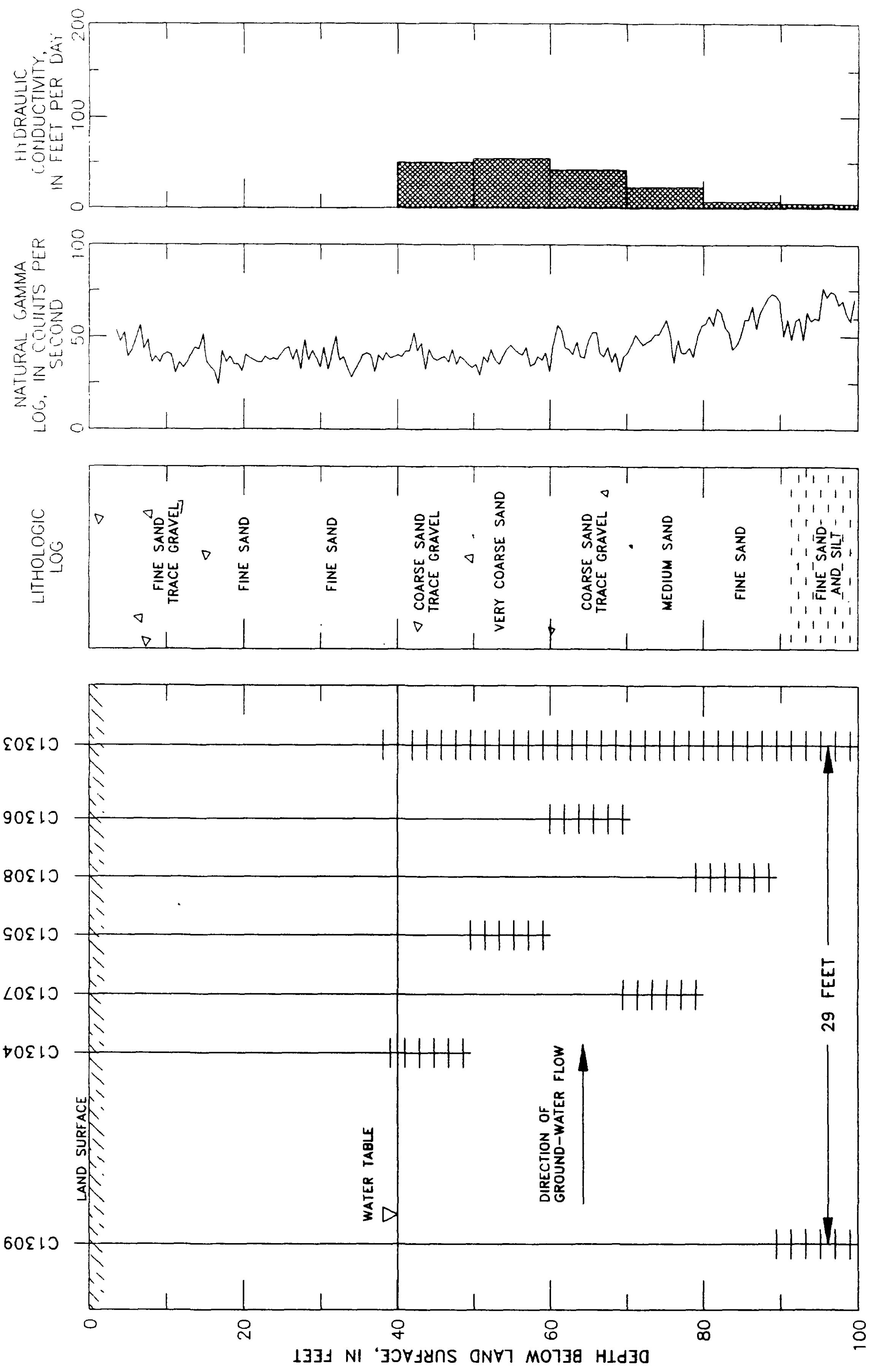


Figure 23. Lithologic logs, gamma logs, and hydraulic conductivity profiles for site C13, near Route 25, southeastern Massachusetts.

Table 6. Characteristics of short-screen wells installed for collection of water-quality data for comparison with water-quality data from long-screen wells, near Route 25, southeastern Massachusetts

[Well site locations (B23 and C13) shown in figures 19 and 20. Diameter of well screen is 2.0 inches. **Well No.:** see explanation in text on well-numbering convention. **Site identification No.:** Unique number for each site based on the latitude and longitude of the site. First six digits are latitude. Next seven digits are longitude and final two digits are a sequence number to uniquely identify each well. ft, feet]

Well no.	Site identification No.	Date well constructed	Altitude of land surface (ft below sea level)	Height of measuring point (ft above land surface)	Depth to top of screen (ft below land surface)	Depth to bottom of screen (ft below land surface)
			SITE B			
B2304	414626070381104	11-15-89	46.83	2.0	29	39
B2305	414626070381105	11-15-89	46.56	2.0	39	49
B2306	414626070381106	11-15-89	46.29	2.0	48	58
B2307	414626070381107	11-15-89	46.69	2.0	59	69
B2308	414626070381108	11-15-89	46.67	2.0	68	78
B2309	414626070381109	11-15-89	46.52	2.0	78	88
B2310	414626070381110	11-15-89	47.23	2.0	89	99
			SITE C			
C1304	414616070383304	11-14-89	58.03	2.0	42	52
C1305	414616070383305	11-14-89	57.71	2.0	52	62
C1306	414616070383306	11-14-89	56.22	2.0	60	70
C1307	414616070383307	11-14-89	58.19	2.0	71	81
C1308	414616070383308	11-14-89	57.31	2.0	82	92
C1309	414616070383309	11-14-89	59.69	2.0	90	100

Water-quality samples were collected monthly from the long-screen wells B2303 and C1303 and the short-screen wells B2304-B2310 and C1304-C1309 from January through June 1990. Collection of water samples from the long-screen wells were from bulk (modified air lift) and packer (bladder pump with packer) methods. Bulk water samples were collected from the short-screened wells by use of an electric submersible pump (helical-rotor pump with packer). Water samples processing methods used were the same as those used for samples collected from the long-screen wells.

The results of this experiment indicated that (1) Long-screen wells did not provide representative water-quality samples, even in a relatively homogeneous, unconfined sand and gravel aquifer such as that beneath Route 25. The water-quality samples collected from the long-screen well at site B23 overestimated the extent of contamination in the aquifer because of downward flow of solute from a contaminated zone near the water table. Upward flow of about 20 borehole volumes per day in the long-screen well at site C13 masked a bimodal distribution of solutes because of the redistribution of relatively pure waters into the zone of contamination. (2) Vertical flow in long-screen wells may contaminate zones of the aquifer that would not otherwise become contaminated in the absence of the long-screen wells. For example, at site B23, the long-screen well is a conduit for the downward flow and redistribution of about one borehole volume a day of contaminant-laden water. (3) Use of borehole-induction logs from fully cased wells is a viable alternative to the use of long-screen wells in contaminant-transport studies for plume detection, and accurate placement of short-screen or multilevel monitoring wells as needed for water-quality sampling. Because of these results, short-screen wells were installed at the test sites for the collection of water-quality samples.

Monitoring Road-Salt Contamination by Use of Short-Screen Wells

A network of short-screen well clusters was installed at each test site in summer and autumn 1990 for collection of water-quality samples, water-level measurements, and borehole induction logs to determine the effectiveness of the highway-drainage systems in preventing road-salt contamination of ground water. Each network is composed of two well clusters, one about 200 ft upgradient and one about 200 ft downgradient from the center of the median strip of the highway along a line parallel to ground-water flow direction (figs. 24 and 25). Two additional well clusters were installed downgradient at site A due to the observed nonuniform distribution of highway runoff along the highway. An additional well was installed about 400 ft downgradient from the median of the highway on the same line as the well clusters at each test site. These wells were used primarily for collection of borehole-induction logs.

The upgradient well cluster consists of a three wells—a well with a 10 ft screen centered on the altitude of the mean water level, a well with a 5 ft screen extending from 5 to 10 ft below mean water level, and a deep well with a 5 ft screen placed at about 60 to 70 ft below the water table. The downgradient well cluster consists of 6 wells—a well with a 10 ft screen centered on the altitude of the mean water level, four wells with 5 ft screens place in 5-foot-increments from 5 to 25 ft below mean water level, and a deep well with a 5 ft screen placed at about 60 to 70 ft below the water table (fig. 26). The well about 400 ft downgradient from the median strip was installed with a 5 ft screen placed at about 60 to 70 ft below the water table.

The short-screen well-cluster sites were labeled by test site (A, B, C, or D) and location relative to the highway; (1) for upgradient and (2) for downgradient. For example, well-cluster sites A1 and A2 are located at site A upgradient and downgradient from the highway, respectively (fig. 24). Individual wells are labeled by well-cluster site and location of screen in the aquifer (1, 2, 3, 4, 5, or 20). For example, wells A201, A202, A205, are located at well-cluster site A2 and are screened from 5 ft above to 5 ft below the mean water table, about 5 to 10 ft below the water table, and about 20 to 25 ft below the water table, respectively (fig. 26). The "20" designation refers to the deep well in each well-cluster. The two additional well-cluster sites at site A are about 200 ft west and about 200 ft east of the A2 well-cluster site and are labeled A4 and A5, respectively (fig. 24). The deep well 400 ft downgradient from the highway is labeled by well site (A, B, C, or D), location relative to the highway (3), and screen placement (20). A listing of these short-screen wells along with associated construction data is provided in table 7.

Water-quality samples and water-level measurements were collected monthly from the shallow wells in the well clusters (screened at 0 to 25 ft below the water table) concurrently with borehole-induction logs from the deep wells (screened at about 60 to 70 ft below the water table) from November 1990 through March 1995. Water samples were collected with an electric submersible, helical-rotor pump with a packer and analyzed for concentrations of dissolved chloride, sodium, and calcium, the primary constituents of road salt. Specific conductance, water temperature, and pH were monitored as samples were collected. Water samples processing methods used were the same as those used for samples collected from the long-screen wells. Water-level measurements, also collected from selected shallow long-screen wells, were used to determine hydraulic gradients. Borehole-induction logs were used to monitor the vertical distribution of the plumes of ground water contaminated by road salt to ensure that well screens spanned the bulk of the contaminant plume at each test site. Ground-water samples collected in the February and August 1991, March, August, and November 1993, and the November 1994 sampling rounds were analyzed for major ions and trace elements to obtain a more complete chemical profile of the ground water at each test site than obtained from analyses of chloride, sodium and calcium concentrations alone.

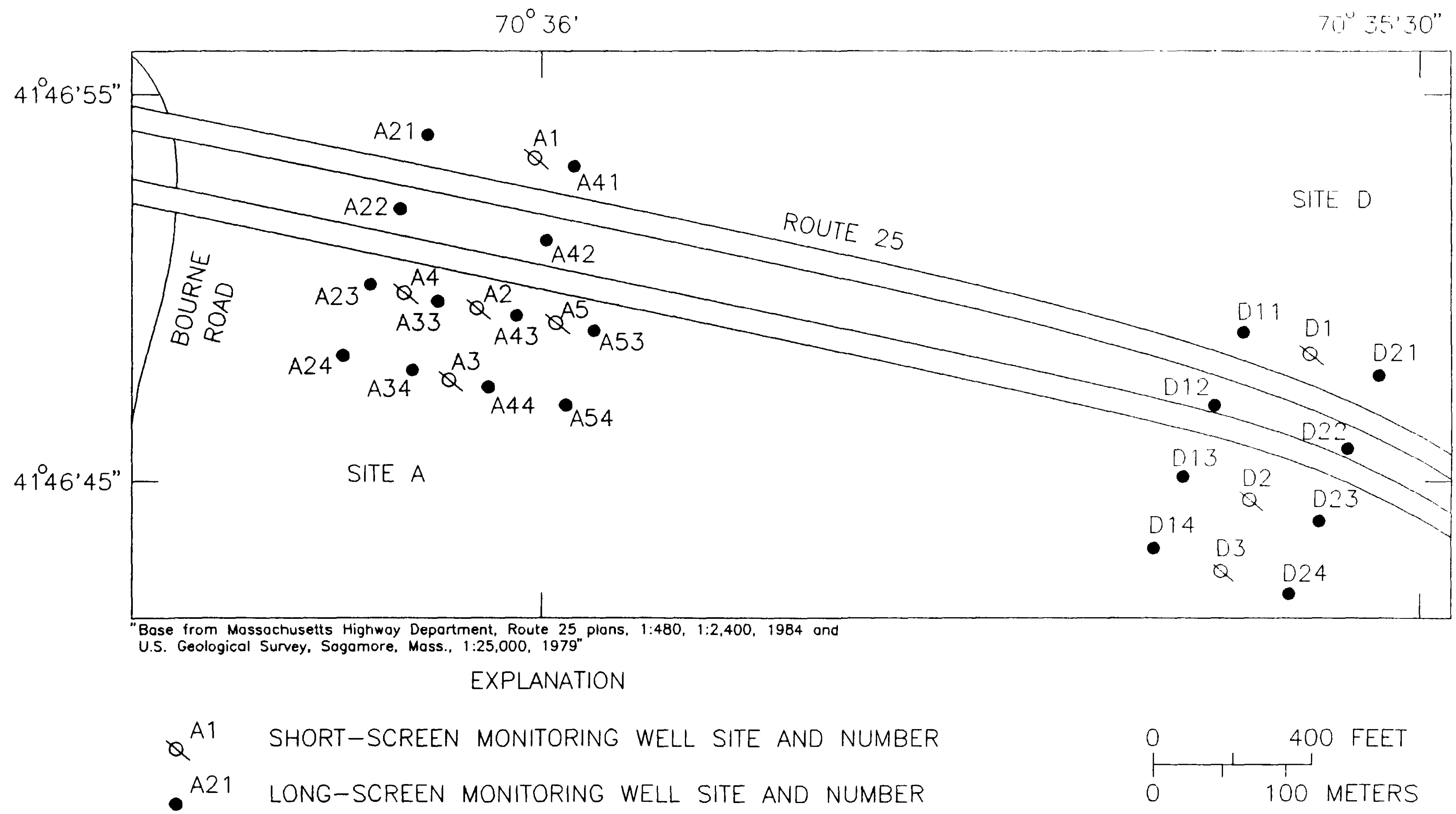


Figure 24. Locations of short-screen well cluster sites for water-level and water quality monitoring and selected long-screen wells for water-level monitoring sites at test sites A and D, near Route 25, southeastern Massachusetts.

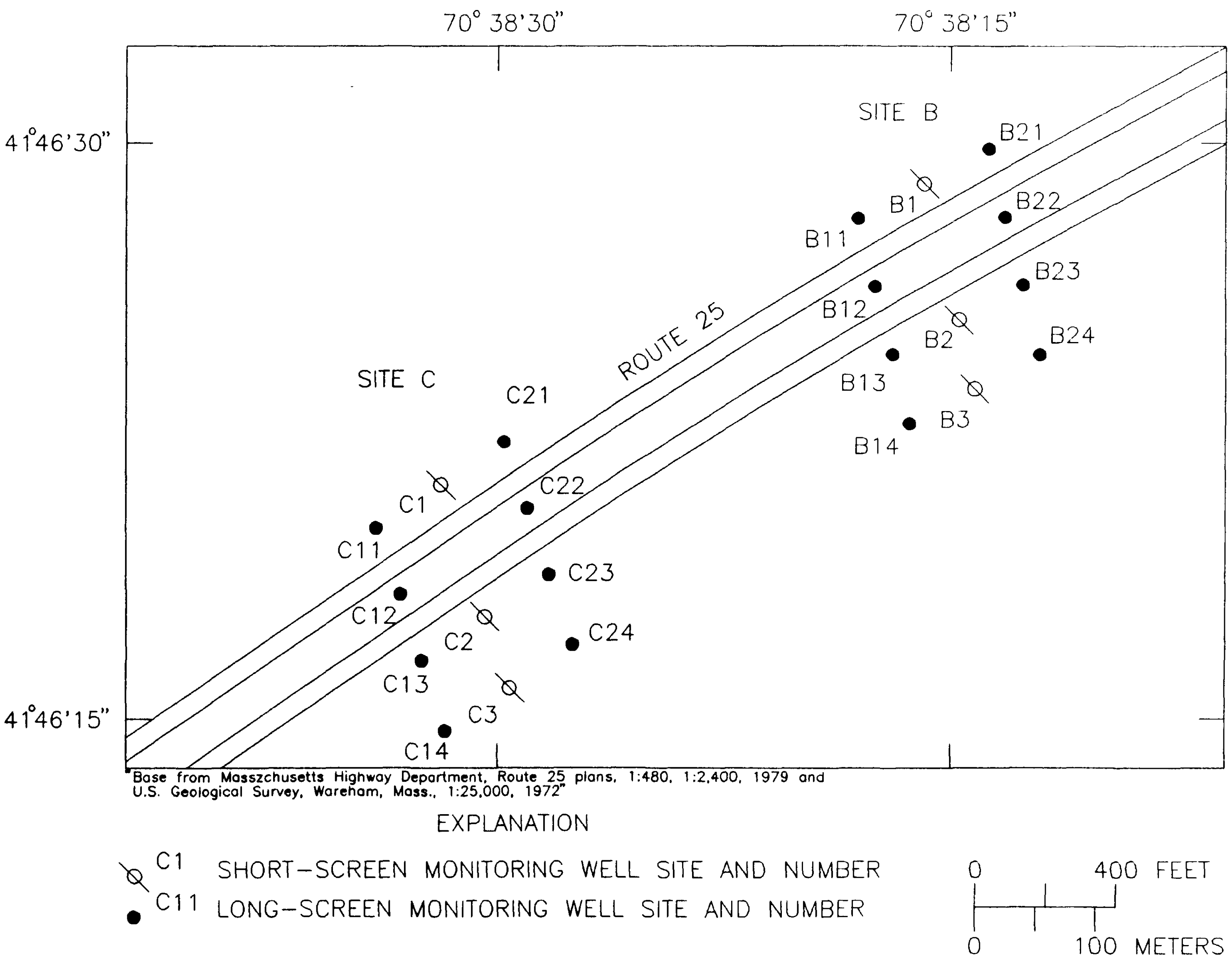


Figure 25. Locations of short-screen well cluster sites for water-level and water quality monitoring and selected long-screen wells for water-level monitoring sites at test sites B and C, near Route 25, southeastern Massachusetts.

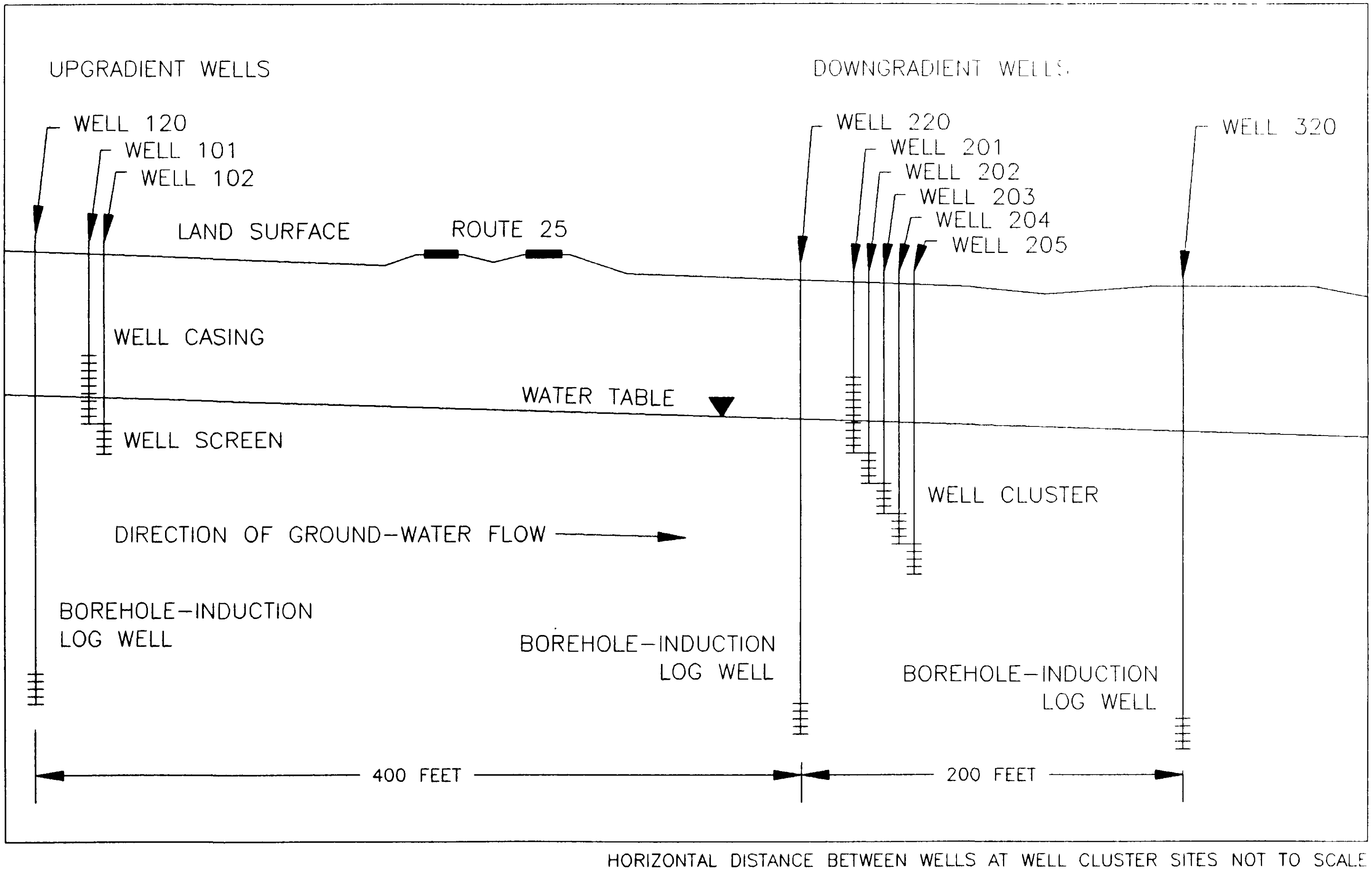


Figure 26. Vertical section of well network at test sites A, B, C, and D, near Route 25, southeastern Massachusetts.

Table 7. Characteristics of short-screen monitoring wells installed for collection of water-quality data, near Route 25, southeastern Massachusetts

[Well site locations shown in figures 24 and 25. **Well No.:** see explanation in text on well-numbering convention. **Site identification No.:** Unique number for each site based on the latitude and longitude of the site. First six digits are latitude. Next seven digits are longitude and final two digits are a sequence number to uniquely identify each well. ft, feet]

Well no.	Site identification no.	Date of construction	Altitude of land surface (ft above sea level)	Height of measuring point (ft above land surface)	Depth to top of screen (ft below land surface)	Depth to bottom of screen (ft below land surface)
			SITE A			
A101	414654070360001	10-22-90	77.22	2.7	42	52
A102	414654070360002	10-23-90	77.12	2.8	52	57
A120	414654070360003	10-30-90	77.80	1.3	96	101
A201	414650070360201	10-18-90	62.20	2.1	28	38
A202	414650070360202	10-22-90	62.41	1.9	38	43
A203	414650070360203	10-18-90	62.78	1.5	43	48
A204	414650070360204	10-22-90	62.86	1.4	48	53
A205	414650070360205	10-19-90	63.18	1.1	53	58
A206	414650070360207	09-06-94	63.49	1.3	58	63
A207	414650070360208	09-02-94	63.48	0.5	63	68
A220	414650070360206	11-05-90	59.97	1.3	97	102
A301	414648070360302	08-29-94	68.70	2.1	35	45
A302	414648070360303	08-29-94	68.89	2.4	45	50
A303	414648070360304	08-30-94	67.93	3.4	50	55
A304	414648070360305	08-30-94	69.27	1.5	55	60
A305	414648070360306	08-31-94	69.45	1.7	63	68
A306	414648070360307	09-01-94	69.60	1.7	68	73
A320	414648070360301	11-01-90	67.33	0.7	75	79
A401	414650070360303	10-31-90	66.89	0.9	34	44
A402	414650070360304	11-02-90	67.83	2.4	45	50
A403	414650070360305	11-01-90	67.98	2.3	50	55
A404	414650070360306	11-05-90	68.52	1.8	56	61
A405	414650070360307	11-02-90	68.83	1.9	61	66
A420	414650070360308	11-06-90	65.85	1.2	94	99
A501	414649070360001	10-24-90	72.33	1.9	38	48
A502	414649070360002	10-31-90	72.23	2.0	48	53
A503	414649070360003	10-29-90	72.22	1.9	53	58
A504	414649070360004	10-31-90	72.04	2.2	58	63
A505	414649070360005	10-29-90	72.00	2.2	65	70
A506	414649070360007	08-26-94	71.24	2.0	70	75
A507	414649070360008	08-26-94	69.88	2.8	75	80
A507A	414649070360009	08-23-94	71.32	2.0	75	80
A508	414649070360010	08-25-94	71.01	1.0	80	85
A509	414649070360011	08-19-94	71.05	2.1	85	90
A520	414649070360006	11-14-90	72.52	1.5	99	103
			SITE B			
B101	414629070381501	09-24-90	47.63	2.4	23	33
B102	414629070381502	09-25-90	47.38	2.6	32	37
B120	414629070381503	09-24-90	48.50	1.2	94	99
B201	414626070381401	09-18-90	47.18	3.2	22	32
B202	414626070381402	09-18-90	47.14	3.0	32	37

Table 7. Characteristics of short-screen monitoring wells installed for collection of water-quality data, near Route 25, southeastern Massachusetts—*Continued*

Well no.	Site identification no.	Date of construction	Altitude of land surface (ft above sea level)	Height of measuring point (ft above land surface)	Depth to top of screen (ft below land surface)	Depth to bottom of screen (ft below land surface)
			SITE B—*Continued*			
B203	414626070381403	09-18-90	47.78	3.0	37	42
B204	414626070381404	09-17-90	47.47	3.3	42	47
B205	414626070381405	09-17-90	48.21	2.7	47	52
B220	414626070381406	09-18-90	46.71	1.7	93	98
B320	414623070381301	09-27-90	38.95	1.0	97	101
			SITE C			
C101	414622070383201	09-25-90	74.56	2.4	50	60
C102	414622070383202	09-26-90	74.68	2.1	63	68
C120	414622070383203	09-25-90	74.22	1.5	96	101
C201	414618070383103	09-19-90	53.81	1.8	33	43
C202	414618070383104	09-19-90	53.40	2.3	43	48
C203	414618070383105	09-20-90	53.06	2.7	47	52
C204	414618070383106	09-20-90	52.77	2.9	52	57
C205	414618070383107	09-20-90	52.56	3.1	57	62
C206	414618070383109	08-16-94	52.77	1.9	60	65
C207	414618070383110	08-16-94	52.71	1.7	65	70
C208	414618070383111	08-12-94	52.30	1.7	70	75
C209	414618070383112	08-15-94	52.33	1.8	75	80
C210	414618070383113	08-12-94	52.21	2.2	80	85
C220	414618070383108	09-19-90	54.87	1.2	94	99
C320	414616070383001	09-26-90	48.54	1.3	96	101
			SITE D			
D101	414648070353401	10-16-90	77.00	1.7	43	53
D102	414648070353402	10-17-90	77.60	1.1	53	58
D120	414648070353403	10-16-90	76.16	1.3	95	100
D201	414645070353601	07-12-90	63.03	2.2	30	40
D202	414645070353602	07-17-90	62.80	2.7	40	45
D203	414645070353603	09-27-90	63.04	2.1	45	50
D204	414645070353604	10-15-90	62.72	2.3	50	55
D205	414645070353605	10-16-90	62.86	2.3	55	60
D220	414645070353606	07-09-90	63.21	1.7	95	100
D320	414643070353601	10-18-90	57.88	1.3	94	99

About 10 percent of all water-quality samples collected from the well-clusters were quality assurance samples. The quality assurance protocol developed was as follows:

1. Replicate ground-water samples were collected during each monthly sampling rounds.
2. Solutions spiked with known concentrations of dissolved chloride, sodium, and calcium were submitted to the NWQL for analysis twice a year (early summer and early winter).
3. Field equipment blanks, samples of deionized water pumped, filtered, and bottled by the same equipment and procedures as actual samples, were collected during trace element sampling rounds and submitted to the NWQL for analysis.

Additional quality-assurance methods used that were applicable to the analysis of road salt in ground water, and to the analysis of road salt diverted from the test sites through the highway-drainage systems were:

1. Analysis of deionized water for dissolved concentrations of chloride, sodium, and calcium and specific conductance to check contamination of rinse water.
2. Analysis of chloride concentrations of 10 mg/L and 100 mg/L chloride solutions and the 1,000 mg/L chloride standards from which the solutions were made to monitor the accuracy of chloride analyses performed in the U.S. Geological Survey Massachusetts Office Laboratory.

An example of data collected during a monthly sampling round is provided in figure 27. The borehole-induction log upgradient from the highway changes little in conductivity with depth as compared to the downgradient log where conductivity increases significantly at and just below the water table. The water-quality data show a similar pattern with background concentrations of chloride, sodium, and calcium and background specific conductances upgradient from the highway and at depths from about 10 ft below the water table to the bottom of the well downgradient from the highway. In contrast, water-quality data in the first 10 ft below the water table downgradient from the highway are significantly higher than background levels.

Water-level and water-quality data from the water-table wells upgradient and downgradient from the highway are shown in figures 28 and 29. Monthly water-level measurements from November 1990 through May 1994 from all wells show similar annual patterns of highest levels in the late spring and early summer and lowest levels in the late autumn and early winter (fig. 28). Differences in altitudes of water levels upgradient and downgradient from the highway at each test site change little with time, however, they differ considerably between sites. Monthly concentrations of chloride, sodium, and calcium and specific conductance of water samples collected from the water-table wells upgradient from the highway from November 1990 through May 1994 show little change with time (fig. 29). In contrast, concentrations of road salt constituents and specific conductance of water samples collected from the water-table wells downgradient from the highway fluctuate on an approximate annual basis and are consistently much higher than those upgradient from the highway.

Highway Drainage

Highway-drainage monitoring stations were installed in the trunkline drainpipes in the highway-drainage systems at sites B, C, and D during highway construction in 1987 (figs. 2 and 3). A trunkline drainpipe does not exist at site A and all drainage occurs on the site (fig. 3). Station names begin with the test-site designation B, C, or D and are followed by three digits referring to their positions along the highway centerline (a reference system used in highway design, construction, and maintenance). The trunkline drainpipes range in diameter from 24 to 42 in., and the drainage areas in which the highway runoff is collected range from 0.011 to 0.028 mi^2 (table 8). Design of the monitoring stations was adapted from that of Kilpatrick and others (1985). Each monitoring station consists of a calibrated Palmer-Bowlus flume (Palmer and Bowlus, 1936) cast into a reinforced-concrete vault in the trunkline drainpipes (fig. 30). Equipment shelters are located over the vaults containing the Palmer-Bowlus flume. The equipment shelters house instrumentation for automatic collection of water samples and for measurement of stage, specific conductance, water temperature, pH, air temperature, relative humidity, and precipitation. A digital-data logger with a storage module was used to record and store all data generated (fig. 31). Data collection began in 1988 and continued through March 1995.

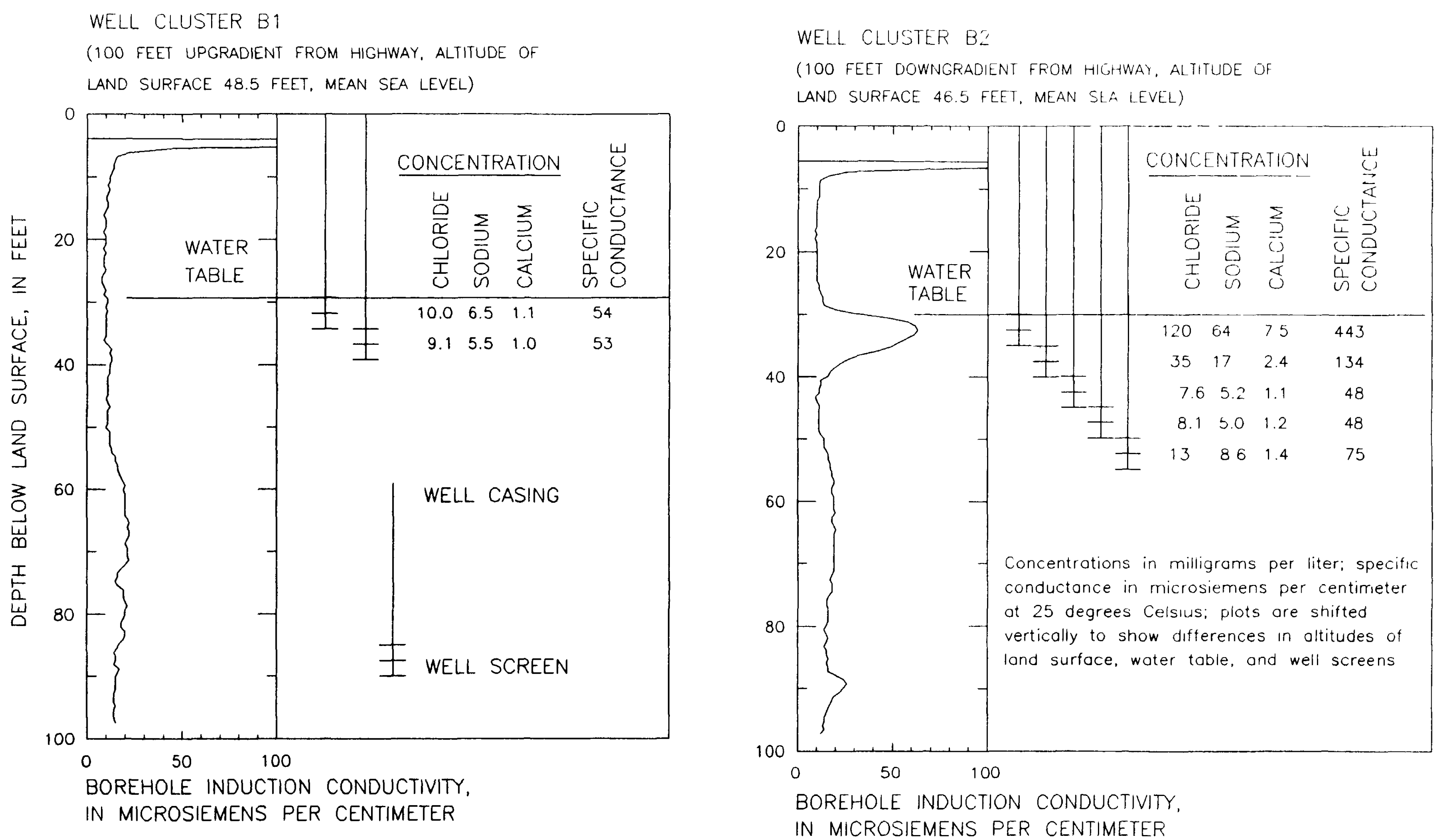


Figure 27. Induction logs and water-quality data collected on July 25, 1991, from well clusters B1 (upgradient from the highway) and B2 (downgradient from the highway) along the same ground-water-flow path, Route 25, southeastern Massachusetts.

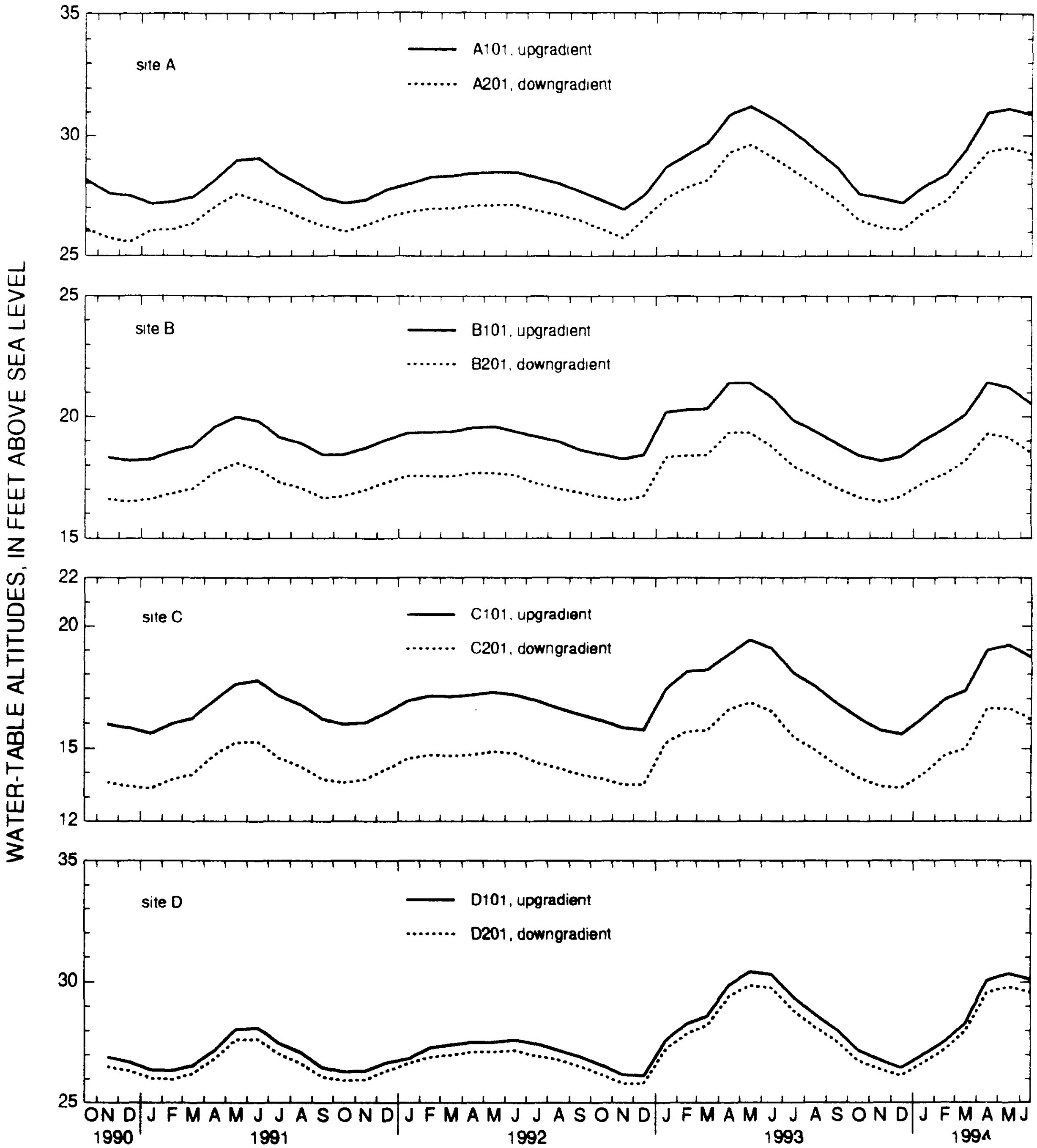


Figure 28. Monthly water-table altitudes at sites A, B, C, and D, upgradient (well 101) and downgradient (well 201) from Route 25, southeastern Massachusetts, November 1990-May 1994.

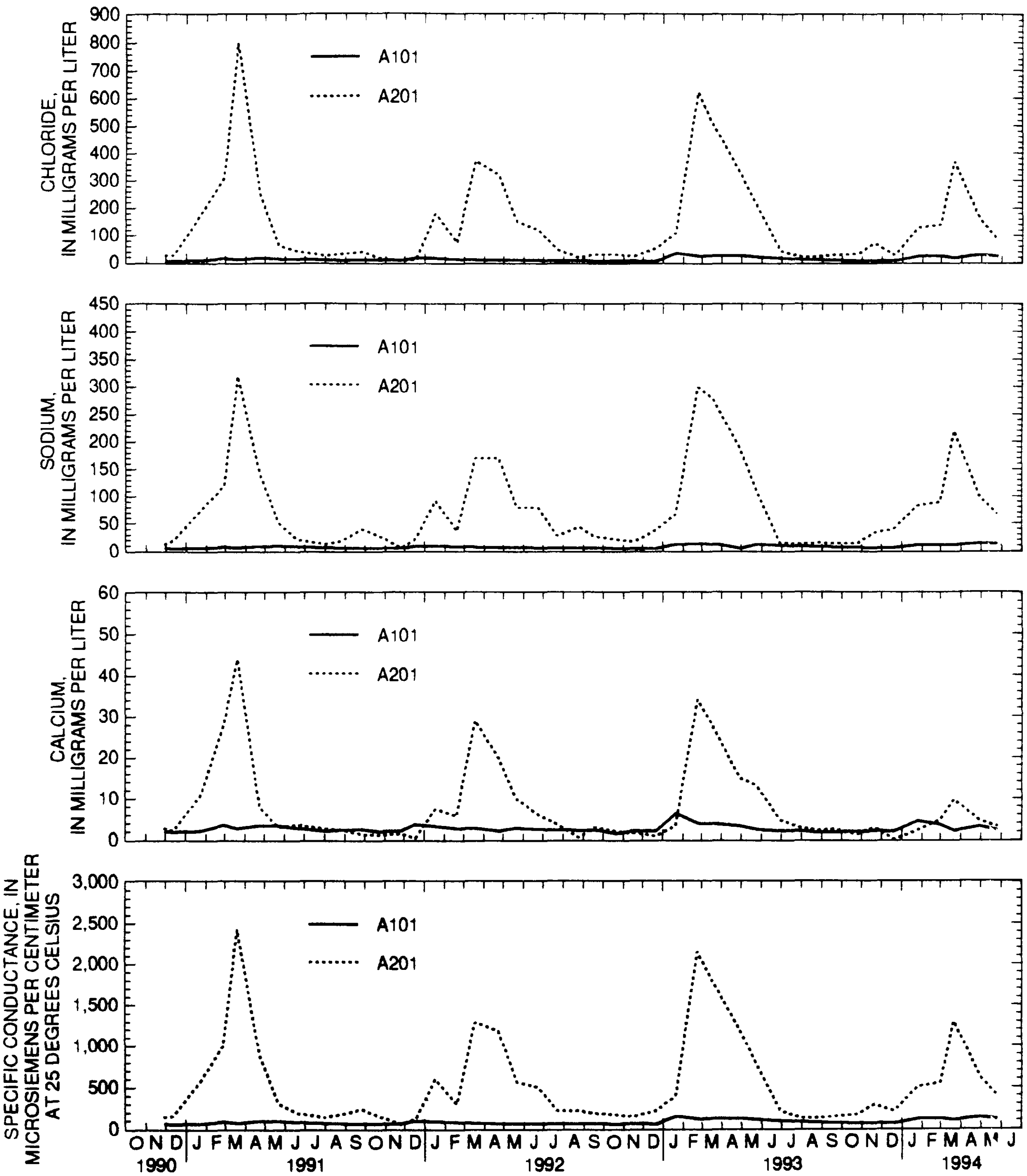


Figure 29. Ground-water quality at sites A, B, C, and D, upgradient (well 101) and downgradient (well 201) from Rout~ 25, southeastern Massachusetts, November 1990-May 1994.

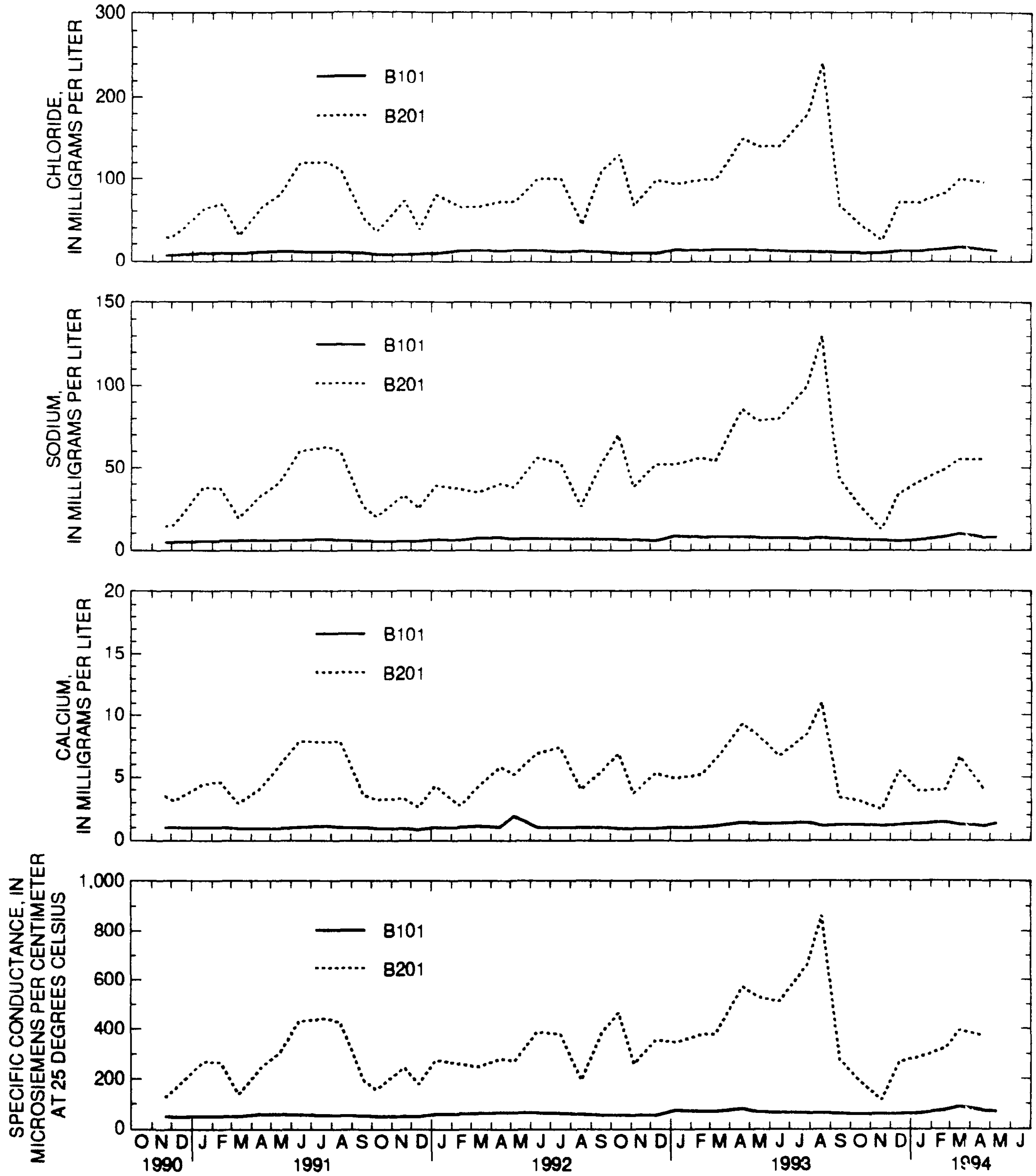


Figure 29. Ground-water quality at sites A, B, C, and D, upgradient (well 101) and downgradient (well 201) from Route 25, southeastern Massachusetts, November 1990-May 1994—*Continued.*

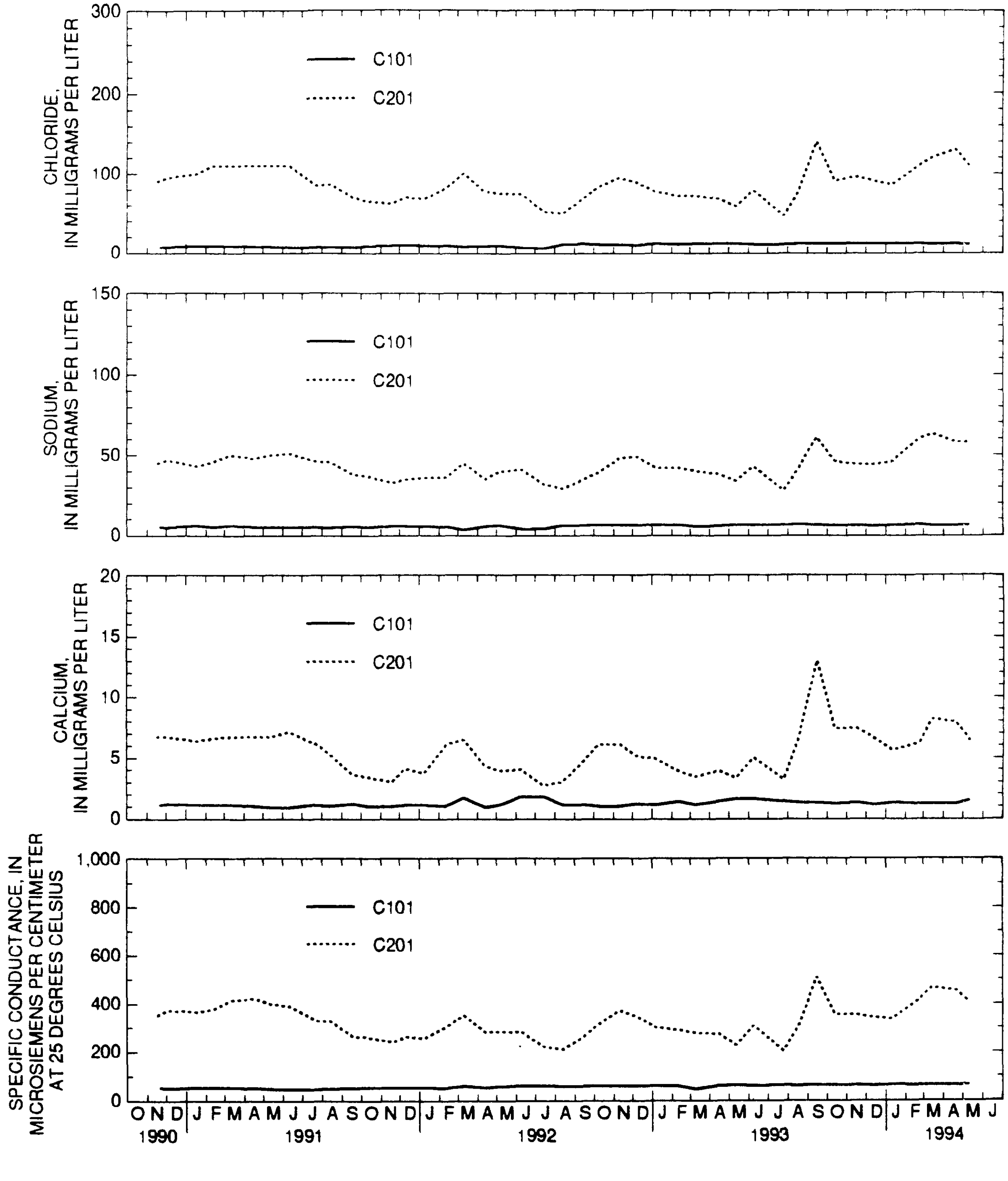


Figure 29. Ground-water quality at sites A, B, C, and D, upgradient (well 101) and downgradient (well 201) from Route 25, southeastern Massachusetts, November 1990-May 1994—*Continued.*

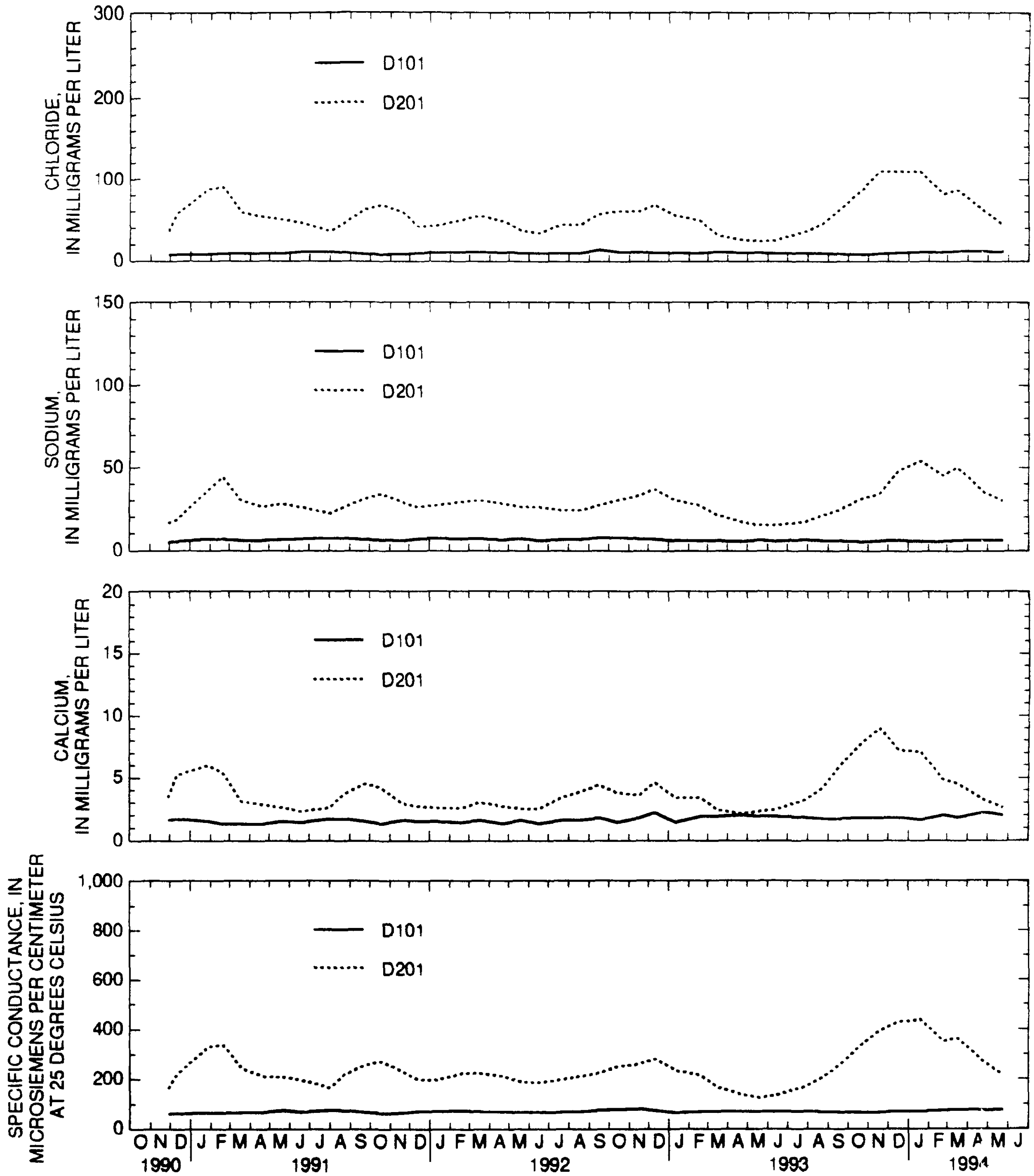


Figure 29. Ground-water quality at sites A, B, C, and D, upgradient (well 101) and downgradient (well 201) from Route 25, southeastern Massachusetts, November 1990-May 1994—*Continued.*

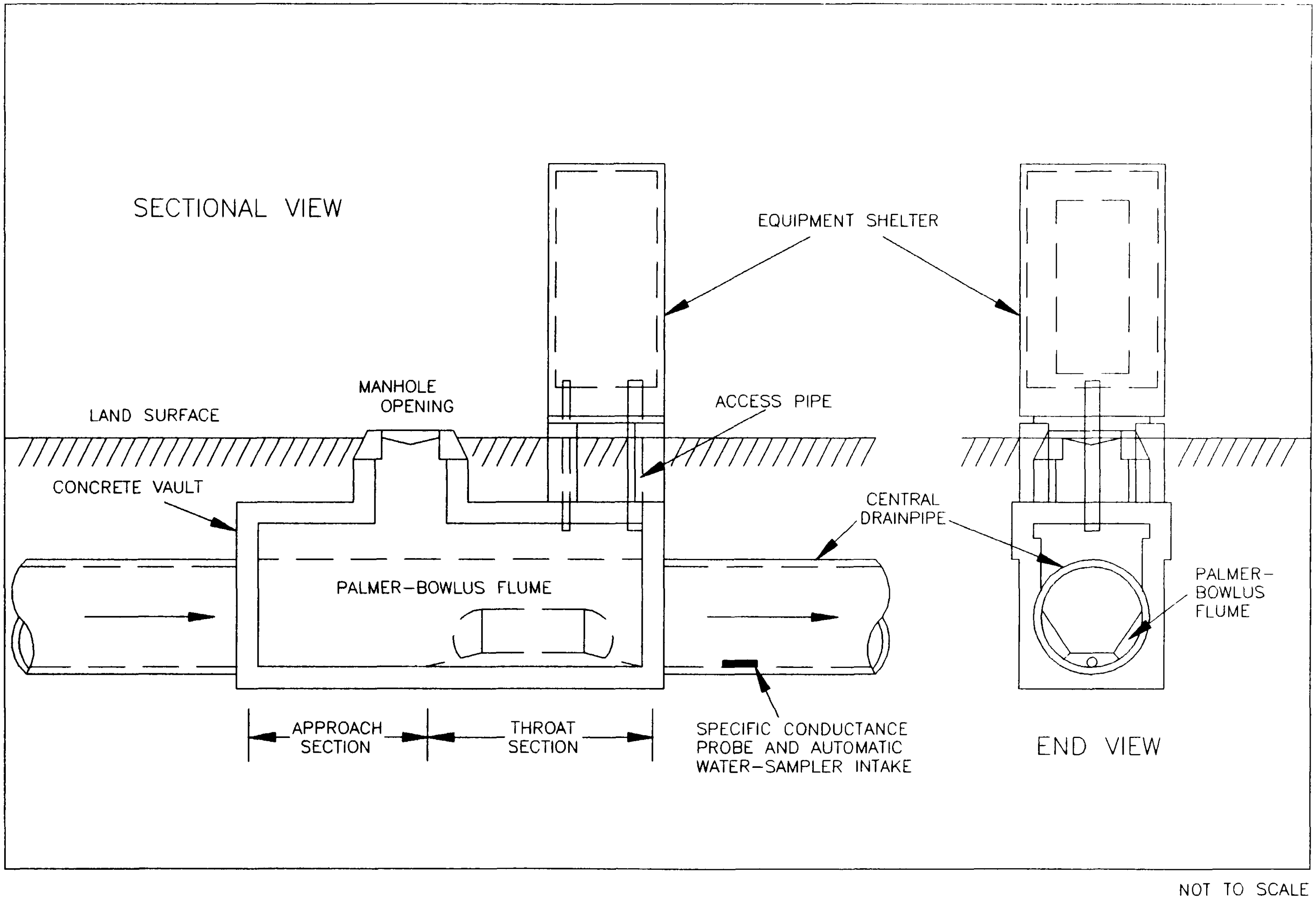


Figure 30. Highway-drainage monitoring station in median strip of Route 25, southeastern Massachusetts.

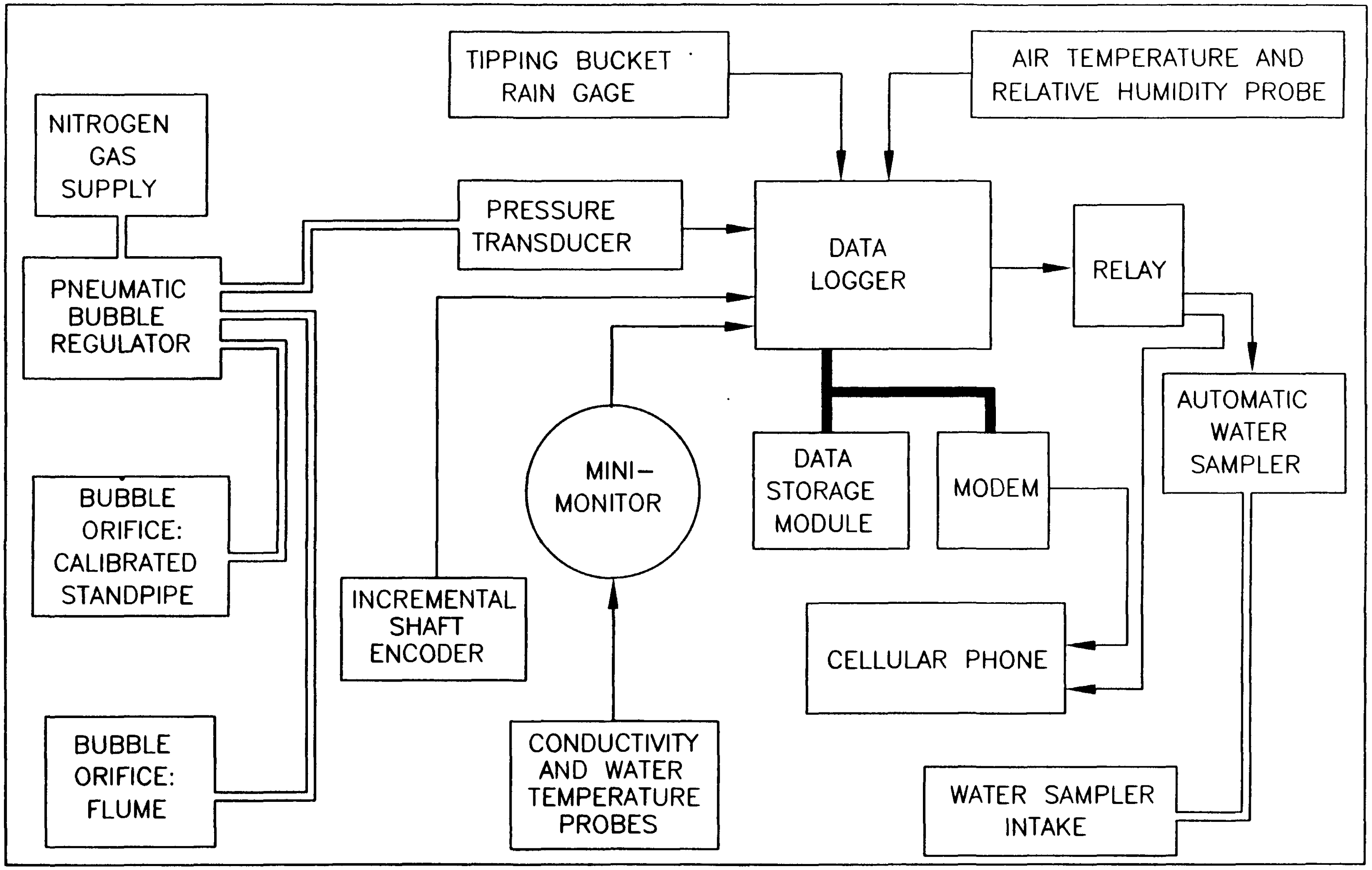


Figure 31. Instrumentation at the highway-drainage monitoring stations at sites B, C, and D in median strip of Route 25, southeastern Massachusetts.

Table 8. Pipe diameters and drainage areas at highway-drainage monitoring stations in the median strip, Route 25, southeastern Massachusetts

[Monitoring stations shown in figures 2 and 3. **Station name:** see explanation in text on station-numbering convention. **Site identification No.:** Unique number for each site based on the latitude and longitude of the site. First six digits are latitude. Next seven digits are longitude and final two digits are a sequence number to uniquely identify each station]

Test site	Station name	Site identification No.	Pipe diameter, in inches	Drainage area, in square miles
B	B619	414631070380601	42	0.028
C	C632	414625070382101	24	.015
D	D492	414643070352801	42	.020
	D504	414648070354201	36	.011

Continual improvements in the highway-drainage data-collection program were the result of new, more accurate, and more reliable instrumentation. Current station instrumentation consists of a Campbell Scientific Inc.[1] (CSI) CR10 data logging system interfaced with a Motorola S1765 transceiver and CSI DC112 Modem, a four-parameter USGS mini-monitor (one for temperature measurements; three for specific conductance measurements), a pressure transducer, a Handar incremental shaft encoder, an ISCO sampler, a CSI A21REL-12 relay driver, CSI air temperature and relative humidity probe, and a Climatronics tipping-bucket rain gage. Power is supplied by two 60 ampere-hour sealed rechargeable batteries maintained by two 10-watt solar panels with voltage regulators.

Air temperature, relative humidity, and precipitation were measured and recorded every hour. Baseline data for stage, water temperature, pH, and conductance were recorded every hour during periods of little or no flow. A pressure-transducer, a strip-chart recorder and float-arm assembly, and an incremental shaft encoder and float-arm assembly were used for measuring stage. A pH probe, a low range (0-10,000 μS/cm) temperature-compensated conductance probe, a high range (10,000-100,000 μS/cm) temperature-compensated conductance probe, and a water-temperature probe were submerged in the approach section of the flume for measurements of pH, specific conductance, and water temperature. A low-range specific conductance probe was downstream of the flume throat for measurement of specific conductance for comparison with specific conductance from the upgradient probe. The data loggers also are programmed to control the frequency of data collection and recording. Although the frequency of baseline data collection is 1 h at all four stations, stage thresholds and recording and sampling frequencies are set independently for each station. Stage thresholds are set on the basis of the pipe diameter, slope, and retention characteristics of the drainage systems. Recording and sampling frequencies are dependent on individual hydrologic and water-quality responses. Stage and specific conductance thresholds were programmed whereby recording and sampling frequencies increase to a minimum of 10 minutes and a maximum of 1 minute in response to changes in stage and specific conductance. The stations were programmed in this way to maximize information about changes in stage and specific conductance and for collection of water-quality samples for calibrating the specific conductance record during runoff, allowing the first flush of dissolved constituents in highway runoff to be better defined. The data-logger programs also prevented collection of voluminous data at times of little or no flow.

[1]The use of trade names in this report is for identification purposes only and does not constitute endorsement by the U.S. Government.

An ISCO sampler was triggered to collect an initial water sample when stage exceeds a specified threshold; if stage permits, subsequent water samples are collected in response to a specified change in conductance at a minimum of every 2 minutes. Water samples collected were processed by the same methods used for samples collected from ground water.

Precipitation data are used as a qualitative check of the recorded stage data. Only the site C and the upgradient site D stations have tipping-bucket rain gauges. Precipitation measurements are not recorded along the highway during the winter because these instruments are not designed for use with snow and ice; since 1994, however, precipitation has been monitored year round by the USGS at the Wareham office of the MHD, about 2 mi west of sites B and C, and about 4 mi west of sites A and D.

Examples of the type of data collected, and their application, are presented in figures 32 and 33. Figure 32 shows an example of highway-runoff data, including stage, specific conductance, water temperature, and pH. The stage and specific conductance are used in stage-discharge and specific conductance road-salts constituent relations to calculate the road-salt loads in highway runoff.Water temperature and pH are measured because these factors can significantly affect the measured specific conductance. Figure 33 shows an example where stage, air temperature, and precipitation are used to determine (1) if a storm event actually occurred (using precipitation) and (2) if the precipitation may have been rain or snow (using air temperature).

Surface Water

Water-level and water-quality data were collected from Red Brook, a stream crossed by Route 25 at the outlet of the site B and C drainage systems (fig. 1), from 1982 to 1991 to monitor road-salt loads in that stream and to evaluate the combined quantity of road salt in highway runoff discharged from the site B and C drainage systems. Highway runoff collected in these drainage systems is discharged to Red Brook after flowing through a sedimentation pool next to the west bank of the stream (fig. 34). Highway runoff from the eastern side of Red Brook also flows through a sedimentation pool before entering Red Brook. Two streamflow-gaging stations are located on Red Brook; one is upstream from the highway (station identification number 01105884), and one is downstream (station identification number 01105885) (fig. 34). Stream stage data were collected continuously and stream discharge measurements were conducted about every 6 weeks at the downstream station from 1982 to 1986. These data were used to develop a rating curve to convert stage measurements into discharges. Temperature and specific conductance were collected continuously from 1982 to 1986 at two locations downstream of the highway; one is just downstream of the Route 25 eastbound roadway culvert, and one is downstream of the sedimentation pool outlets. Stage, water temperature, and specific conductance were collected intermittently from 1982 to 1991 at the upstream station and from 1987 to 1991 at the station downstream of the highway.

Red Brook stations was equipped with mercury manometers for measuring stage and USGS Minimonitors for measuring water temperature and specific conductance from 1982-86. Data were recorded by use of punch-tape recorders. In 1987, the manometers were replaced with pressure transducers and the punch-tape recorders were replaced with digital-data loggers. During periods of continuous monitoring, stage was recorded at 15-minute intervals and water temperature and specific conductance were recorded at 1-hour intervals. Water samples were collected manually from locations where water temperature and specific conductance were recorded. These samples were collected concurrently with discharge measurements and were analyzed for dissolved concentrations of chloride, sodium, and calcium and specific conductance.

Monitoring of Red Brook was discontinued in 1991. Data from Red Brook were no longer needed after the highway-drainage monitoring stations at sites B and C were installed and put into operation.

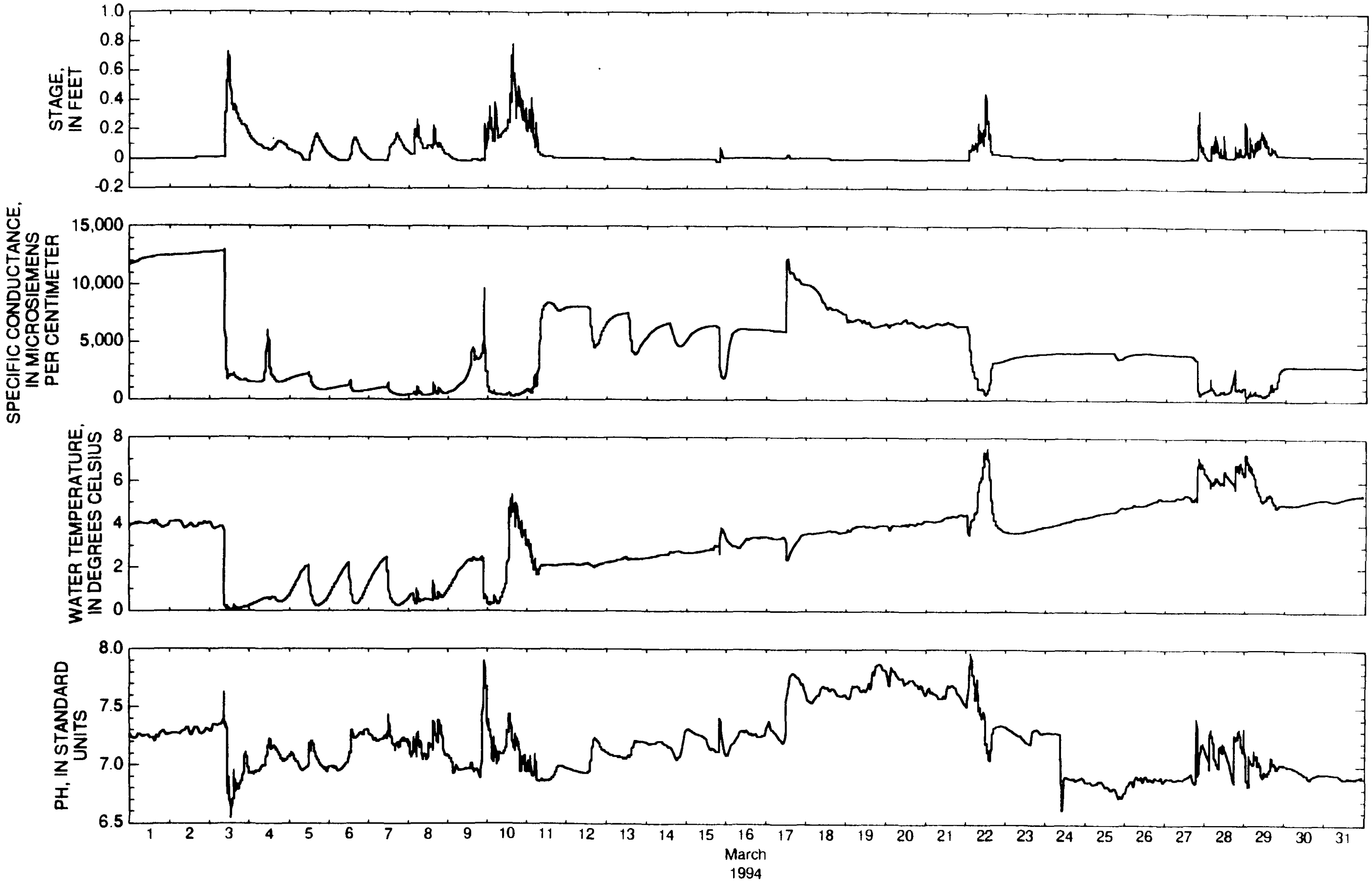


Figure 32. Stage, specific conductance, water temperature, and pH measured in highway runoff at highway-drainage monitoring station B619, March 1- 31, 1994, Route 25, southeastern Massachusetts.

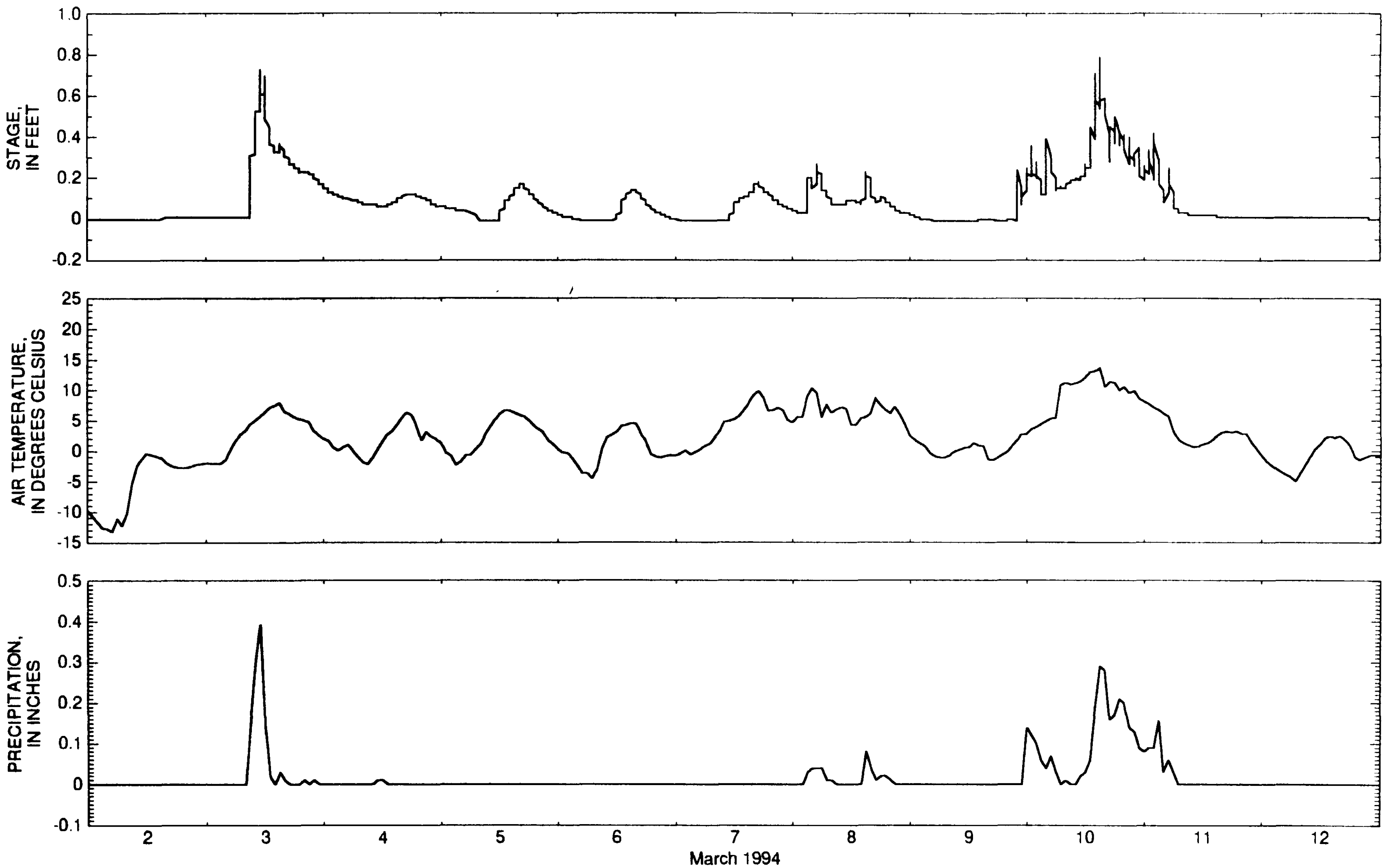


Figure 33. Stage, air temperature, and precipitation measured during precipitation and snowmelt events at highway-drainage monitoring station B619, March 2-12, 1994, Route 25, southeastern Massachusetts.

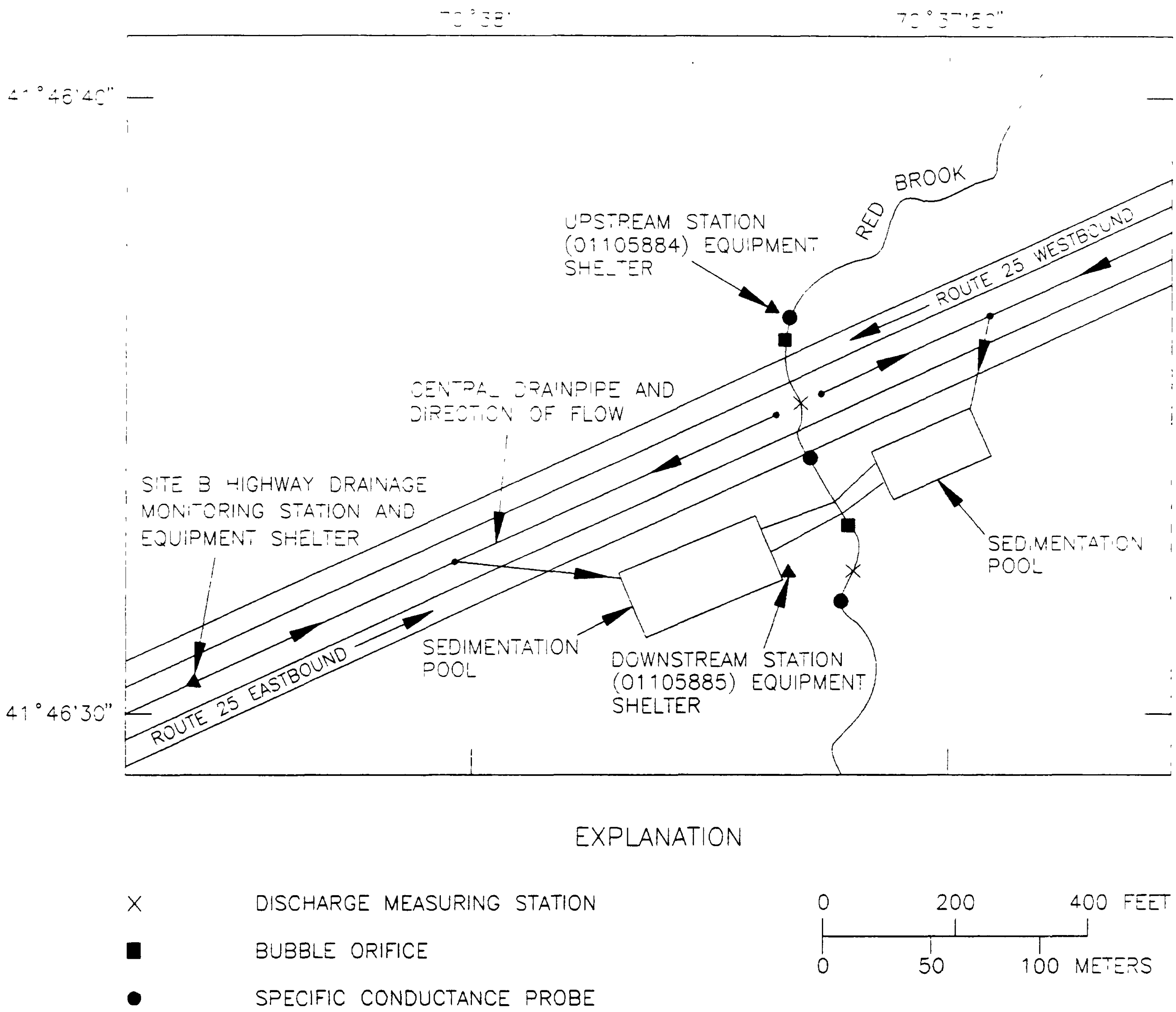


Figure 34. Location of monitoring stations on Red Brook relative to site B highway-drainage monitoring station, near Route 25, southeastern Massachusetts.

METHODS FOR COMPUTATION OF ROAD-SALT LOADS IN GROUND WATER AND FROM HIGHWAY-DRAINAGE SYSTEMS

A road salt budget will be calculated for each test site so that the effectiveness of the different highway-drainage designs in preventing contamination of ground water by road salt can be determined. The input to the salt budget at each test site is the road salt applied to the highway. The output of the salt budget at each test site is the sum of the road-salt load discharged through the highway-drainage system, if present, and the road-salt load passing through each test site in ground water. Any chloride, sodium, or calcium already in the ground water is accounted for by subtracting the upgradient concentrations from the downgradient concentrations. Outputs to surface water through overland flow are assumed to be negligible because of the high rate of infiltration into the sandy soils at each test site.

The road-salt application data provided by the MHD represents the total amount applied to each of the eastbound and westbound roadways of the 7-mile section of Route 25. Road-salt application varies greatly from storm to storm and year to year, depending on weather, traffic, and road conditions. Nevertheless, road-salt loads applied at each test site are assumed to be equal because all four sites are between the same two interchanges on Route 25. Records of road-salt application to Route 25 are converted from tons per 7-mile section of highway to pounds per lane-mile for comparison with road salt in ground water and from the highway-drainage station at each test site. A summary of available salt-application data is presented in table 9.

Table 9. Summary of road-salt application data, Route 25, southeastern Massachusetts, 1987-94

[Values are tons per 7-mile section of Route 25]

Time period	Application data	
	Salt	Premix
Winter of 1987-88	351.7	60.5
Winter of 1988-89	334.7	24.4
Winter of 1989-90	405.9	37.9
Winter of 1990-91	261.8	10.7
Winter of 1991-92	311.2	43.7
Winter of 1992-93	571.9	74.9
Winter of 1993-94	552.9	19.5

Determination of the amount of road salt in ground water at the test sites requires calculation of the mass flux of highway-related chloride, sodium, and calcium through a specific vertical section of the aquifer downgradient from the highway. The chloride, sodium, and calcium concentrations attributable to road-salt applications are calculated by subtracting chloride, sodium, and calcium concentrations at wells upgradient from the highway (background concentrations) from concentrations at wells downgradient from the highway. The mass flux of road-salt related chloride, sodium, and calcium through the aquifer (QC_d), in pounds per day, is then computed as follows:

$$QC_d = (K)(I)(A)(C)(m), \qquad (1)$$

where

- K is estimated horizontal hydraulic conductivity of the aquifer, in feet per day;
- I is water-table gradient, in feet per feet, (dimensionless);
- A is area of vertical section through which the ground water is flowing, in square feet;
- C is the concentration of road-salt related chloride, sodium, or calcium, in milligrams per liter; and
- m is a constant 6.246×10^{-5}, in pound-liter per cubic foot-milligram (for conversion of cubic foot-milligram per day-liter to pounds per day).

The use of this equation to calculate monthly loads requires the assumption that constituent concentrations measured during the monthly sampling rounds represent the constituent concentrations for the other days of the month. This assumption is valid because ground-water velocities at the test sites are relatively slow compared to that of surface water and because the conductance of the salt plume has been demonstrated to have little to no variation when measured on a weekly basis (Church and Friesz, 1993b). Monthly loads of sodium, calcium, and chloride transported past the monitoring wells are calculated by summing the calculated daily flux of chloride, sodium, and calcium determined by equation 1 for a 1-month period. These values are then converted to pounds per lane-mile per month. Monthly data are accumulated for the period of record of ground-water sampling collection from the short-screen well clusters for comparison between test sites.

Monthly road-salt loads also are calculated for each highway-drainage monitoring station. Stage and specific conductance are recorded continuously. Discharge at each station is determined from theoretical relations between stage and discharge (Kilpatrick and Schneider, 1983). Relations between specific conductance and chloride, sodium, and calcium concentrations developed from results of water-quality analyses are used to predict constituent concentrations from recorded specific-conductance records. A road-salt load is computed for every stage and specific-conductance measurement. Chloride, sodium, and calcium loads (QC_t), in pounds per time interval since last measurement, are computed as follows:

$$QC_t = (Q)(C)(T)(m), \quad (2)$$

where

Q is discharge of water, in cubic feet per second;
C is the concentration of chloride, sodium, or calcium, in milligrams per liter;
T is time interval since last measurement, in seconds; and
m is a constant 6.246×10^{-5}, in pound-liter per cubic foot-milligram (for conversion of cubic foot-milligram per liter to pounds per time interval).

The values calculated in equation 2 are summed over a daily period to provide chloride, sodium, and calcium loads in pounds per day. Daily loads of chloride, sodium, and calcium diverted from the test sites through the highway-drainage systems are summed by month and expressed in units of pounds per lane-mile per month. Monthly data are accumulated for the same period of record as the ground-water data for comparison between test sites. Because the site C drainage system drains directly into the site B system fig. 3), chloride, sodium, and calcium loads measured at site C (station C632) are subtracted from those at site B (station B619) to determine sodium, calcium, and chloride loads from site B alone. The site C drainage area is defined by a topographic drainage divide; therefore, the road-salt constituent loads measured at station C632 represent site C only. Site D chloride, sodium, and calcium loads are determined by subtracting loads from the upgradient station (D504) from loads from the downgradient station (D492) (fig. 2).

SUMMARY

Four test sites, each representing a separate highway-drainage system designed for a different amount of highway-runoff control, were selected and instrumented to determine their relative effectiveness in preventing road-salt contamination of ground water. These distinct designs were incorporated into the construction of a 7-mile extension of Route 25 in southeastern Massachusetts that was completed in 1987. The test sites are designated sites A, B, C, and D in order of increasing highway-runoff control. Site A represents a typical country-drainage design where highway runoff collected in catch basins on the roadway surface is discharged locally. Sites B, C, and D, however, contain trunkline drainpipes beneath the median strip through which captured highway runoff is carried away and discharged into a nearby stream or coastal waterway. These three drainage designs differ only in the way highway runoff is captured. At site B, highway runoff is collected in catch basins on the roadway surface and is then piped beneath the highway to the trunkline drainpipe. The drainage design at site C is similar to that of site B; however, the eastbound roadway shoulder is underlain with an impervious layer of bituminous concrete (snow berm) from which highway runoff is piped to the trunkline drainpipe. Both roadway shoulders and the median strip are underlain with snow berms at site D. This type of drainage system is designed to intercept all highway runoff and pipe it to the trunkline drainpipe.

Test sites are on an outwash plain bounded to the north and west by till and bedrock hills and to the south and east by the Cape Cod Canal. Surficial materials of this outwash plain consist primarily of sands with gravel; scattered boulders lie at and near the surface, whereas silty sands are present at depth. The climate in this area is characterized by warm summers, cold winters, and a mean annual precipitation of about 48 in. Because of the sandy surficial materials, much of the precipitation infiltrates the soil and overland flow is minimal.

Data-collection programs were developed to determine the relative effectiveness of the different highway-drainage systems in preventing contamination of ground water by road salt. These programs were designed to monitor the application of road salt to the highway, and the movement of road salt through the local ground-water system, the highway drainage systems, and the local surface-water systems.

The MHD maintains records of road salt applied to Route 25 and forwards these records to the USGS. Road-salt application data are compared with road-salt loads calculated from data collected in the ground-water and from the highway-drainage systems.

The ground-water data-collection program was conducted in several phases starting with the installation of observation wells and collection of water-level data for the selection of test sites representing the four highway-drainage designs. Test sites were selected where ground-water-flow direction is nearly perpendicular to the highway. Site selection was complete in 1984. Installation of long-screen wells for collection of water-quality samples was complete in 1988. These wells are arranged along two lines nearly perpendicular to the highway, parallel to ground water flow, extending upgradient to downgradient from the highway at each test site. During installation of the long-screen wells, new information about transport of chemical constituents in ground water became available, and the reliability of water-quality samples collected from long-screen wells representing the water-quality of the aquifer was questioned. Consequently, in 1989, two clusters of short-screened wells were installed just upgradient of two long-screen wells for collection of water-quality samples and analysis of concentrations of road-salt constituents for comparison with analyses of water-quality samples collected concurrently from the long-screen wells. Results of this experiment, completed in June 1990, indicated that water-quality samples from the long-screen were not representative of the water-quality of the aquifer. Short-screen well clusters were installed upgradient and downgradient from the highway at each test site in autumn 1990. Monthly collection of water-quality samples from short-screen well clusters at each test site for monitoring road-salt contamination of ground water began in November 1990 and continued through March 1995.

The highway-drainage data-collection program was designed to measure the amount of road salt diverted through the highway-drainage systems. The highway-drainage monitoring stations at sites B, C, and D, installed during highway construction in 1987, consist of calibrated Palmer-Bowlus flumes within the trunkline drainpipe from which stage and specific conductance were continuously monitored and recorded. Precipitation was monitored and recorded at sites C and D as a qualitative check of the recorded stage data. Automatic water samplers were used to collect water-quality samples during runoff. Water samples were analyzed for dissolved chloride, sodium, and calcium concentrations and for specific conductance. Quantities of road salt passing through the highway-drainage systems are computed by use of relations between stage and discharge and between specific conductance and sodium, calcium, and chloride concentrations. Data collection began in 1988 and continued through March 1995.

The surface-water data-collection program consisted of monitoring the amount of road salt from Route 25 entering Red Brook, a stream that flows beneath the highway. Streamflow-gaging stations were installed on Red Brook, one upgradient and one downgradient from Route 25. Stage and specific conductance were continuously monitored and recorded at the downgradient station between 1982 and 1986. Stage and specific conductance were monitored intermittently from 1982 to 1991 at the upstream station and from 1987 to 1991 at the downgradient station. Water samples were collected and analyzed for dissolved chloride, sodium and calcium concentrations and for specific conductance.

A salt budget will be calculated for each test site so that the effectiveness of the different highway-drainage designs in preventing contamination of ground water by road salt can be determined. The input to the salt budget at each test site is the road salt applied to Route 25. Road-salt application data are provided by the MHD. The output of the salt budget at each test site is the sum of road-salt load in ground water and the road-salt load discharged through the drainage system. Road-salt loads in ground water are calculated from monthly measurements of dissolved chloride, sodium, and calcium concentrations, monthly measurements of hydraulic gradients, and hydraulic conductivities estimated at each test site. Road-salt loads discharged through the drainage systems will be calculated by applying continuous records of stage and specific conductance to relations between stage and discharge and between specific conductance and constituents of road salt.

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