HYDROLOGIC EFFECTS OF HIGHWAY-DEICING CHEMICALS IN MASSACHUSETTS

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FACTORS FOR CONVERTING INCH-POUND UNITS TO INTERNATIONAL SYSTEM OF UNITS

The following factors may be used to convert the inch-pound units published herein to the International System of Units (SI):

Multiply inch-pound	by	to obtain SI Units
foot (ft)	0.3048	meter (m)
cubic foot per second (ft^3/s)	.02832	cubic meter per second (m^3/s)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
pounds avoirdupois (lb avoirdupois)	.4536	kilogram (kg)
ton, short (2000 lbs)	.9072	megagram (mg)

DEFINITIONS OF SELECTED GROUND-WATER TERMS

(Adapted from Sammel and others, 1966; Lohman and others, 1972; and U.S. Water Resources Council, 1973.)

Aquifer--A geologic formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs. See Ground-water reservoir.

Aquifer test--A test involving the withdrawal of measured quantities of water from, or addition of water to, a well (or wells) and the measurement of resulting changes in head in the aquifer both during and after the period of discharge or addition.

Artificial recharge--Recharge at a rate greater than natural, resulting from deliberate or incidental actions of man.

Bedrock--The consolidated rock of the earth's crust.

Contact--The plane or surface where two different rock types come together.

Discharge, ground-water--Removal of water from an aquifer by evapotranspiration, by natural flow to streams, or by pumping.

Equipotential line--A line along which the total energy of the fluid, or head, of a body of ground water is the same.

Evapotranspiration--Combined discharge of water to the air by direct evaporation and plant transpiration.

Flow line--The path which a particle of water follows in its movement through saturated, permeable rocks.

Geologic unit--A group of rocks having common or closely related characteristics.

Ground water--Water in rock materials beneath the surface of the earth. Ground water is distinguished from soil moisture in this report.

Ground-water reservoir--All rocks in the zone of saturation. See Aquifer.

Hydraulic conductivity--The volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area of a porous medium that is isotropic and the fluid is homogeneous, measured at right angles to the direction of flow.

Hydraulic gradient--The change in static head per unit of distance in a given direction.

Hydraulic head--The height above a standard datum of the surface of a column of water (or other liquid) that can be supported by the static pressure at a given point. In ground water, where velocities are small, the velocity head is negligible and the total head is the sum of the elevation head and the pressure head. In a nonflowing well, the head is measured as the elevation of the water level referenced to an established datum; in a flowing well, it is the elevation to which water will rise in a pipe extended high enough to prevent the well from flowing, also referenced to an established datum.

Interface--In hydrology, the contact plane between two different fluids.

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

Permeability--The capacity of rock materials to transmit fluid. Permeability depends largely on the shape and size of pore spaces and their interconnections; in general, the larger the openings, the greater the permeability.

Porosity--The porosity of a rock or soil is the ratio of the volume of interstices (pores) to the total volume of a rock. It may be expressed as either a decimal fraction or a percentage.

Porosity, effective--The amount of interconnected pore space available for fluid transmission. It is expressed as a percentage of the total volume occupied by interconnecting interstices.

Potentiometric surface--An imaginary surface representing the static head of ground water.

Recharge--The processes of addition of water to the zone of saturation, that zone beneath the water table.

Specific yield--The quantity of water that a fully saturated rock will yield by gravity drainage; expressed as a percentage which is the ratio of (1) the volume of water yielded to (2) the volume of the rock.

Storage coefficient--The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.

Transmissivity--The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of an aquifer under a unit hydraulic gradient.

Unsaturated zone--A subsurface zone containing water under pressure less than that of the atmosphere, including water held by capillarity; and, containing air or gases generally under atmospheric pressure. Limited above by the land surface and below by the water table.

Water budget--An accounting of the inflow to, outflow from, and storage changes in a hydrologic unit.

Water table--The surface in an unconfined aquifer at which the pressure is atmospheric. It is the level at which water stands in wells that just penetrate the upper part of the aquifer.

Zone of saturation--A subsurface zone in which all the interstices are filled with water under pressure greater than atmospheric. The upper surface of the zone of saturation is the water table.

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ABSTRACT

Methods of estimating annual mean and annual maximum chloride concentrations and sodium concentrations in streams were developed using multiple and simple linear regression techniques and data collected during the 1972-77 water years. Independent variables are easily obtainable parameters such as total salt application within a basin, annual precipitation, and drainage basin characteristics. Methods for obtaining gross estimates of chloride loads and sodium loads from salt-application data and estimates of nonhighway-related chloride and sodium were suggested.

A chloride budget was calculated for a small drainage basin containing a section of interstate highway. The chloride budget was described in terms of percentages in direct runoff to the stream, in ground-water discharges to the stream, in storage in the ground, and in the amount unaccounted for.

Attempts were made to relate chloride concentrations in ground water adjacent to highways to quantities of salt applied to the highways on an annual basis, annual precipitation, depth of wells below land surface, depth of wells below the water table, and distance of wells from edge of pavement. Little correlation was observed between annual salt-application values and annual mean chloride concentrations in ground water near highways. The irregular distribution of highway runoff, due to topographic differences between sites, and variations in salting and runoff during individual storms seem to affect correlation between quantities of salt applied and chloride concentrations in ground water near highways.

INTRODUCTION

The policy of the MDPW (Massachusetts Department of Public Works) in the past two decades has been to maintain Massachusetts highways in a "high level of service" condition during the entire year (Massachusetts Department of Public Works, 1976). This "high level of service" condition during the winter has been achieved through application of deicing chemicals, principally sodium chloride.

Deicing chemicals, however, enter the hydrologic environment. Public agencies, industrial water users, and private citizens have expressed concern over numerous reports of increasing sodium and chloride concentrations in water supplies.

The MDPW wishes to continue the policy of maintaining Massachusetts highways in a "high level of service" condition during the winter and to reduce or eliminate undesirable effects of deicing chemicals on the hydrologic environment. Accordingly, in January of 1970, the USGS (U.S. Geological Survey) and MDPW began a cooperative study to determine the effects of highway salt on specific hydrologic environments and to develop techniques for predicting these effects as a step toward designing highway drainage systems to protect sensitive areas. Included in this study are: (1) an evaluation of the proportion of highway salt that is transported from the highway by streams and (2) an evaluation of the degree to which ground water is affected by highway salt.

The study had three segments: (1) Investigation of the total amount of salt leaving drainage basins in streams, (2) investigation of the quantity of salt entering and moving with ground water near highways, and (3) a "budget site" at which deicing chemicals discharged in a stream and discharged or stored in ground-water bodies was calculated and related to salt applied to a nearby highway.

STREAM-MONITORING SITES

Stream-monitoring sites were selected to measure total discharge of salt from a drainage basin. From a network of more than 100 gaging stations, operated by the U.S. Geological Survey in cooperation with State and other Federal agencies, about 30 that monitor streamflow from small drainage areas were evaluated as sites for recording salt discharge from the basin. Criteria for selecting sites included: (1) highways are located in the basin, (2) the amount of salt applied could be determined, and (3) that there be little interference from sources of salt other than highway deicing chemicals.

All but 11 of the 30 sites were rejected, principally because urbanization within the basins was indicative of potential sources of salt other than highway deicing chemicals. Two of the 11 remaining sites were rejected because salt-storage piles were located near proposed monitoring sites. Nine sites finally selected for study are listed below and are shown in figure 1.

U.S. Geological Survey station name and location	U.S. Geological Survey station number
South Branch Ashuelot River at Webb, near Marlborough, New Hampshire	01160000
Beaver Brook at Wilmington, Vermont	01167800
Boulder Brook near East Bolton, Massachusetts (upstream gage)	01096906
Boulder Brook at East Bolton, Massachusetts (downstream gage)	01096910
Browns Brook near Webster, Massachusetts	01124750
Hop Brook near New Salem, Massachusetts	01174000
Moose Brook near Barre, Massachusetts	01173260
Nashoba Brook near Acton, Massachusetts	01097300
Walker Brook near Becket Center, Massachusetts	01180800

The stream-monitoring sites were equipped to measure the total quantity of salt leaving the drainage basins in streams. This quantity was then related to the quantity of highway salt applied, precipitation on the basin, and basin characteristics. It was assumed that salt entering both surface-water and ground-water bodies in the basin ultimately leaves the basin in streamflow.

Continuous records of streamflow, specific conductance, and stream temperature were obtained from recording instruments, and water samples were collected periodically for laboratory analyses of specific conductance, sodium concentration and chloride concentration. Equations for converting specific conductance to sodium concentrations and chloride concentrations were derived by relating the laboratory specific-conductance values to the laboratory sodium-concentration values and chloride-concentration values, respectively, through regression techniques. These concentrations and streamflow data were used to compute loads (tons) for comparison with the tons of salt applied to highways. Records of highway salt application were obtained from MDPW, precipitation data from records of the National Oceanographic and Atmospheric Administration (1971-77), and drainage-basin characteristics from Wandle (1977).

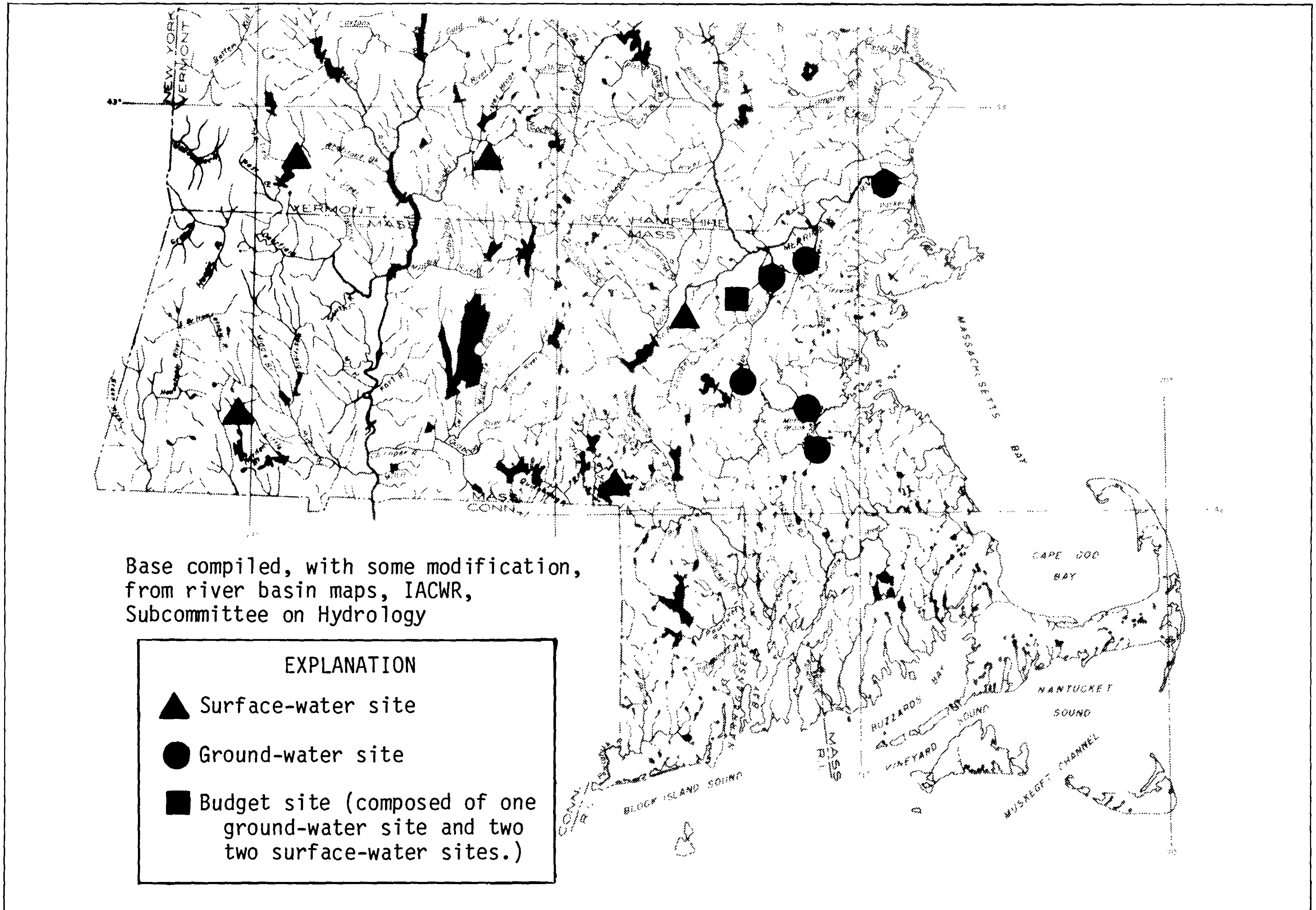


Figure 1.--Locations of monitoring sites

Equations for Estimating Chloride and Sodium Concentrations and Loads in Streamflow

Chloride and sodium concentrations were statistically related to variables that affect concentrations and can be easily measured, such as basin characteristics (drainage area, slope, storage), quantity of salt applied, precipitation, and lane-miles of highway salted within a drainage basin.

Multiple-regression analyses of the 5-6 years of chloride and sodium concentration data were used to obtain equations for estimating maximum daily chloride concentration and mean daily chloride concentration. Independent variables (factors that effect chloride concentration) used in the regression analyses were selected on the basis of hydrologic principles and their linear correlation with chloride concentrations. Table 1 lists and describes the variables used in correlation and regression analyses.

Statistics (means, standard deviations, maximums, and minimums) of the data set used in correlation and regression analyses for the stream-monitoring site are listed in table 2.

The first step to obtain equations for estimating mean and maximum chloride concentrations and mean stream discharge was to compute correlation coefficients (table 3) for each pair of variables.

Table 1.—Names and descriptions of variables used in correlation and regression analyses

Variable name	Description of variable (units)
MEAN_CL	Annual average of daily mean chloride concentrations (mg/L).
MAX_CL	Annual maximum of daily mean chloride concentrations (mg/L).
CL_LOAD (tons/day)	Annual sum of daily values of chloride concentrations (mg/L) x discharge (ft^3/s) x 0.0027.
MEAN_NA	Annual average of daily mean sodium concentrations (mg/L).
MAX_NA	Annual maximum of daily mean sodium concentrations (mg/L).
NA_LOAD (tons/day)	Annual sum of daily values of sodium concentration (mg/L) x discharge (ft^3/s) x 0.0027.
SALT_APP	Annual sum of tons of chloride applied to roadways in the basin.
PRECIP	Annual sum of rainfall and snowfall (in).
DR_AREA	Area enclosed by topographic divide from which precipitation normally drains by gravity into the stream above a specified point (mi^2).
SLOPE	Slope of main channel, in feet per mile, between points 10 percent and 85 percent along the stream from monitoring site to the topographic divide.
STORAGE	Area of lakes and ponds expressed as a percentage of the drainage area plus 0.5 percent.
LANE_MIS	Number of lane miles of highway salted within the drainage basin.
ANAVFLOW	Annual mean rate of water discharge (ft^3/s).
CONCSALT	SALT_APP divided by ANAVFLOW.
LPRECIP	Natural logarithm of PRECIP.
LANAVFLO	Natural logarithm of ANAVFLOW.
LDR_AREA	Natural logarithm of DR_AREA.

Table 2.--Statistics of the data set used in correlation and regression analyses of stream data

(All values were computed to eight decimal places by computer and truncated to two decimal places.)

Variable	Number of observations	Mean	Standard deviation	Minimum	Maximum
MEAN_CL	36	19.05	10.23	7.40	46.00
MAX_CL	36	40.63	21.98	12.00	100.00
CL_LOAD	36	222.50	247.05	10.60	713.80
MEAN_NA	31	9.70	4.34	4.60	20.00
MAX_NA	31	20.66	9.23	8.10	42.00
NA_LOAD	31	99.87	133.34	7.50	434.90
SALT_APP	35	154.10	184.31	1.70	760.00
PRECIP	37	53.63	7.82	41.70	71.50
DR_AEA	37	8.71	11.68	.49	36.00
SLOPE	37	103.70	48.73	22.60	182.00
STORAGE	37	2.58	1.71	.53	5.04
LANE_MIS	37	20.24	16.41	1.70	43.30
ANAVFLOW	37	18.75	24.05	1.05	88.30
CONCSALT	35	11.01	8.99	1.25	31.92
LPRECIP	37	3.97	.14	3.73	4.26
LANAVFLO	37	2.10	1.37	.04	4.48
LDR_AREA	37	1.30	1.38	-.71	3.58

Table 3.--Correlation coefficients for variables in data set for stream-monitoring sites, part 1

CORRELATION COEFFICIENTS / PROB > |R| UNDER H0:RHO=0 / NUMBER OF OBSERVATIONS

	MEAN_CL	MAX_CL	CL_LOAD	MEAN_NA	MAX_NA	NA_LOAD	SALT_APP	PRECIP	DR_AREA	SLOPE	STORAGE	LANE_MIS	ANAVFLOW
MEAN_CL	1.00000 0.0000 36	0.93324 0.0001 36	0.03636 0.8333 36	0.96851 0.0001 31	0.95011 0.0001 31	-0.22205 0.2299 31	0.14917 0.3998 34	0.11664 0.4981 36	-0.23567 0.1664 36	-0.35142 0.0356 36	-0.09750 0.5716 36	-0.06701 0.6978 36	-0.27193 0.1086 36
MAX_CL	0.93324 0.0001 36	1.00000 0.0000 36	-0.09180 0.5944 36	0.92304 0.0001 31	0.95978 0.0001 31	-0.14172 0.4470 31	0.01219 0.9455 34	0.16694 0.3305 36	-0.20147 0.2387 36	-0.23751 0.1631 36	-0.28287 0.0946 36	-0.15543 0.3654 36	-0.24285 0.1535 36
CL_LOAD	0.03636 0.8333 36	-0.09180 0.5944 36	1.00000 0.0000 36	-0.16256 0.3823 31	-0.05725 0.7597 31	0.99945 0.0001 31	0.89893 0.0001 34	-0.03333 0.8470 36	0.84247 0.0001 36	-0.59498 0.0001 36	0.85850 0.0001 36	0.82524 0.0001 36	0.83008 0.0001 36
MEAN_NA	0.96851 0.0001 31	0.92304 0.0001 31	-0.16256 0.3823 31	1.00000 0.0000 31	0.95486 0.0001 31	-0.18835 0.3102 31	-0.05279 0.7779 31	0.27636 0.1323 31	-0.28912 0.1147 31	-0.03853 0.8370 31	-0.22393 0.2259 31	-0.38621 0.0319 31	-0.32215 0.0772 31
MAX_NA	0.95011 0.0001 31	0.95978 0.0001 31	-0.05725 0.7597 31	0.95486 0.0001 31	1.00000 0.0000 31	-0.08456 0.6511 31	0.04763 0.7991 31	0.33158 0.0684 31	-0.17920 0.3347 31	-0.20561 0.2671 31	-0.22598 0.2216 31	-0.20065 0.2791 31	-0.21394 0.2478 31
NA_LOAD	-0.22205 0.2299 31	-0.14172 0.4470 31	0.99945 0.0001 31	-0.18835 0.3102 31	-0.08456 0.6511 31	1.00000 0.0000 31	0.97605 0.0001 31	0.06729 0.7191 31	0.98188 0.0001 31	-0.28078 0.1260 31	0.79264 0.0001 31	0.73880 0.0001 31	0.97403 0.0001 31
SALT_APP	0.14917 0.3998 34	0.01219 0.9455 34	0.89893 0.0001 34	-0.05279 0.7779 31	0.04763 0.7991 31	0.97605 0.0001 31	1.00000 0.0000 35	-0.04754 0.7863 35	0.63742 0.0001 35	-0.68448 0.0001 35	0.79570 0.0001 35	0.78985 0.0001 35	0.60064 0.0001 35
PRECIP	0.11664 0.4981 36	0.16694 0.3305 36	-0.03333 0.8470 36	0.27636 0.1323 31	0.33158 0.0684 31	0.06729 0.7191 31	-0.04754 0.7863 35	1.00000 0.0000 37	-0.09704 0.5678 37	0.10710 0.5281 37	-0.12699 0.4539 37	-0.07060 0.6780 37	-0.01782 0.9166 37
DR_AREA	-0.23567 0.1664 36	-0.20147 0.2387 36	0.84247 0.0001 36	-0.28912 0.1147 31	-0.17920 0.3347 31	0.98188 0.0001 31	0.63742 0.0001 35	-0.09704 0.5678 37	1.00000 0.0000 37	-0.32237 0.0517 37	0.67398 0.0001 37	0.69704 0.0001 37	0.97658 0.0001 37
SLOPE	-0.35142 0.0356 36	-0.23751 0.1631 36	-0.59498 0.0001 36	-0.03853 0.8370 31	-0.20561 0.2671 31	-0.28078 0.1260 31	-0.68448 0.0001 35	0.10710 0.5281 37	-0.32237 0.0517 37	1.00000 0.0000 37	-0.29086 0.0807 37	-0.79521 0.0001 37	-0.31026 0.0616 37
STORAGE	-0.09750 0.5716 36	-0.28287 0.0946 36	0.85850 0.0001 36	-0.22393 0.2259 31	-0.22598 0.2216 31	0.79264 0.0001 31	0.79570 0.0001 35	-0.12699 0.4539 37	0.67398 0.0001 37	-0.29086 0.0807 37	1.00000 0.0000 37	0.60145 0.0001 37	0.64192 0.0001 37
LANE_MIS	-0.06701 0.6978 36	-0.15543 0.3654 36	0.82524 0.0001 36	-0.38621 0.0319 31	-0.20065 0.2791 31	0.73880 0.0001 31	0.78985 0.0001 35	-0.07060 0.6780 37	0.69704 0.0001 37	-0.79521 0.0001 37	0.60145 0.0001 37	1.00000 0.0000 37	0.69937 0.0001 37
ANAVFLOW	-0.27193 0.1086 36	-0.24285 0.1535 36	0.83008 0.0001 36	-0.32215 0.0772 31	-0.21394 0.2478 31	0.97403 0.0001 31	0.60064 0.0001 35	-0.01782 0.9166 37	0.97658 0.0001 37	-0.31026 0.0616 37	0.64192 0.0001 37	0.69937 0.0001 37	1.00000 0.0000 37

Table 3.--Correlation coefficients for variables in data set for stream-monitoring sites, part 2

CORRELATION COEFFICIENTS / PROB > |R| UNDER H0:RHO=0 */ NUMBER OF OBSERVATIONS

	MEAN_CL	MAX_CL	CL_LOAD	MEAN_NA	MAX_NA	NA_LOAD	SALT_APP	PRECIP	DR_AREA	SLOPE	STORAGE	LANE_MIS	ANAVFLOW
CONCSALT	0.92925 0.0001 34	0.83847 0.0001 34	0.08123 0.6479 34	0.90462 0.0001 31	0.90120 0.0001 31	-0.22651 0.2205 31	0.39220 0.0198 35	0.04667 0.7901 35	-0.17245 0.3219 35	-0.54513 0.0007 35	-0.03716 0.8321 35	0.10978 0.5301 35	-0.21710 0.2103 35
LPRECIP	0.12025 0.4848 36	0.17131 0.3178 36	-0.01750 0.9193 36	0.26930 0.1429 31	0.32941 0.0704 31	0.08024 0.6678 31	-0.03485 0.8424 35	0.99745 0.0001 37	-0.08002 0.6378 37	0.08221 0.6286 37	-0.13222 0.4354 37	-0.04719 0.7815 37	-0.00045 0.9979 37
LANAVFLO	-0.11581 0.5012 36	-0.13630 0.4280 36	0.85559 0.0001 36	-0.22346 0.2269 31	-0.07047 0.7064 31	0.87204 0.0001 31	0.72037 0.0001 35	0.24106 0.1506 37	0.83153 0.0001 37	-0.58055 0.0002 37	0.63079 0.0001 37	0.87752 0.0001 37	0.85373 0.0001 37
LDR_AREA	-0.04471 0.7957 36	-0.06020 0.7273 36	0.87908 0.0001 36	-0.17904 0.3352 31	-0.01864 0.9207 31	0.89480 0.0001 31	0.76036 0.0001 35	0.14139 0.4039 37	0.85946 0.0001 37	-0.65241 0.0001 37	0.62645 0.0001 37	0.89529 0.0001 37	0.85877 0.0001 37

	CONCSALT	LPRECIP	LANAVFLO	LDR_AREA
MEAN_CL	0.92925 0.0001 34	0.12025 0.4848 36	-0.11581 0.5012 36	-0.04471 0.7957 36
MAX_CL	0.83847 0.0001 34	0.17131 0.3178 36	-0.13630 0.4280 36	-0.06020 0.7273 36
CL_LOAD	0.08123 0.6479 34	-0.01750 0.9193 36	0.85559 0.0001 36	0.87908 0.0001 36
MEAN_NA	0.90462 0.0001 31	0.26930 0.1429 31	-0.22346 0.2269 31	-0.17904 0.3352 31
MAX_NA	0.90120 0.0001 31	0.32941 0.0704 31	-0.07047 0.7064 31	-0.01864 0.9207 31
NA_LOAD	-0.22651 0.2205 31	0.08024 0.6678 31	0.87204 0.0001 31	0.89480 0.0001 31
SALT_APP	0.39220 0.0198 35	-0.03485 0.8424 35	0.72037 0.0001 35	0.76036 0.0001 35
PRECIP	0.04667 0.7901 35	0.99745 0.0001 37	0.24106 0.1506 37	0.14139 0.4039 37

	CONCSALT	LPRECIP	LANAVFLO	LDR_AREA
DR_AREA	-0.17245 0.3219 35	-0.08002 0.6378 37	0.83153 0.0001 37	0.85946 0.0001 37
SLOPE	-0.54513 0.0007 35	0.08221 0.6286 37	-0.58055 0.0002 37	-0.65241 0.0001 37
STORAGE	-0.03716 0.8321 35	-0.13222 0.4354 37	0.63079 0.0001 37	0.62645 0.0001 37
LANE_MIS	0.10978 0.5301 35	-0.04719 0.7815 37	0.87752 0.0001 37	0.89529 0.0001 37
ANAVFLOW	-0.21710 0.2103 35	-0.00045 0.9979 37	0.85373 0.0001 37	0.85877 0.0001 37
CONCSALT	1.00000 0.0000 35	0.05607 0.7490 35	-0.01604 0.9271 35	0.07115 0.6846 35
LPRECIP	0.05607 0.7490 35	1.00000 0.0000 37	0.25711 0.1245 37	0.15989 0.3445 37
LANAVFLO	-0.01604 0.9271 35	0.25711 0.1245 37	1.00000 0.0000 37	0.98333 0.0001 37
LDR_AREA	0.07115 0.6846 35	0.15989 0.3445 37	0.98333 0.0001 37	1.00000 0.0000 37

*Probability of obtaining a sample correlation coefficient (R) greater than the absolute value of that shown from a population wherein the correlation coefficient (RHO) equals zero.

The independent variables that are highly correlated with MEAN-CL (the dependent variable), as indicated by correlation coefficients in table 3, were used in regression analysis to obtain an estimating equation for MEAN-CL. SLOPE and CONCSALT are the most highly correlated, as indicated by correlation coefficients (rounded to two places) of -0.35 and 0.93, respectively. The regression equation obtained and a scatter diagram of observed MEAN-CL versus estimated MEAN-CL are shown in figure 2. A line representing perfect estimation is included to illustrate the accuracy with which the equation estimates MEAN-CL.

The independent variables CONSALT and STORAGE were used to obtain an estimating equation for MAX-CL. Although the correlation coefficient for MAX-CL and SLOPE (table 3) is not much lower than that for MAX-CL and STORAGE, the correlation coefficient for SLOPE and STORAGE indicated that these two variables were themselves more highly correlated than either alone was with MAX-CL. Therefore, only STORAGE, with the higher of the two correlation coefficients with MAX-CL, was included in the analysis. Figure 3 shows the regression equation obtained, a scatter diagram of observed MAX-CL versus estimated MAX-CL, and a line representing hypothetical perfect estimation.

Similar approaches were taken to obtain estimating equations for CL_LOAD, MEAN_NA, MAX_NA, and NA_LOAD. The estimating equations, multiple-correlation coefficients (R), and standard errors of estimate (SE) are as follows:

$$\text{MEAN\_CL} = -0.94 + 1.22 \times \frac{\text{SALT\_APP}}{\text{ANAVFLOW}} + 0.06\ \text{SLOPE}$$

R = 0.91 SE 3.3 mg/L

$$\text{MAX\_CL} = 26.1 + 2.1 \times \frac{\text{SALT\_APP}}{\text{ANAVFLOW}} - 3.2 \times \text{STORAGE}$$

R = 0.76 SE = 12 mg/L

$$\text{CL\_LOAD} = -37.8 = 50.0\ \text{STORAGE} + 0.816\ \text{SALT\_APP}$$

R = 0.93 SE = 90 tons

$$\text{MEAN\_NA} = 5.13 + 0.483 \times \text{CONCSALT}$$

R = 0.90 SE = 1.9 mg/L

$$\text{MAX\_NA} = 11.0 + 1.02 \times \text{CONCSALT}$$

R = 0.90 SE = 4.0 mg/L

$$\text{NA\_LOAD} = -36.4 + 14.9\ \text{STORAGE} + 1.02\ \text{SALT\_APP}$$

R = 0.98 SE = 26 tons

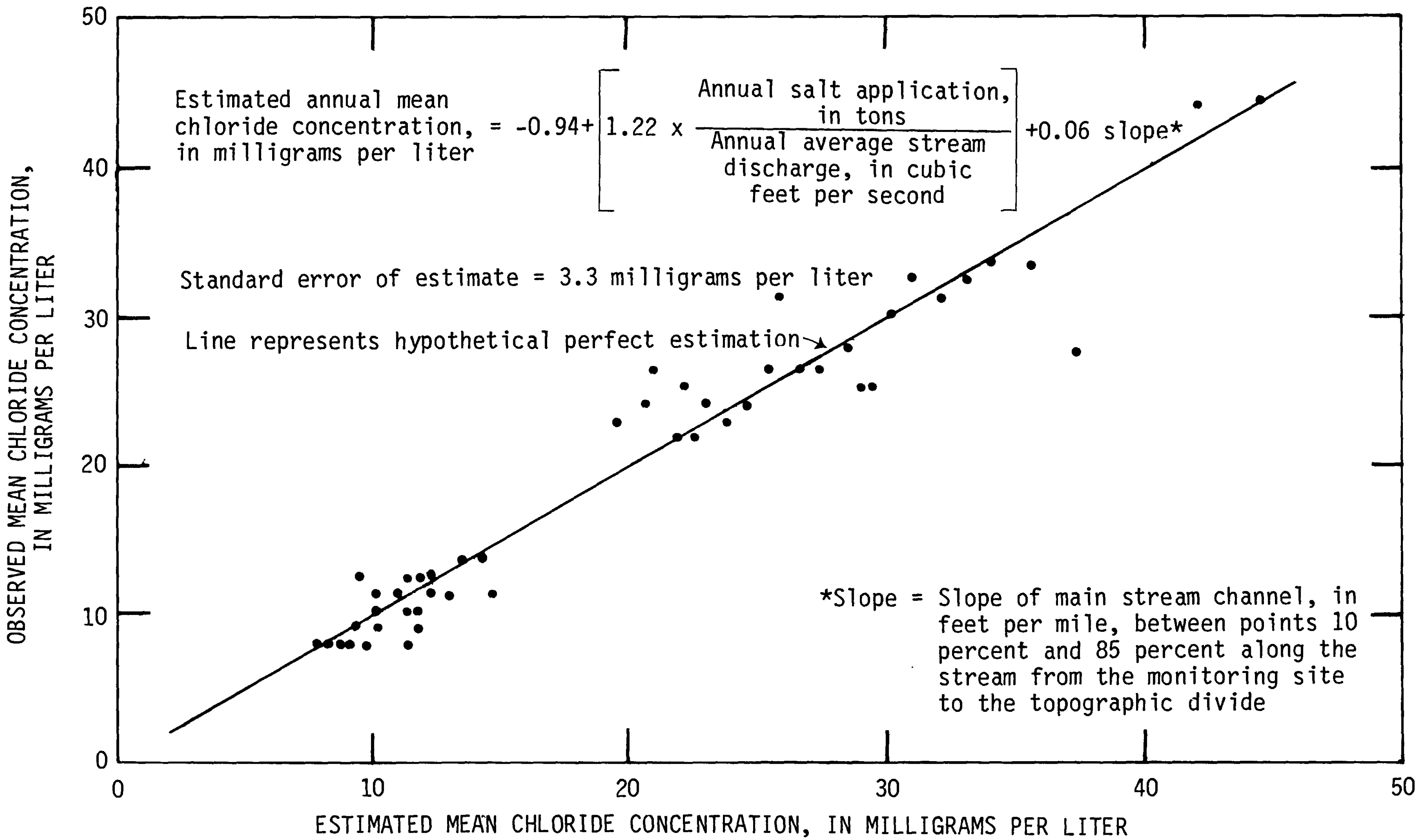


Figure 2.--Scatter diagram showing observed annual mean chloride concentration versus estimated annual mean chloride concentrations for stream-monitoring sites

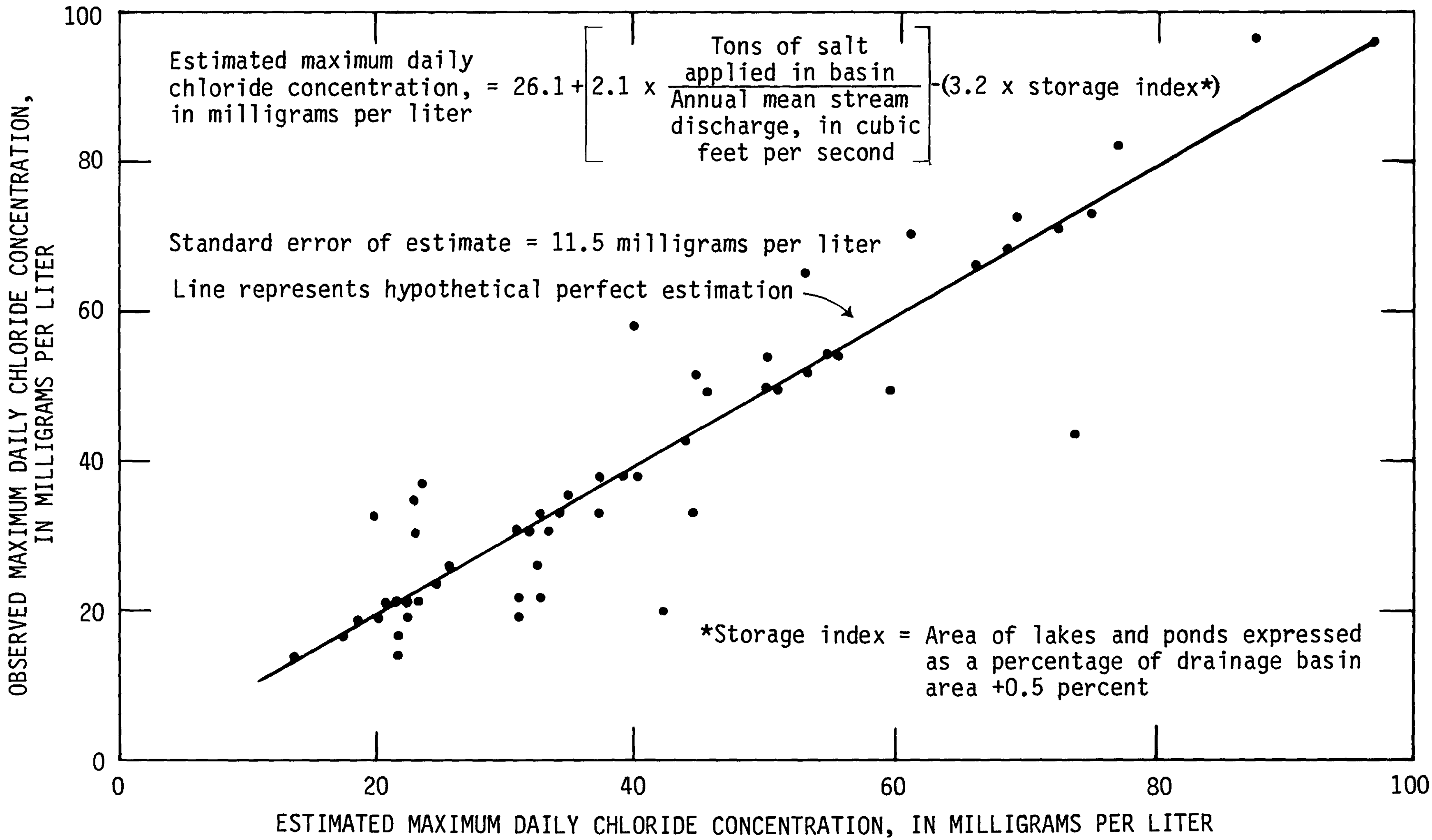


Figure 3.--Scatter diagram of observed annual maximum daily chloride concentrations versus estimated annual maximum daily chloride concentrations for stream-monitoring sites

In the methods for estimating both MEAN-CL and MAX-CL, the values of SALT-APPL and ANAVFLOW must be known or estimated. SALT-APPL may be estimated from local or regional salt-applicaton rates, adjusted, if necessary, for the nature of the highway under consideration. In the absence of gaging station records, ANAVFLOW may be reasonably estimated (fig. 4) from DR-AREA, PRECIP, and regression equations obtained from data for nearby gaging stations. Regionalizations of precipitation data such as the one by Knox and Nordenson (1955) are available for estimation of PRECIP values.

The procedure by which values of MEAN-CL, MAX-CL, MEAN_NA, MAX_NA, CL_LOAD, and NA_LOAD may be estimated by the preceding regression equations are as follows:

1. Delineate on a topographic map the drainage area above the point of interest.
2. Identify section of highway draining to potentially affected stream.
3. Estimate quantity of salt required to maintain the section of highway (SALT_APP).
4. Calculate the SLOPE and STORAGE, as indicated by their descriptions in table 1.
5. Estimate PRECIP from regionalization studies or from nearby records of precipitation at weather stations.
6. Calculate ANAVFLOW from the equation shown on figure 4.
7. Use equations shown on page 8.

The effect of application of sodium chloride as a deicing chemical is well accounted for in the relationships between sodium concentrations and salt application and chloride concentrations and salt application. However, chloride loads for all monitoring sites ranged from 68 percent to 660 percent of applied chloride.

The higher percentages were obtained for the Browns Brook site, a small drainage basin (0.49 mi^2) in which an average of 2.2 tons of sodium chloride and an undetermined but small amount of calcium chloride were applied. A nonhighway-related contribution of 9 mg/L accounts for the higher percentages. The average percentage of applied chloride appearing in runoff, excluding Browns Brook, was 139. In most places, an estimated 5 mg/L background concentration accounts for the difference between applied and discharged chloride. Although estimating equations are provided for chloride or sodium load, it would also be possible to indicate the maximum load expected in a stream by summing the chloride or sodium applied, in tons, and the corresponding background load estimated as follows:

$$\text{Estimated background load} = \text{Estimated background concentration of sodium or chloride} \times \text{Mean annual flow} \times 365 \times 0.0027$$

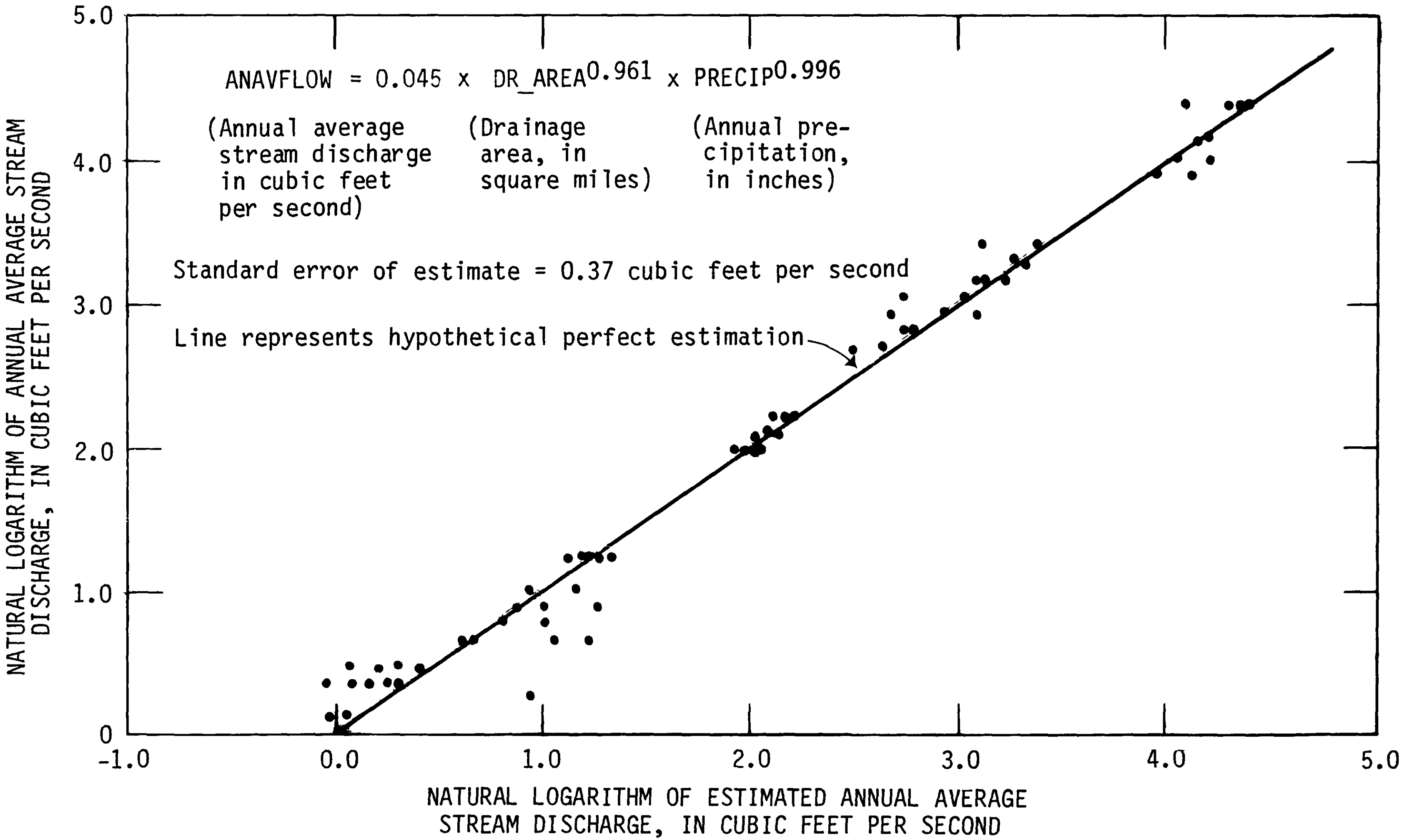
A range of background concentrations indicated by comparing salt-application data and loads calculated during this study would be between 5 and 10 mg/L.

The fraction of applied chloride and sodium appearing in stream load was not determined because the background loads were not known.

The Short-Term Response of a Small Stream to Salt Application

The short-term response of a stream to salt application (response to single storms over periods of several days) was investigated at Boulder Brook by graphically comparing hydrographs of stream discharge, specific conductance, air temperature, salt application, and chloride load. The periods were selected to show conditions during early winter (December 30, 1974-January 3, 1975), midwinter (January 18-20, 1974), and late winter (March 13-17, 1975). Salt (chloride) applications in the drainage basin ranged from 0.24 tons to 3.1 tons during these periods.

Figure 5 shows the stream's response to two applications of highway salt totaling 1.8 tons of chloride applied in the stream's drainage basin during a snowfall of 2.5 inches from December 30, 1974, to January 3, 1975. Air temperature was just above freezing until noon on January 1, when it rose to 7.5°C. The increase in runoff caused by rising temperature was not great enough to be detected by the stream gage. A slight increase in specific conductance was observed, however, indicating that some salty runoff entered the stream.



Fiqure 4.--Scatter diagram of logarithms of observed annual average stream discharge versus logarithms of estimated annual average stream discharge for the stream-monitoring sites

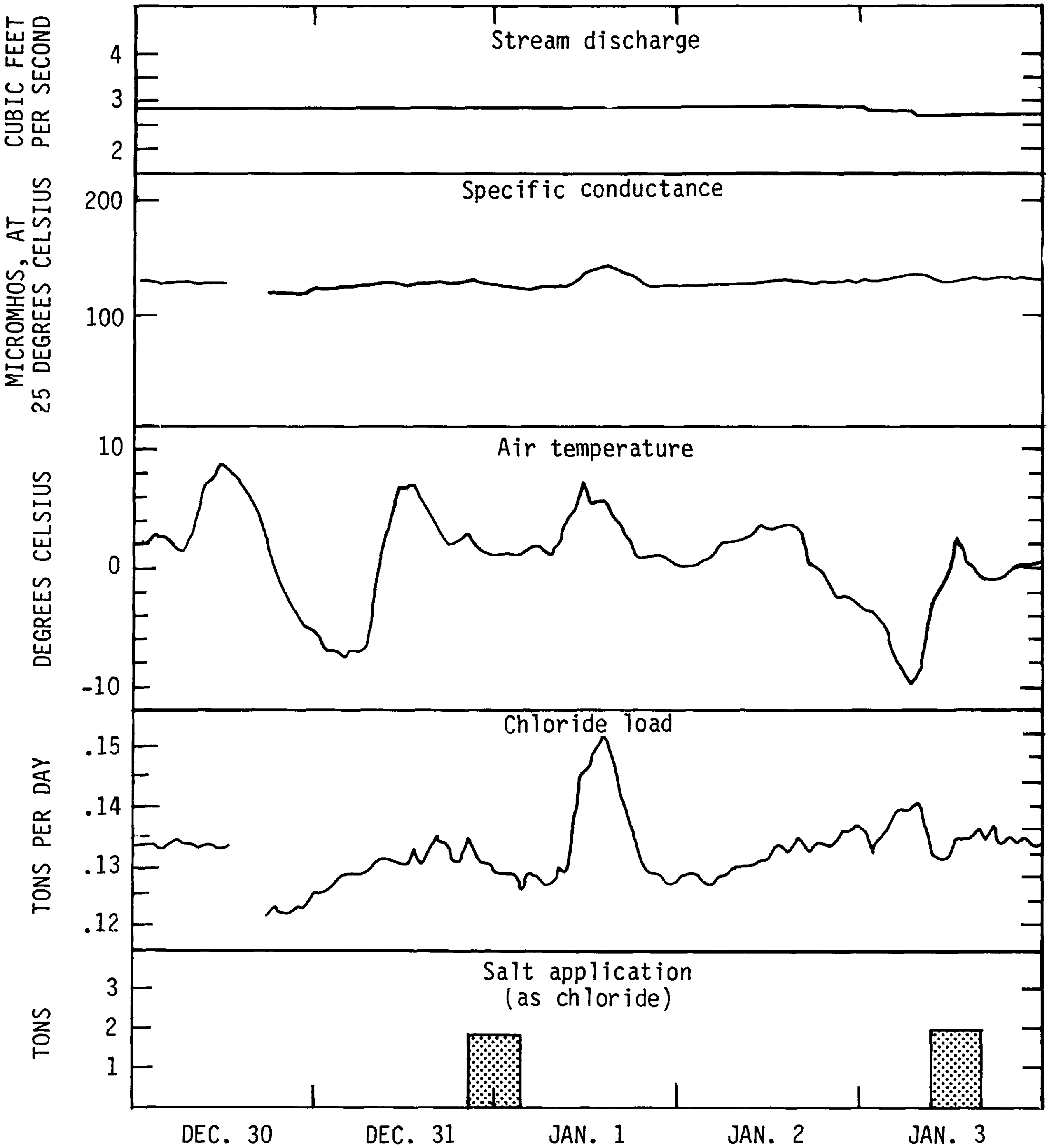


Figure 5.--Selected parameters during December 30, 1974, to January 3, 1975, at the monitoring site on Boulder Brook at East Bolton, Massachusetts (downstream from I-495)

Figure 6 shows a much greater response to application of highway salt totalling 2.75 tons of chloride on January 18 and 19, 1974, when air temperatures were below freezing and precipitation was in the form of freezing rain. Large quantities of salt are commonly applied during such conditions. Response to salting occurred after temperatures rose above freezing on January 19 (fig. 6). After about 12 hours of above freezing air temperature, freezing conditions returned and conductance decreased rapidly. About 36 hours later (about noon January 21), the temperature again rose slightly above freezing, rain continued, and the conductance rose again. The relatively small increase in conductance during this second response to rising temperature indicates that whatever salt remained on the road surface was quickly washed off. Rain and above freezing temperatures continued after noon on January 21, discharge increased, and the dissolved-solids concentrations and conductance decreased. Chloride load remained fairly constant during the period of low conductance and high discharge. Although chloride concentrations (as indicated by conductance) were lower during the morning of January 22, a greater volume of water was being discharged, resulting in loads similar to those earlier during the sub-freezing temperatures of January 20 and 21. In anticipation of falling temperatures, a small salt application (0.24 tons) was made on January 22, but it caused only slight increases in conductance and load.

Data for March 13-17, 1975 (fig. 7), indicate little if any response of stream conductance to salt application. Precipitation on March 14 was 5 inches of snow, and the temperature was below freezing for about a day after the salt application. The stream responded only slightly when temperatures rose above freezing, indicating that most of the salt had probably been plowed from the roadway rather than having immediately been washed into the stream. The precise delay time of the stream's response to salt application is not known because the times when salt was applied to the highway are not known.

GROUND-WATER-MONITORING SITES

Several hundred potential ground-water-monitoring sites were examined in the field. Criteria for evaluating ground-water sites and the evaluation of sites screened from those examined during the site-selection process are shown in table 4. Seven sites finally selected for study are listed below and are shown in figure 1.

Site name	Highway number
Andover	I-93
Bolton	I-495
Canton	I-95
Chelmsford	3
Needham	Massachusetts Rt. 128
Wayland	Massachusetts Rt. 30
West Newbury	Massachusetts Rt. 113

Criteria for site selection included:

(1) Preferably, a location alongside a major highway.
(2) The availability of year-to-year salt-application rates for the highway and, preferably, a record of salt-application data before this study.
(3) No construction planned on or near the highway or test site that might affect drainage or salt runoff during the 7-year study.
(4) The water table should be within at least 30 feet of land surface so that water samples could be collected with a suction pump.
(5) Direction of ground-water flow should be across the highway, preferably at right angles.
(6) The aquifer should have a saturated thickness of at least 10 feet to permit monitoring of vertical head distribution and vertical distribution of chloride below the water table.
(7) Two sites were in till, two in swamp deposits, and two in sand and gravel, the most common materials in eastern Massachusetts.
(8) Permission could be obtained from property owners to install and have access to wells at distances 1,000 feet from the edge of the highway on the downgradient side and beyond the splash-affected area on the upgradient side.
(9) The highway should be the only major source of salt, and chloride contribution to the aquifer from sources of salt other than from the highway should be measurable.

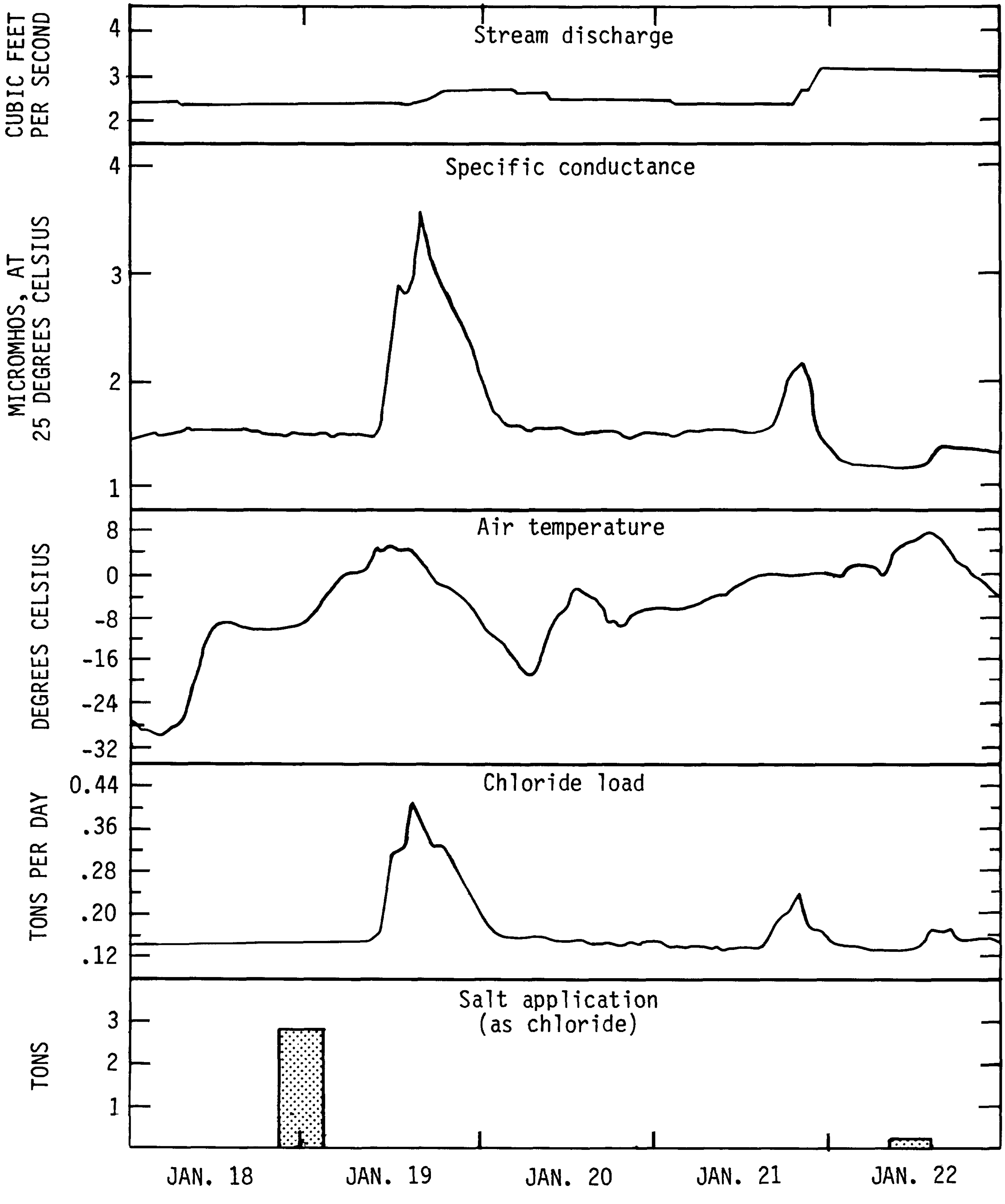


Figure 6.--Selected parameters during January 18-22, 1974, at the monitoring site on Boulder Brook at East Bolton, Massachusetts (downstream from I-495)

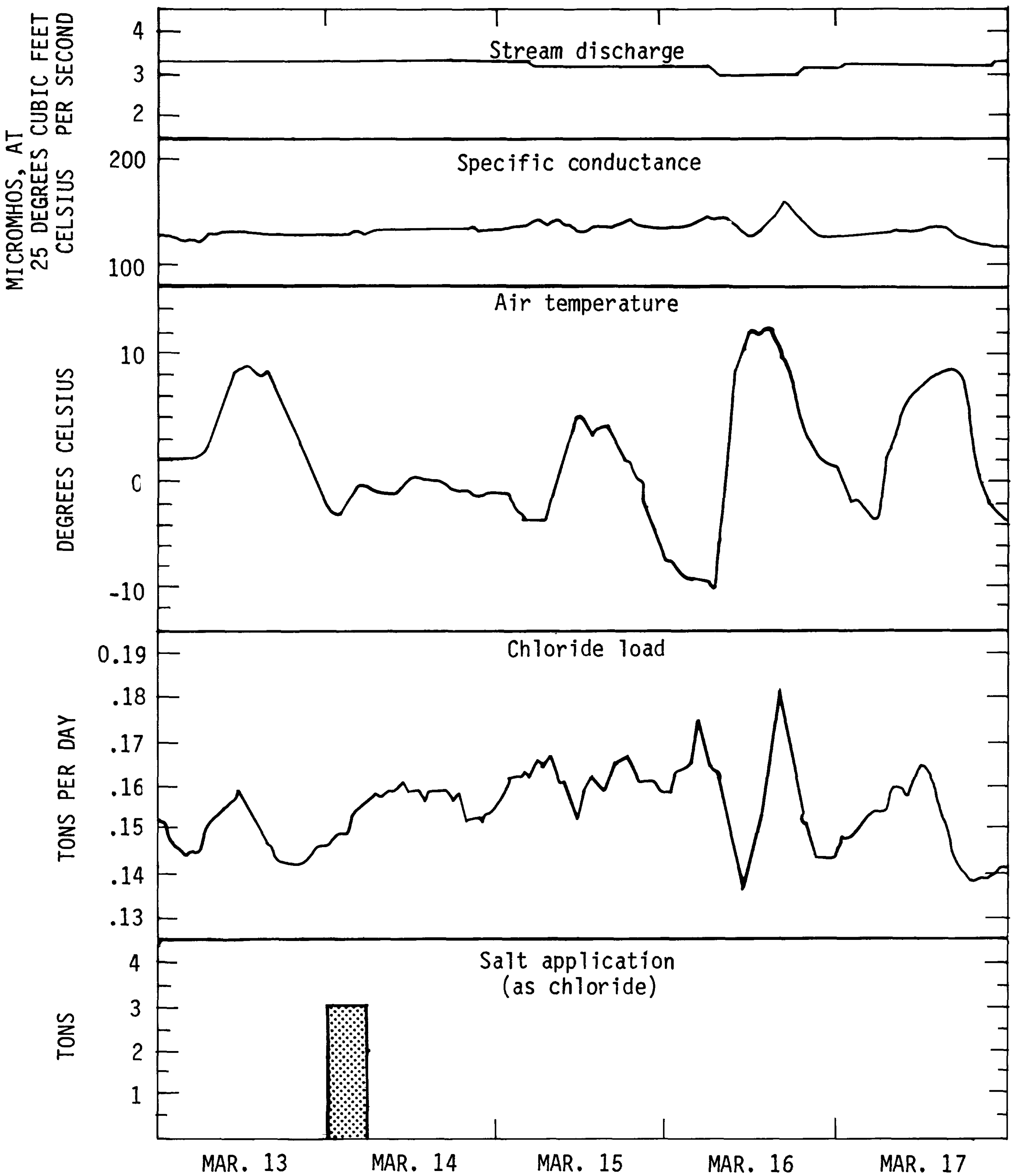


Figure 7.--Selected parameters during March 13-17, 1975, at the monitoring site on Boulder Brook at East Bolton, Massachusetts (downstream from I-495)

Table 4.--Check sheet for documenting acceptability of ground-water-monitoring sites

Site location		Site description																										
		Highway					Geology and hydrology													Well site								
City or town	Highway number	No. lanes	Salt data available	Drainage system		Construction planned	Depth to water table		Direction of hydraulic gradient		Depth to bedrock (approx)	Aquifer saturated thickness	Previous hydrologic data	Till	Swamp	Sand and gravel	Vegetation			Permission to install instruments	Accessible to truck-mounted equipment	Other salt sources in area	Plan for development by owner	Can be instrumented to at least 300 ft. from highway	Underground utilities in area	Site accepted or rejected		No. of wells
				Open	Closed		<30 ft	>30 ft	across highway	parallel to highway							open field	low bush	wood							Accept	Reject	
Chelmsford	3	4	yes	partly	partly	no	X		X		60	40	yes			X	X			X	X	no	no	yes	no	X		41
Bolton	I-495	6	yes	partly	partly	no	X		X		15	10	no		X		X	X		X	poor	no	no	yes	no	X		15
Andover	I-93	6	yes	partly	partly	no	X			X	60	45	yes			X	X			X	X	no	no	yes	no		X	7
Andover	I-93	6	yes		X	safety proj.	X		X		20	12	no	X			X	X		X	poor	no	no	yes	no	X		25
Wayland	30	2	yes	X		no	X		X		60	45	yes			X			X	X	X	no	no	yes	no	X		18
Weston	30	2	yes	X		no	X		X		8	0	no	X			X	X		X	X	no	no	yes	no		X	0
Lincoln	2	4	yes	X		no	X		X	?	10	10	no		X			X	X	X	no	no	no	yes	yes	?	X	0
Concord	2	4	yes	partly	partly	yes	X		?	?	10	?	yes			X	X			X	X	no	no	yes	yes	?	X	0
Acton	2	4	yes	partly	partly	yes	X		?	?	appears shallow		no	X			X			?	yes	no	?	yes	?		X	0
Westford	I-495	6	yes	partly	partly	no	X			X	?	?	no		X			X	X	X	no	no	no	yes	no		X	0
Bedford	62	2	?	X		?	X			X	?	?	no		X			X		?	partially	no	?	yes	?		X	
Andover	114	3	yes	X		no	X		X		?	?	no	X			X			no	yes	no	no	yes	?		X	
Weston	Wellesley St.	2	yes	X		no	X		?	?	5	0	no	X			X	X		?	yes	no	?	yes	?		X	
Concord	2	4	yes	X		yes		X	X		>50	?	yes			X		X	X	?	partially	no	no	yes	yes		X	
Wrentham	I-495	6	yes	partly	partly	no	X			X	?	?	yes		X			X		?	yes	no	?	yes	?		X	
Middleboro	25	4	yes	partly	partly	no	X			X	20	10	yes	X			X		X	?	X	no	?	X	no		X	0
Norfolk	1A	2	yes	X		no	X		?	?	60	50	yes			X	X			yes	yes	yes	no	no	no		X	0
Wenham	128	4	yes	partly	partly	no	X		?	?	?	?	yes		X		X			yes	yes	no	no	no	no		X	0
Duxbury	3	4	yes	X		no	X		?	?	?	?	yes		X			X		yes	partially	no	?	no	?		X	0
Westford	I-495	6	yes	partly	partly	no	X		?	?	?	?	no		X			X		?	no	yes	?	yes	?		X	0
Acton	2	4	yes	X		no	X		X		?	?	no			X	X			?	yes	yes	?	yes	?		X	0
Gardner	2	4	yes	partly	partly	no	X			X	?	?	no		X			X		yes	partially	no	no	yes	no		X	
Northboro	I-290	6	yes	partly	partly	no	X			X	?	?	no		X			X		?	partially	no	?	yes	?		X	
Harvard	2	4	yes	partly	partly	no	X			X	?	?	no	X			X	X		?	partially	no	?	yes	?		X	
Harvard	2	4	yes	partly	partly	no	X			X	?	?	no		X			X		?	partially	no	?	yes	?		X	
Merrimac	I-495	6	yes	partly	partly	no	?	?	?	?	?	?	no	X					X	?	no	no	?	yes	?		X	
Weymouth	3	4	yes	partly	partly	no	X			X	?	?	yes			X	X	X		?	yes	no	?	yes	?		X	
Billerica	3	4	yes	partly	partly	no	X		X		10	0	no	X					X	?	partially	no	no	yes	no		X	
Canton	I-95	6	yes	partly	partly	no	X		X		50	45	no		X				X	yes	no	no	no	yes	no	X		18
Needham	128	6	yes	partly	partly	no	X		X		40	40	no		X			X		yes	no	no	no	yes	no	X		17
West Newbury	113	2	yes	partly	partly	no	X		X		25	15	no	X				X		yes	yes	no	no	yes	no		X	5
West Newbury	113	2	yes	partly	partly	no	X		X		>40	>35	no	X			X			yes	yes	no	no	yes	no	X		20

The seven ground-water-monitoring sites selected are in eastern Massachusetts adjacent to highway systems ranging from two-lane State highways to six-lane, divided, interstate highways. From 15 to 41 wells were installed at ground-water-monitoring sites for measuring water levels and sampling ground-water. All wells were within 1,100 feet of the roadways and ranged in depth from approximately 5 feet to approximately 60 feet.

Geologic information on the unconsolidated deposits at the seven sites was obtained from highway borings and from lithologic logs prepared by the MDPW boring crew during well installation. Geologic information on bedrock was obtained from published reports; only one of the wells installed for this study penetrated bedrock.

Most sampling of ground water was done to measure specific conductance and to determine chloride concentrations. Several samples were also collected to determine concentrations of major dissolved chemical constituents. In addition, a few samples were analyzed for iron, manganese, and zinc.

Annual salt-application rates reported for MDPW repair sections were used to estimate the quantities of salt applied at ground-water-monitoring sites. Efforts were made to obtain more complete salt-application data, including data for town roads, for a site in Bolton, Massachusetts, for calculating a chloride budget.

Occurrence and Transport of Chloride in Ground Water

The occurrence and movement of chloride in ground water resulting from highway deicing chemicals depend on many factors, some of which are listed below:

Form of precipitation
Application of deicing chemicals
Snow removal
Snowmelt
Highway drainage features
Distribution of runoff
Infiltration characteristics of soil
Lithology (unsaturated and saturated zones)
Ground-water flow
Mixing and dispersion
Ground-water discharge, removal, or storage

Precipitation may be rain, freezing rain, or snow during the winter when air temperatures fluctuate above or below freezing for extended periods. The form of precipitation affects the quantity and timing of highway salt application, snowmelt, snow removal by plowing, runoff from highways, and runoff directly over the land surface. Deicing chemicals are applied as early in a storm as possible to prevent bonding between snow or ice and the highway. Precipitation as rain at air temperatures above freezing may require little, if any, salt application. Precipitation as freezing rain or snow requires relatively large amounts of salt and subsequent removal of snow by plowing. The manner in which chloride runs off the highway and the timing and quantity of highway runoff that infiltrates the soil and reaches the ground-water body varies, depending on whether chloride is dissolved in highway runoff from rain or light snow or is incorporated in snow plowed to the sides after heavy snowfalls.

Three basic types of highway drainage systems affect the distribution of highway runoff and infiltration to the soil and ground-water bodies. Closed drainage systems divert a proportion of highway runoff from the segment of highway drained, closed drainage systems with snow berms direct all highway runoff from the site, and open ("country") drainage systems allow all highway runoff to move off the highway, depending only on the topography immediately adjacent to the highway.

On leaving the highway or drainage system, the fate of runoff is influenced by infiltration characteristics of surface materials and the topography near the highway. The rate of infiltration depends on the permeability of soil, antecedent moisture content of soil, and the amount of water available for infiltration. In materials of low permeability, such as silt or clay, or materials already saturated to field capacity, runoff may move directly across the land surface to rills and gulleys and eventually evaporate or enter a stream. In materials of high permeability, such as sand or gravel, runoff may infiltrate the soil adjacent to the highway. Except when evapotranspiration rates are high, as during the growing season, most water infiltrating the soil percolates to the water table. Percolation rates are highly variable in nonhomogeneous materials. Layers of low vertical permeability may cause the percolating water to move laterally and thus broaden the zone through which the water moves to the water table. Upon reaching the water table, the movement of highway runoff is governed by the ground-water-flow system.

Variations in the above conditions may influence both the timing and magnitude of chloride input to the ground-water-flow system.

Correlation and Regression Analyses

Chloride concentration data from the ground-water sites were analyzed statistically to determine the extent to which they were associated with factors that might influence the entry and movement of highway runoff in the ground-water body. Although the assumptions of random sampling and normality of variate distributions may not be satisfied by the available data, correlation and regression techniques were employed to evaluate the usefulness of simple straightforward analytical methods.

The list of variables, names, and descriptions shown in table 5 includes those used either directly in correlation and regression analyses or indirectly to compute values of other variables used in correlation and regression analyses.

Table 5.--Names and descriptions of variables used in analyses of data from ground-water-monitoring sites

Variable name	Description
CHLORIDE	Annual mean chloride concentration for individual wells (mg/L).
MAXCHLOR	Annual maximum chloride concentration for individual wells (mg/L).
SALTAPPL	Salt application, in tons of sodium chloride per road mile (one side of divided highway).
DECMRPPT	Precipitation, in inches, during the December through March period for each site.
PRECIP	Annual precipitation, in inches, for each site.
DELPPT	Difference between DECMRPPT and PRECIP.
DISTANCE	Horizontal distance of a well from the edge of pavement (ft).
DEPTHBLS	Vertical distance of between the land surface and the bottom of the screened intervals in the well (ft).
ALTLAND	Altitude of land surface.
AVWTRLVL	Altitude of annual mean water level.
SCREENAT	Altitude of the bottom of the well screen.
SCRNBLWL	Vertical distance between the mean water level altitude and the bottom of the well screen (ft).
ANNLSALT	Annual salt application (SALTAPPL) divided by precipitation (PRECIP).

The site-by-site analyses in the following sections are done in two steps: First, correlation tables are obtained so that the significant independent variables (factors that influence chloride concentrations) can be identified. Second, multiple, least-squares linear regression analyses are performed on data for each site to develop equations for estimating chloride concentrations.

The initial correlation analyses for several sites were performed using all wells within 100 feet of the roadway at each site. Generally, the analyses indicated little correlation between chloride concentration and any of the selected independent variables. However, scatter diagrams show that chloride concentrations in the upper part of the saturated zone differ from concentrations in lower parts. Relationships between CHLORIDE and DISTANCE and DEPTHBLS at the Andover site show improvement in the comparison of observed and estimated values of chloride concentration when the width of the roadway (both sides of divided highway plus median strip) is added to DISTANCE for the deep wells. The improvement in chloride concentration estimates, together with hydraulic head distribution in wells near the highway, indicate that chloride entering ground-water bodies from highway runoff on the side of the roadway nearest the wells moves downgradient away from the roadway before it reaches the water in the deeper part of the aquifer. Chloride entering the ground on the upgradient side of the highway (side farthest from the wells) travels beneath the roadway, and some of it, at least, reaches the deeper part of the aquifer. Ground-water-flow systems, generalized from lithology and hydraulic head distributions, indicate that chloride inputs from the side of the roadway nearest the wells generally do not affect the deeper wells close to the roadway. Therefore, in this report, correlation and regression analyses are made only for wells in the upper part of the saturated ground-water zone (generally 15 feet or less below the mean water level). In addition, because the velocity of transport is assumed to be slow, although not accurately known, values of CHLORIDE and SALTAPPL from the same years are paired and data used from only those wells with DISTANCE less than 100 feet. Tables of correlation coefficients (tables 6 and 7) list two numbers for each pair of variables. The upper number is the linear correlation coefficient, and the lower number is the probability of obtaining that correlation coefficient from a population in which the two variables have zero correlation, given the number of observations (N) shown at the top of the table. Statistical significance is attributed to correlation coefficients whose values have equal to or less than a 10 percent chance of occurrence when no true correlation exists (significance at the 90 percent confidence level).

Andover monitoring site

Table 6 shows the correlation coefficients obtained between pairs of variables for the data set that includes data from both deep and shallow wells. The only variables that are both hydrologically and statistically significant with respect to CHLORIDE are DEPTHBLS (r = -0.62) and SCRNBLWL (r = -0.44). DEPTHBLS and SCRNBLWL are themselves highly correlated because well depth selection was made relative to two layers of glacial till at this site, and the contact between layers approximately parallels the land surface. Therefore, only SALTAPPL, DISTANCE, and SCRNBLWL are included as independent variables in the regression analysis for this site. SALTAPPL, although showing little correlation with CHLORIDE, is the variable of most concern and thus is included in regression analysis.

The result of the multiple-regression analyses of CHLORIDE, SALTAPPL, DISTANCE, and SCRNBLWL using data for both deep and shallow wells is shown in figure 8 both as the regression equation and as a scatter diagram of estimated chloride concentrations versus observed concentrations (CHLORIDE). The line representing perfect correction (CHLORIDE versus CHLORIDE) is included in the figure to provide reference from which to evaluate the estimating equation.

Table 7 and figure 9 show correlations and results of regression analyses, respectively, for the shallow wells only. These, when compared to table 6 and figure 8, respectively, demonstrate the more intense correlation and improved estimation that result from removing the deep wells from the analysis. By removing the deeper wells from the analysis, the standard error of estimate was reduced from 140 mg/L to 46 mg/L.

Table 6.--Correlation table for a data set which includes data from both deep and shallow wells at the Andover, Massachusetts, ground-water-monitoring site

CORRELATION COEFFICIENTS / PROB > |R| UNDER H0:RHO=0 / N = 44

	CHLORIDE	MAXCHLOR	SALTAPPL	DECMRPPT	PRECIP	DISTANCE	DEPTHBLS	ALTLAND	AVWTRLVL	SCREENAT	SCRNBLWL
CHLORIDE	1.00000	0.92498	-0.00467	0.05966	0.03844	-0.05685	-0.62100	0.46270	0.64325	0.66763	-0.44186
	0.0000	0.0001	0.9760	0.7005	0.8043	0.7140	0.0001	0.0016	0.0001	0.0001	0.0027
MAXCHLOR	0.92498	1.00000	-0.04274	0.11706	0.07504	-0.07006	-0.73773	0.46464	0.60722	0.76663	-0.56407
	0.0001	0.0000	0.7829	0.4492	0.6283	0.6513	0.0001	0.0015	0.0001	0.0001	0.0001
SALTAPPL	-0.00467	-0.04274	1.00000	-0.18633	-0.80304	0.00000	0.00000	-0.00000	0.00277	-0.00000	0.00119
	0.9760	0.7829	0.0000	0.2259	0.0001	1.0000	1.0000	1.0000	0.9858	1.0000	0.9939
DECMRPPT	0.05966	0.11706	-0.18633	1.00000	0.50492	0.00000	0.00000	0.00000	0.02027	0.00000	0.00874
	0.7005	0.4492	0.2259	0.0000	0.0005	1.0000	1.0000	1.0000	0.8961	1.0000	0.9551
PRECIP	0.03844	0.07504	-0.80304	0.50492	1.00000	-0.00000	0.00000	0.00000	0.04432	-0.00000	0.01912
	0.8043	0.6283	0.0001	0.0005	0.0000	1.0000	1.0000	1.0000	0.7751	1.0000	0.9020
DISTANCE	-0.05685	-0.07006	0.00000	0.00000	-0.00000	1.00000	0.04973	-0.77694	-0.21313	-0.19756	0.12092
	0.7140	0.6513	1.0000	1.0000	1.0000	0.0000	0.7485	0.0001	0.1648	0.1986	0.4343
DEPTHBLS	-0.62100	-0.73773	0.00000	0.00000	0.00000	0.04973	1.00000	-0.30890	-0.28280	-0.98039	0.93436
	0.0001	0.0001	1.0000	1.0000	1.0000	0.7485	0.0000	0.0413	0.0629	0.0001	0.0001
ALTLAND	0.46270	0.46464	-0.00000	0.00000	0.00000	-0.77694	-0.30890	1.00000	0.73806	0.45565	-0.17254
	0.0016	0.0015	1.0000	1.0000	1.0000	0.0001	0.0413	0.0000	0.0001	0.0019	0.2627
AVWTRLVL	0.64325	0.60722	0.00277	0.02027	0.04432	-0.21313	-0.28280	0.73806	1.00000	0.37338	0.02911
	0.0001	0.0001	0.9858	0.8961	0.7751	0.1648	0.0629	0.0001	0.0000	0.0125	0.8512
SCREENAT	0.66763	0.76663	-0.00000	0.00000	-0.00000	-0.19756	-0.98039	0.45565	0.37338	1.00000	-0.91641
	0.0001	0.0001	1.0000	1.0000	1.0000	0.1986	0.0001	0.0019	0.0125	0.0000	0.0001
SCRNBLWL	-0.44186	-0.56407	0.00119	0.00874	0.01912	0.12092	0.93436	-0.17254	0.02911	-0.91641	1.00000
	0.0027	0.0001	0.9939	0.9551	0.9020	0.4343	0.0001	0.2627	0.8512	0.0001	0.0000

Table 7.--Correlation table for a data set for shallow wells (less than 17 feet deep) less than 100 feet from the roadway at the Andover, Massachusetts, ground-water-monitoring site

CORRELATION COEFFICIENTS / PROB > |R| UNDER H0:RHO=0 / N = 15

	CHLORIDE	MAXCHLOR	SALTAPPL	DECMRPPT	PRECIP	DISTANCE	DEPTHBLS	ALTLAND	AVWTRLVL	SCREENAT	SCRNBLWL
CHLORIDE	1.00000	0.44077	-0.13890	0.48166	0.31698	0.25619	0.70362	-0.34547	-0.16817	-0.77955	0.74004
	0.0000	0.1001	0.6215	0.0691	0.2497	0.3567	0.0034	0.2072	0.5491	0.0006	0.0016
MAXCHLOR	0.44077	1.00000	-0.03764	0.47041	0.28897	0.22956	-0.01757	-0.22451	-0.07480	-0.04054	0.02423
	0.1001	0.0000	0.8941	0.0768	0.2962	0.4105	0.9504	0.4211	0.7911	0.8859	0.9317
SALTAPPL	-0.13890	-0.03764	1.00000	-0.08672	-0.78408	-0.07857	-0.07595	0.07775	0.02770	0.09456	-0.08819
	0.6215	0.8941	0.0000	0.7586	0.0005	0.7807	0.7879	0.7830	0.9219	0.7375	0.7546
DECMRPPT	0.48166	0.47041	-0.08672	1.00000	0.43501	0.11280	0.10903	-0.11161	-0.01058	-0.13574	0.13290
	0.0691	0.0768	0.7586	0.0000	0.1051	0.6890	0.6989	0.6921	0.9701	0.6295	0.6368
PRECIP	0.31698	0.28897	-0.78408	0.43501	1.00000	0.09125	0.08820	-0.09029	0.12858	-0.10981	0.13712
	0.2497	0.2962	0.0005	0.1051	0.0000	0.7464	0.7546	0.7490	0.6479	0.6968	0.6260
DISTANCE	0.25619	0.22956	-0.07857	0.11280	0.09125	1.00000	-0.15940	-0.98945	-0.93996	-0.09824	-0.10508
	0.3567	0.4105	0.7807	0.6890	0.7464	0.0000	0.5704	0.0001	0.0001	0.7276	0.7094
DEPTHBLS	0.70362	-0.01757	-0.07595	0.10903	0.08820	-0.15940	1.00000	0.05868	0.15534	-0.96642	0.99599
	0.0034	0.9504	0.7879	0.6989	0.7546	0.5704	0.0000	0.8354	0.5804	0.0001	0.0001
ALTLAND	-0.34547	-0.22451	0.07775	-0.11161	-0.09029	-0.98945	0.05868	1.00000	0.93939	0.19980	0.00381
	0.2072	0.4211	0.7830	0.6921	0.7490	0.0001	0.8354	0.0000	0.0001	0.4753	0.9893
AVWTRLVL	-0.16817	-0.07480	0.02770	-0.01058	0.12858	-0.93996	0.15534	0.93939	1.00000	0.08933	0.12691
	0.5491	0.7911	0.9219	0.9701	0.6479	0.0001	0.5804	0.0001	0.0000	0.7515	0.6522
SCREENAT	-0.77955	-0.04054	0.09456	-0.13574	-0.10981	-0.09824	-0.96642	0.19980	0.08933	1.00000	-0.97661
	0.0006	0.8859	0.7375	0.6295	0.6968	0.7276	0.0001	0.4753	0.7515	0.0000	0.0001
SCRNBLWL	0.74004	0.02423	-0.08819	0.13290	0.13712	-0.10508	0.99599	0.00381	0.12691	-0.97661	1.00000
	0.0016	0.9317	0.7546	0.6368	0.6260	0.7094	0.0001	0.9893	0.6522	0.0001	0.0000

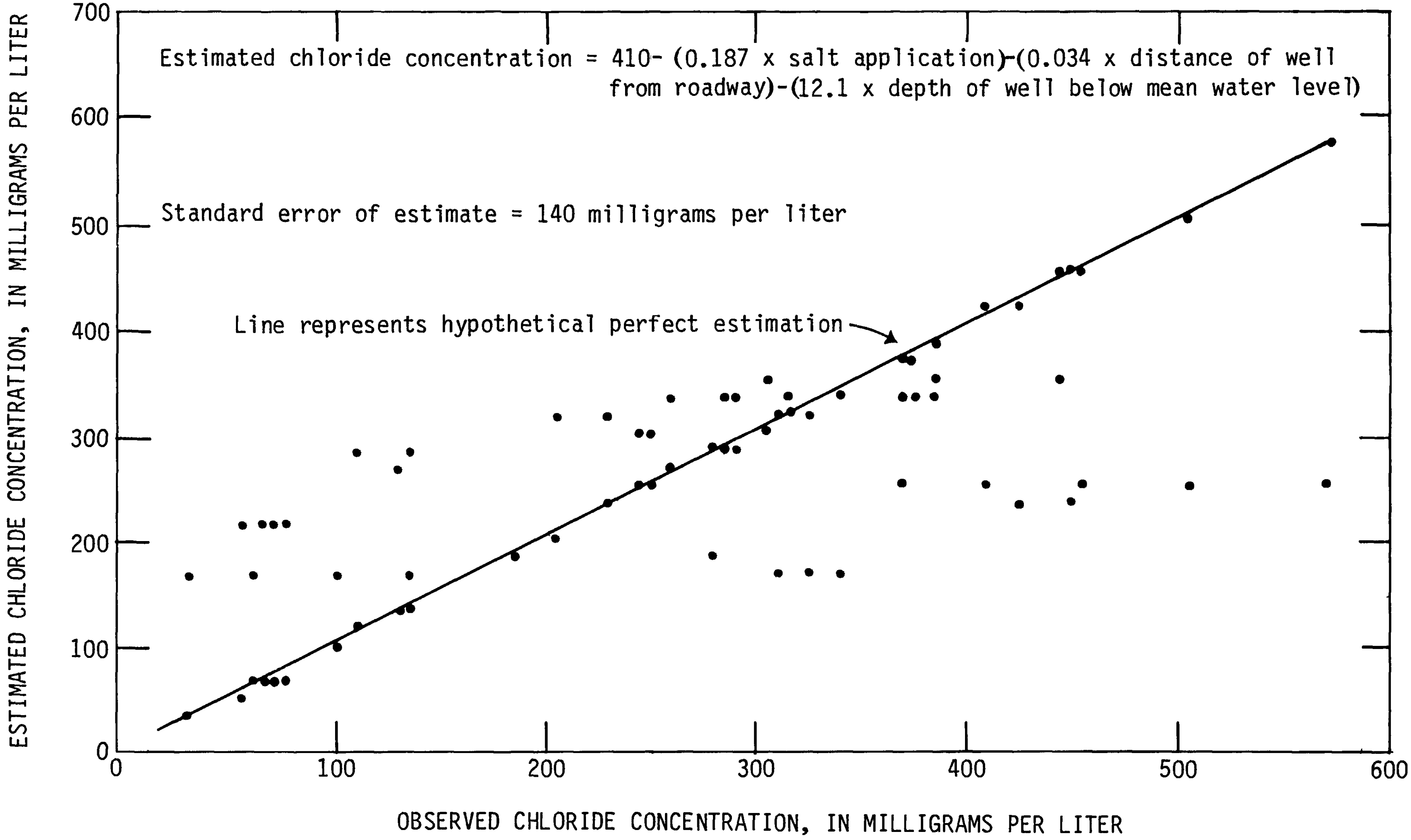


Figure 8.--Scatter diagram of estimated annual mean chloride concentration versus observed annual mean chloride concentration for wells less than 100 feet from the edge of the roadway at the Andover, Massachusetts, ground-water-monitoring site

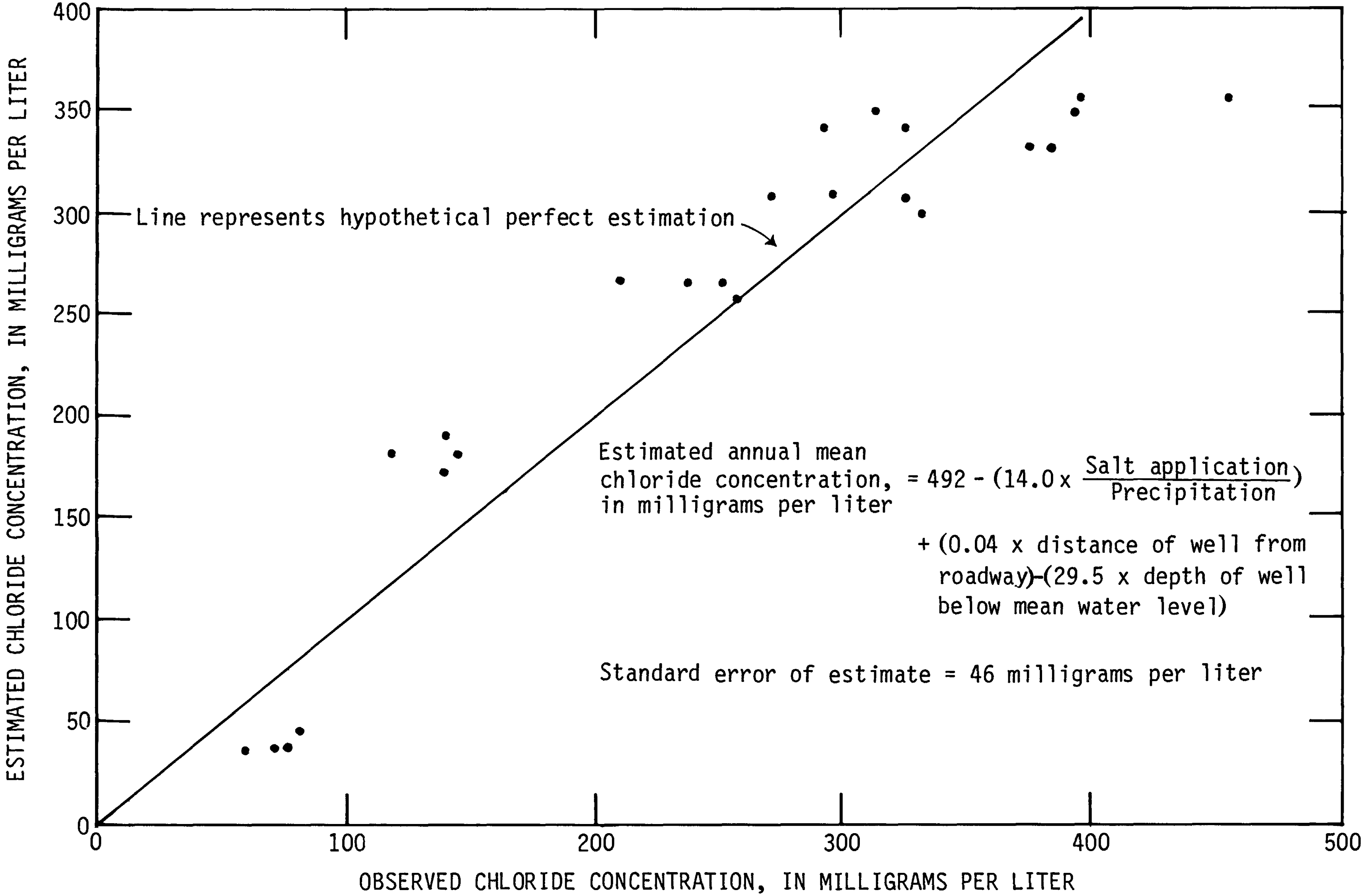


Figure 9.--Scatter diagram of estimated annual mean chloride concentration versus observed annual mean chloride concentration for shallow wells (less than 17 feet deep) less than 100 feet from the edge of the roadway at the Andover, Massachusetts, ground-water-monitoring site

Removing the deep wells from the analysis improved most of the correlation coefficients; however, some became illogical, such as the inverse relationship shown by the negative correlation coefficient for CHLORIDE and SALTAPPL. In both cases, this coefficient indicates no significant statistical correlation. The correlation coefficient for CHLORIDE and DISTANCE indicates that within 100 feet of the highway at this site, chloride concentrations increase with distance. This discredits an original assumption that all or most of the deicing salt enters the ground at the edge of the highway, but it is explained by the presence of gullies in the graded roadfill bank that carry some highway runoff beyond the wells nearest the roadway before infiltration occurs.

Wayland monitoring site

Correlation coefficients were significant at the 90 percent level for DISTANCE and CHLORIDE (r = -0.32) and for SCRNBLWL and CHLORIDE (r = -0.58) for shallow wells near the roadway at the Wayland ground-water-monitoring site. The correlation coefficients for both DISTANCE and SCRNBLWL with CHLORIDE are negative, indicating that greater values of each correlated with lower values of CHLORIDE. The correlation coefficient for CHLORIDE and SALTAPPL (r = -0.13) is not statistically significant and is inverse, as it is at the Andover site.

Chelmsford monitoring site

The correlation between CHLORIDE and SALTAPPL (r = 0.36) for the Chelmsford site, is logically correct and statistically significant. The correlation coefficient between CHLORIDE and DISTANCE (r = 0.27) is not significant and is positive. The positive CHLORIDE-DISTANCE correlation coefficient probably results from transport of overland runoff from the highway through a gully eroded to a distance greater than 100 feet from the edge of the roadway.

Land surface near the edge of the roadway is sandy and lacks a developed soil. These conditions ordinarily allow rapid infiltration of runoff, but in this instance runoff from the highway surface exceeds that which can infiltrate the ground nearby. Possibly, the permeability of the surficial materials has been decreased by accumulation of dust and other particulate matter from the roadway surface and vehicle exhaust emissions. The correlation coefficient for SCRNBLWL and CHLORIDE (r = -0.37) is marginally significant.

Needham monitoring site

The Needham site is in swamp deposits and differs from other sites in that a peat ridge acts as a barrier to overland flow of highway runoff and causes chloride to enter the ground near the highway. Wells distant from the highway are, therefore, farther from the source of chloride than at the Andover and Chelmsford sites, where infiltration is more dispersed. In addition, a layer of sand and gravel at a depth of approximately 10 feet may serve as a conduit for water that infiltrates the ground on the upgradient side of the highway and (or) in the median strip. Movement of water through this sand and gravel layer may cause concentrations of chloride in wells of intermediate depth to be more variable than if the materials were homogeneous.

The correlation coefficient for CHLORIDE and SCRNBLWL (r = -0.24) is lower at this site than at others, possibly due to the influence of the sand and gravel layer. The variable most highly correlated with CHLORIDE is DISTANCE (r = -0.91).

The absence of a significant correlation between CHLORIDE and SALTAPPL (r = -0.08) may be due to the presence of the sand and gravel layer because it provides a means by which highway runoff on both sides of the roadway can affect the wells of shallow and intermediate depth. The presence of the sand and gravel layer may allow salt, applied for more than 1 year, to affect CHLORIDE for the shallow and deep wells.

Canton Monitoring Site

The Canton site is characterized by a naturally very flat land surface. Correlation coefficients involving ALTLAND are zero because ALTLAND is nearly the same for all wells. At this site, water is often ponded at the land surface between wells 15 and 30 feet from the edge of the highway. A component of flow between the roadway and the nearest wells is downward, but owing to a silt layer that underlies surficial peat and sand, flow is mostly lateral in the rest of the site. This flow system results in a significant correlation coefficient for CHLORIDE and SCRNBLWL (r = 0.91). However, the correlation coefficient is positive, indicating that chloride concentrations increase with depth. Water entering the ground near the edge of the highway moves downward through a permeable sand layer and then laterally just above the less permeable silt, resulting in higher concentrations just above the silt than at shallower depths. Near the surface, lower concentrations probably result from recharge by precipitation.

The correlation between CHLORIDE and DISTANCE (r = 0.08) is probably affected by the combination of low concentrations in both near and far shallow wells. Water in shallow wells in the path of recharge moving into the sand layer has lower chloride concentrations than that which would result from lateral transport from the road. Although water in wells very close to the roadway generally has higher chloride concentrations, the correlation between CHLORIDE and DISTANCE is lessened by the wide range of chloride concentrations in more distant wells. The fact that the water in shallow wells at all distances is lower in concentration than that in deeper wells also lessens the correlation of CHLORIDE with DISTANCE.

The correlation between CHLORIDE and SALTAPPL (r = 0.12) is not significant. Flow is sufficiently slow at this site to make it very probable that chloride measured for a particular year was the result of salt application in other than the previous winter.

Bolton Monitoring site

Most wells at the Bolton site were installed along the edge of the roadway rather than at right angles to the roadway. The wells are spaced over a distance of 800 feet along the roadway and roadside conditions vary more than at other sites. Some wells are near a highway drainage outlet, and some wells are in a ditch along the base of the highway roadfill bank. Correlation coefficients indicate that, of the variables that might logically be correlated with CHLORIDE, only SCRNBLWL (r = 0.59) shows a statistically significant correlation. The positive correlation coefficient indicates a direct relationship, which probably results from high concentrations of chloride in water from deep wells in the median. The head distribution indicates flow from the vicinity of the median probably influences chloride concentrations in the deeper wells downgradient from the highway.

West Newbury Monitoring Site

The West Newbury site is underlain by till and has a much greater land surface slope than the other sites. Overland runoff and discharge from the highway drainage system are carried more than 300 feet beyond the edge of the highway. In addition, a ditch near the base of the roadfill bank probably serves to collect some runoff from the highway near the edge of the pavement. Accordingly, correlation coefficients indicate that only DEPTHBLS (r = 0.31) and SCRNBLWL (r = 0.59) are significantly correlated with CHLORIDE and that SALTAPPL (r = 0.16) is not significantly correlated with CHLORIDE.

Observation wells were installed at the West Newbury site in 1974, and less data were available than at other sites.

Aggregate of all ground-water-monitoring sites

In addition to site-by-site statistical analyses of factors that influence the occurrence and movement of highway deicing salt in ground water, statistical analyses were made using the aggregate of ground-water data collected at all seven sites (table 8).

Regression analyses for the aggregated data provide poor relationships for estimating chloride concentrations, as indicated by the scatter of data points in figure 10. The lack of correlation between CHLORIDE and the factors that logically should influence its occurrence in ground water results in a nearly horizontal alinement of estimated versus observed values of chloride concentration at approximately the mean value of observed chloride concentration (195 mg/L). For the lower values of observed chloride in figure 10, many estimated values exceed observed values by 200 percent; for the higher values of observed chloride, estimated values are 50 percent lower than observed values in many cases.

The poor estimating relations shown in figure 10 reflect the correlation coefficients shown in table 8. These indicate that DEPTHBLS is a statistically significant variable if the sites are grouped. SCRNBLWL is also significant, as it was for individual site analyses. Although ANNLSALT was not a significant variable in the individual analyses, it does become significant if the sites are grouped. DISTANCE, however, is not significant, nor was it significant in most of the individual site analyses, indicating that, in general, the location and types of highway drainage systems and topography in the immediate vicinity of highways are probably more important factors than distance in influencing the entry and subsequent movement of highway runoff in ground water.

Summary of regression analyses of ground-water data

Regression equations for estimating chloride concentrations in ground water at seven sites were obtained by correlation techniques to identify the significant variables (factors) that influence the entry and movement of highway runoff in ground-water bodies and then using the significant variables in multiple-regression analyses. Correlations among the potential factors that influence entry and movement of chloride in ground-water bodies show that the significant variables include SCRNBLWL (all seven sites), DEPTHBLS (four sites), DISTANCE (two sites), and SALTAPPL (one site; table 9).

Note that the correlation between CHLORIDE (annual mean chloride concentrations) and ANNLSALT (the annual salt application divided by the corresponding annual precipitation) was poor. The correlation varies from site to site, probably due to differences in distribution of highway runoff, in geology, in location of the screens of selected wells in the ground-water-flow system, or differences in infiltration characteristics of the roadside soil. Also, poor quality control for the salt-application data and inconsistency of analytical procedures for chloride concentrations from the beginning to the end of the study may contribute to the poor correlation.

Transport of Chloride in Ground Water

Transport (movement and mixing) of chloride in ground water is governed by displacement of ground water, convective dispersion (mixing caused by complex ground-water flow paths) and diffusion (movement caused by molecular movement due to concentration gradients). Transport of chloride through molecular diffusion is significant only in very slowly moving or stagnant ground water. Chloride in moving ground water is mixed largely by convective dispersion. Convective dispersion, due to the torturous flow paths and mixing due to various flow rates in layered materials, result in generally lower chloride concentrations as the distance from the source increases. Great variation in chloride concentrations may be observed in a vertical column of ground water due to direction of flow and different rates of flow in layers of materials of different permeabilities.

Table 8.--Correlation table for a data set representing the aggregate of data sets used for the individual sites in tables 7-13

CORRELATION COEFFICIENTS / PROB > |R| UNDER H0:RHO=0 / N = 134

	CHLORIDE	MAXCHLOR	SALTAPPL	DECMRPPT	PRECIP	DISTANCE	DEPTHBLS	ALTLAND	AVWTRLVL	SCREENAT	SCRNBLWL	DELPPT	ANNLSALT
CHLORIDE	1.00000 0.0000	0.89226 0.0001	0.19756 0.0221	0.11293 0.1939	-0.02201 0.8007	0.09018 0.3001	-0.47419 0.0001	0.04728 0.5875	0.08860 0.3087	0.10913 0.2094	-0.43951 0.0001	-0.07347 0.3989	0.20022 0.0204
MAXCHLOR	0.89226 0.0001	1.00000 0.0000	0.13840 0.1108	0.09294 0.2855	-0.05051 0.5622	0.05852 0.5018	-0.40817 0.0001	0.01176 0.8927	0.04489 0.6065	0.06403 0.4623	-0.41488 0.0001	-0.09857 0.2572	0.15023 0.0832
SALTAPPL	0.19756 0.0221	0.13840 0.1108	1.00000 0.0000	-0.31958 0.0002	-0.14159 0.1027	0.20857 0.0156	-0.29068 0.0007	-0.12605 0.1467	-0.09995 0.2505	-0.09042 0.2988	-0.22364 0.0094	-0.03192 0.7142	0.97656 0.0001
DECMRPPT	0.11293 0.1939	0.09294 0.2855	-0.31958 0.0002	1.00000 0.0000	0.56635 0.0001	0.09004 0.3009	-0.11302 0.1935	0.52708 0.0001	0.54748 0.0001	0.54902 0.0001	0.04276 0.6237	0.24494 0.0043	-0.36348 0.0001
PRECIP	-0.02201 0.8007	-0.05051 0.5622	-0.14159 0.1027	0.56635 0.0001	1.00000 0.0000	-0.06645 0.4456	0.12541 0.1488	0.49227 0.0001	0.48341 0.0001	0.48269 0.0001	0.08358 0.3370	0.93778 0.0001	-0.30750 0.0003
DISTANCE	0.09018 0.3001	0.05852 0.5018	0.20857 0.0156	0.09004 0.3009	-0.06645 0.4456	1.00000 0.0000	-0.58248 0.0001	-0.04075 0.6401	0.02395 0.7836	0.03512 0.6870	-0.24255 0.0047	-0.11610 0.1816	0.23272 0.0068
DEPTHBLS	-0.47419 0.0001	-0.40817 0.0001	-0.29068 0.0007	-0.11302 0.1935	0.12541 0.1488	-0.58248 0.0001	1.00000 0.0000	0.17098 0.0482	0.07193 0.4088	0.04491 0.6064	0.60471 0.0001	0.19515 0.0238	-0.33366 0.0001
ALTLAND	0.04728 0.5875	0.01176 0.8927	-0.12605 0.1467	0.52708 0.0001	0.49227 0.0001	-0.04075 0.6401	0.17098 0.0482	1.00000 0.0000	0.99435 0.0001	0.99193 0.0001	0.19259 0.0258	0.35703 0.0001	-0.22882 0.0078
AVWTRLVL	0.08860 0.3087	0.04489 0.6065	-0.09995 0.2505	0.54748 0.0001	0.48341 0.0001	0.02395 0.7836	0.07193 0.4088	0.99435 0.0001	1.00000 0.0000	0.99899 0.0001	0.16227 0.0610	0.33802 0.0001	-0.19886 0.0213
SCREENAT	0.10913 0.2094	0.06403 0.4623	-0.09042 0.2988	0.54902 0.0001	0.48269 0.0001	0.03512 0.6870	0.04491 0.6064	0.99193 0.0001	0.99899 0.0001	1.00000 0.0000	0.11785 0.1750	0.33652 0.0001	-0.18899 0.0287
SCRNBLWL	-0.43951 0.0001	-0.41488 0.0001	-0.22364 0.0094	0.04276 0.6237	0.08358 0.3370	-0.24255 0.0047	0.60471 0.0001	0.19259 0.0258	0.16227 0.0610	0.11785 0.1750	1.00000 0.0000	0.08030 0.3563	-0.24521 0.0043
DELPPT	-0.07347 0.3989	-0.09857 0.2572	-0.03192 0.7142	0.24494 0.0043	0.93778 0.0001	-0.11610 0.1816	0.19515 0.0238	0.35703 0.0001	0.33802 0.0001	0.33652 0.0001	0.08030 0.3563	1.00000 0.0000	-0.20860 0.0156
ANNLSALT	0.20022 0.0204	0.15023 0.0832	0.97656 0.0001	-0.36348 0.0001	-0.30750 0.0003	0.23272 0.0068	-0.33366 0.0001	-0.22882 0.0078	-0.19886 0.0213	-0.18899 0.0287	-0.24521 0.0043	-0.20860 0.0156	1.00000 0.0000

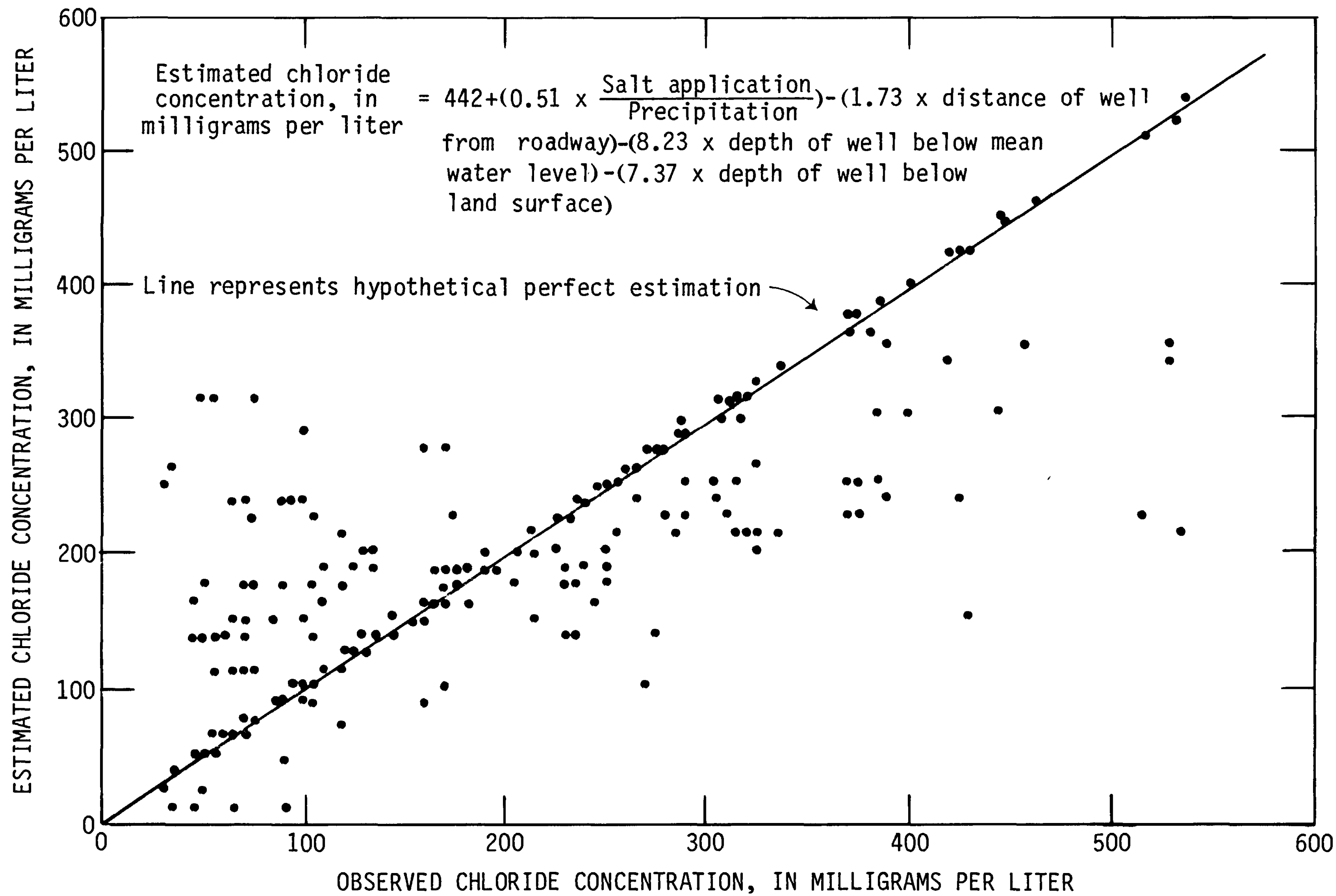


Figure 10.--Scatter diagram of estimated annual mean chloride concentration versus observed annual mean chloride concentration for wells less than 16 feet below the mean water level and less than 100 feet from the roadway at seven ground-water-monitoring sites in Massachusetts

Table 9.--Variables found to be significantly correlated (at the 90 percent confidence level) with chloride concentrations in ground water

(Monitoring sites: A = All sites; B = Andover; C = Wayland; D = Chelmsford; E = Needham; F = Canton; G = Bolton; H = West Newbury.)

Variable name	Monitoring site(s)[1]								Description of variable
	A	B	C	D	E	F	G	H	
SALTAPPL	M			X					Salt application, in tons of sodium chloride per road mile (one side of divided highway).
DECMRPPT									Precipitation, in inches, during the December through March period for each site.
PRECIP									Annual precipitation, in inches, for each site.
DELPPT									Difference between DECMRPPT and PRECIP.
DISTANCE		M			X				Horizontal distance of a well from the edge of pavement.
DEPTHBLS	X	X			X	X		X	Vertical distance of between the land surface and the bottom of the screened intervals in the well.
ALTLAND		O	O	O	O		O		Altitude of land surface (feet above sea level).
AVWTRLVL		O				O	O		Altitude of annual mean water level (feet above sea level).
SCREENAT		O	O	O		O	O	O	Altitude of the bottom of the well screen (feet above sea level).
SCRNBLWL	X	X	X	X		X	X	X	Vertical distance between the mean water level altitude and the bottom of the well screen.
ANNLSALT	X			M					Annual salt application (SALTAPPL) divided by PRECIP.

[1] M = marginal statistical significance; O = statistically but not hydrologically significant; X = hydrologically and statistically significant.

Data from the Andover ground-water-monitoring site was used to calibrate a two-dimensional solute-transport model (Konikow and Bredehoeft, 1978) in an attempt to better understand the movement of chloride ions from a highway to and throughout the adjacent ground-water system. The model was modified for use in cross section (vertical plane) by interchanging the x and z axes, assigning an aquifer thickness of unity, and allowing recharge only at those nodes representing the land surface. Strata of different permeabilities were identified from well logs. The distribution of recharge was initially chosen to reflect known or assumed site features such as increased recharge adjacent to the paved surfaces and decreased recharge in areas of steep land-surface slope. Most of the values used for permeabilities and recharge rates are estimates made from lithologic and climatic data.

Hydraulic conductivities of till ranging from 1.34 to 13.4 feet per day were selected based on grain size-permeability relationships (Ryder and others, 1970). The assignment of values from this range was based on descriptions of particle sizes in drillers' logs of test holes and observation wells. A material described as "clayey or very compact till" was assigned a value from the lower end of the range, whereas a material described as "sandy or easily penetrated till" was assigned a value near the upper end of the range. A value of 2.0 for anisotropy (the ratio of horizontal permeability to vertical permeability) was assigned, after several preliminary model runs, in an effort to more closely simulate observed water-level data. Effective porosity, a characteristic that directly influences the velocity of ground water and thus the transport of chloride, was assigned a value of 20 percent, which is probably a reasonable estimate based on laboratory analyses of the porosity of till (Baker and others, 1964, p. 25).

Recharge rates were set initially at 9 inches per year based on recharge rates estimated for till by Ryder and others (1970); however, early model runs showed this rate to be too high for the Andover site, and, furthermore, the distribution of recharge was indicated by simulated head distributions to be variable over the site. Accordingly, recharge in the range of 5.7 to 9.1 inches per year was assigned for use in the model. The rate assigned to nodes near the edge (within 35 feet) of the paved surface was 5.7 inches per year, and the rate for nodes beyond 35 feet from the edge of the highway was 9.1 inches per year. In addition to recharge from precipitation, recharge from water in bedrock underlying the till had to be accounted for to duplicate a water-level (head) distribution in the model similar to that observed in the field.

The model was calibrated for steady-state conditions (rate of change of recharge with time and rate of change of chloride concentration with time equals zero), and water levels simulated with the model were compared to mean water levels for the 1975-77 water-year period (fig. 11).

Inputs to and dimensions of the model for the Andover site simulation are shown below:

Number of rows = 40 (y direction, longitudinal)
Number of columns = 6 (x direction, transverse)
Node size (transverse x longitudinal) = 7 feet x 17 feet
Effective porosity = 20 percent
$\frac{\text{Vertical permeability}}{\text{Horizontal permeability}} = 2.0$
Longitudinal dispersivity = 2.0 feet
Ratio of transverse to longitudinal dispersivity = 0.30
Range of horizontal permeabilities = 0.39 to 3.50 feet per day
Recharge rate = 5.7 to 9.1 inches per year
Recharge rate from bedrock = 3.8 inches per year

Concentrations of chloride in recharge from highway runoff were estimated from calculations based on the amount of salt applied and the precipitation on a fixed length of highway. Although all the precipitation was included in the calculations (without consideration of evapotranspiration), calculated chloride concentrations were high (about 2400 mg/L), and, when the calculated values for chloride in highway runoff were used as input to the model, higher than observed concentrations of chloride in ground water resulted.

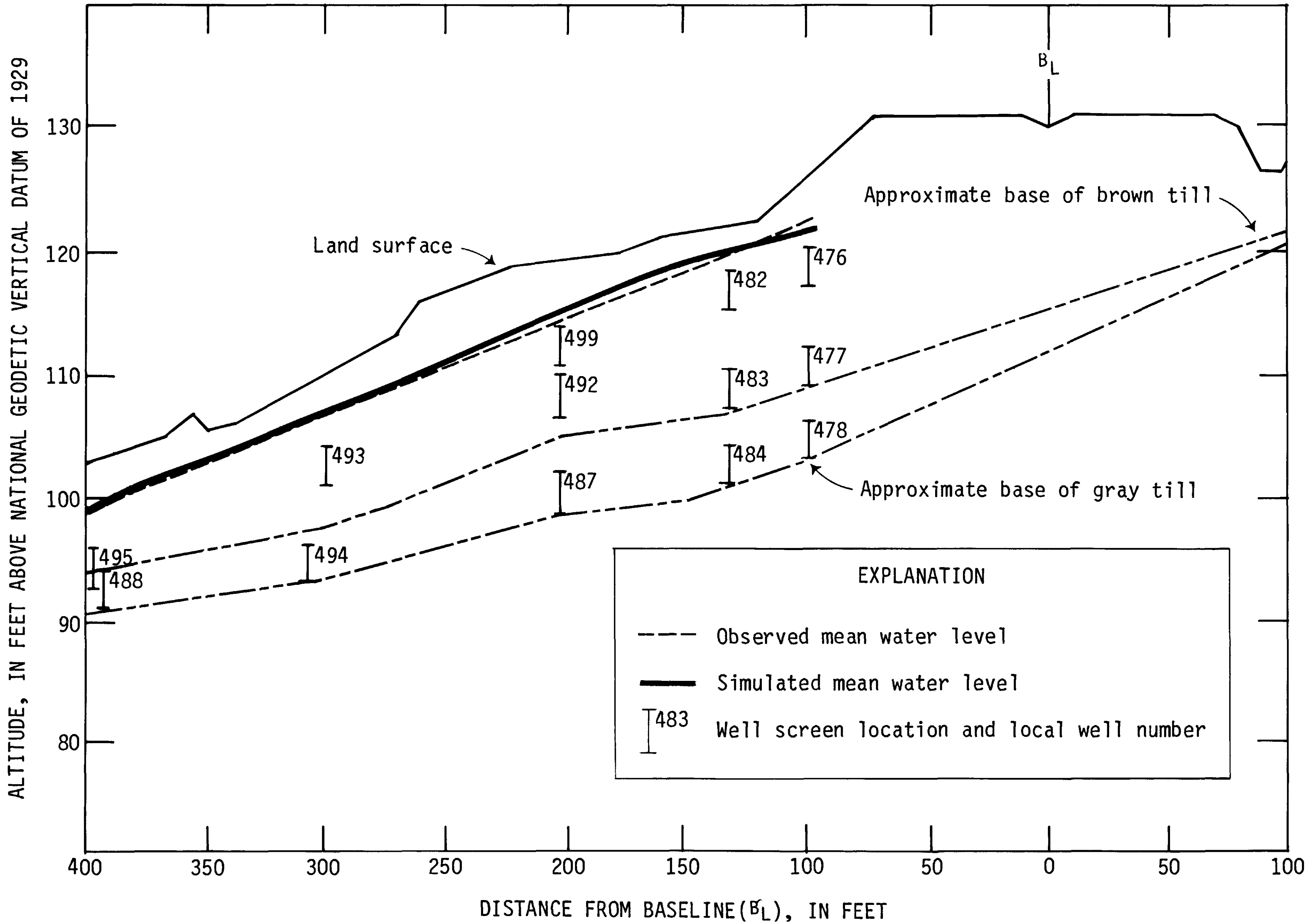


Figure 11.--Simulated and observed locations of the water table in a cross section of the Andover, Massachusetts, ground-water-monitoring site

Based on drillers' logs, an upper and a lower till at this site were distinguished by color. Drillers' logs also indicate that the lower till was more difficult to penetrate with the auger used to install the monitoring wells. Specific data for particle size and distribution are not included in the logs, and permeability variations within each till layer were not assigned. Figure 12, showing the observed chloride distribution, indicates that permeability of the materials constituting the till is highest near the contact between the two tills. The simulated chloride distribution (fig. 13) does not reflect the variations near the contact between the two tills shown in figure 12; however, the general distribution of chloride concentrations near the water table is similar to observed concentrations.

The model was run to simulate a 9-year period, 1969-77, coincident with the record of salt application at this location. The simulation was examined at several selected locations corresponding to observation wells and times to determine if steady-state concentrations were achieved. Figure 14 shows that concentrations simulated by the model at a point 135 feet from the pavement and 9 feet below land surface change very little after about 7 years and that the model is probably simulating near steady-state conditions for this location at the end of the 9-year period.

Chloride concentrations assigned to recharge ranged from 600 mg/L in the median to 5.0 mg/L beyond 170 feet from the downgradient edge of pavement and resulted in reasonably favorable comparisons between simulated and observed chloride concentrations in ground water. The best agreement between observed and simulated concentrations was obtained by assigning recharge concentrations as follows:

Median strip	=	600 mg/L
0 to 34 feet from pavement	=	300 mg/L
35 to 85 feet from pavement	=	400 mg/L
86 to 170 feet from pavement	=	100 mg/L
170 feet and beyond	=	5 mg/L

The concentration assigned to discharge from bedrock was 10 mg/L.

Although the values of the parameters used as input to the model were estimated, as discussed above, calibration of the model indicated that recharge from highway runoff was greatly different in areal distribution from the assumption (made during the planning stages of this study) that most of the recharge from highway runoff entered the ground-water system within 15 feet of the edge of the pavement. The model inputs required to obtain reasonable comparisons between observed and simulated chloride concentrations in ground water indicate that recharge is of highly variable concentration throughout the site. Roadside topography, plowing techniques, and splash and spray are probable causes of the variations. In addition, the highway drainage system at this site carries highway runoff to a small, unnamed brook, and possibly much of the highway runoff enters the brook directly rather than the ground-water system.

Trends of Chloride Concentrations in Ground Water

Chloride hydrographs of four wells were selected at each of the ground-water sites (figs. 15-21) to illustrate trends in concentrations of chloride in ground water and to demonstrate the importance of well location in analysis of concentration data. Wells were selected to show concentrations upgradient from the roadway, at intermediate distances between the downgradient edge of the highway and the well farthest downgradient from the highway, and at the well farthest downgradient from the highway.

The time period shown in the graphs is short, with respect to length of time sodium chloride has been used as a deicing chemical. General reductions occurred in the amount of sodium chloride used after the 1971-72 winter season except at Wayland and West Newbury. The general decrease in salt application after 1972 is evident in the chloride graph for well Chelmsford 397 (fig. 15).

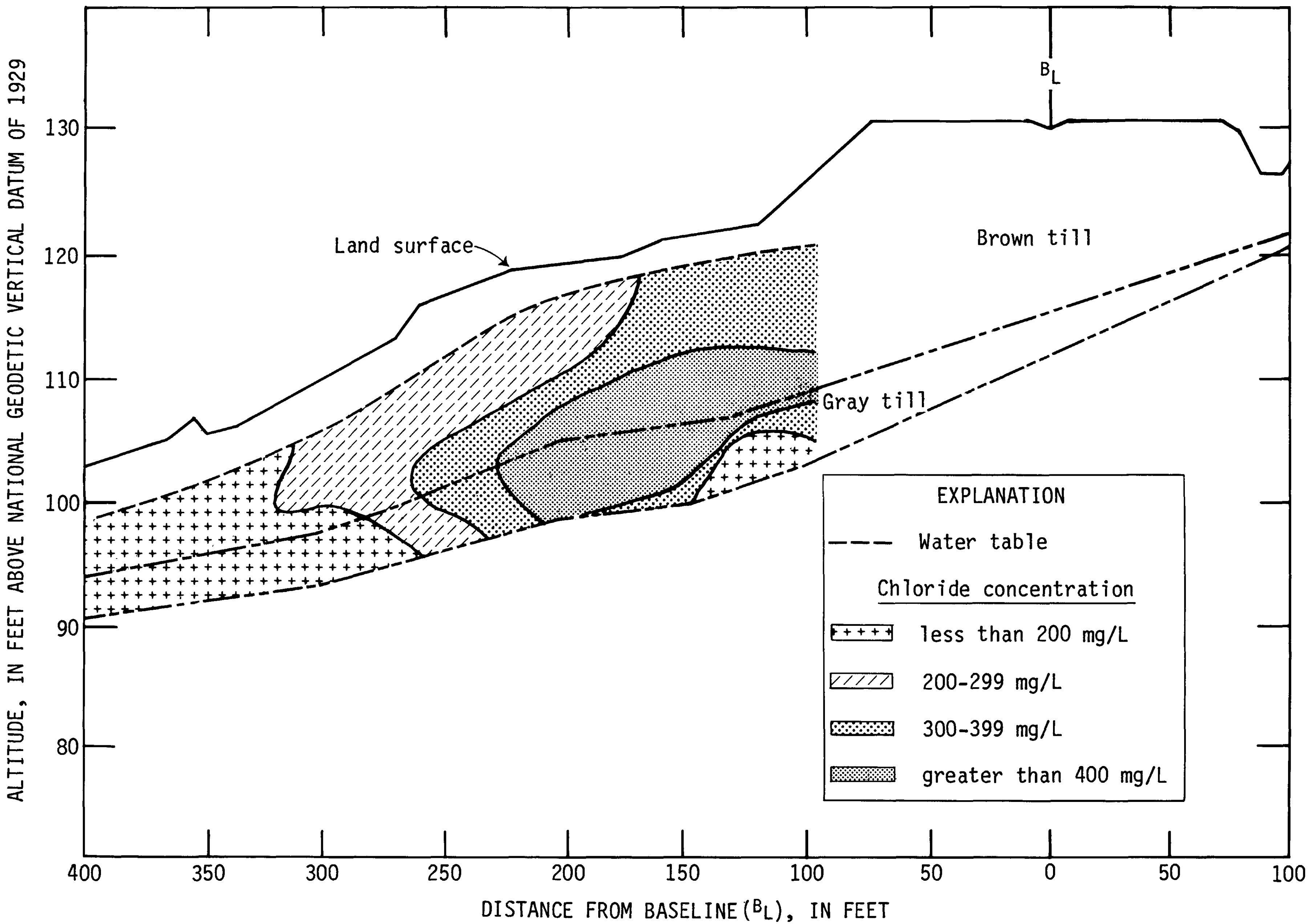


Figure 12.--Distribution of observed mean chloride concentration for 1975-77 water years at the Andover, Massachusetts, ground-water-monitoring site

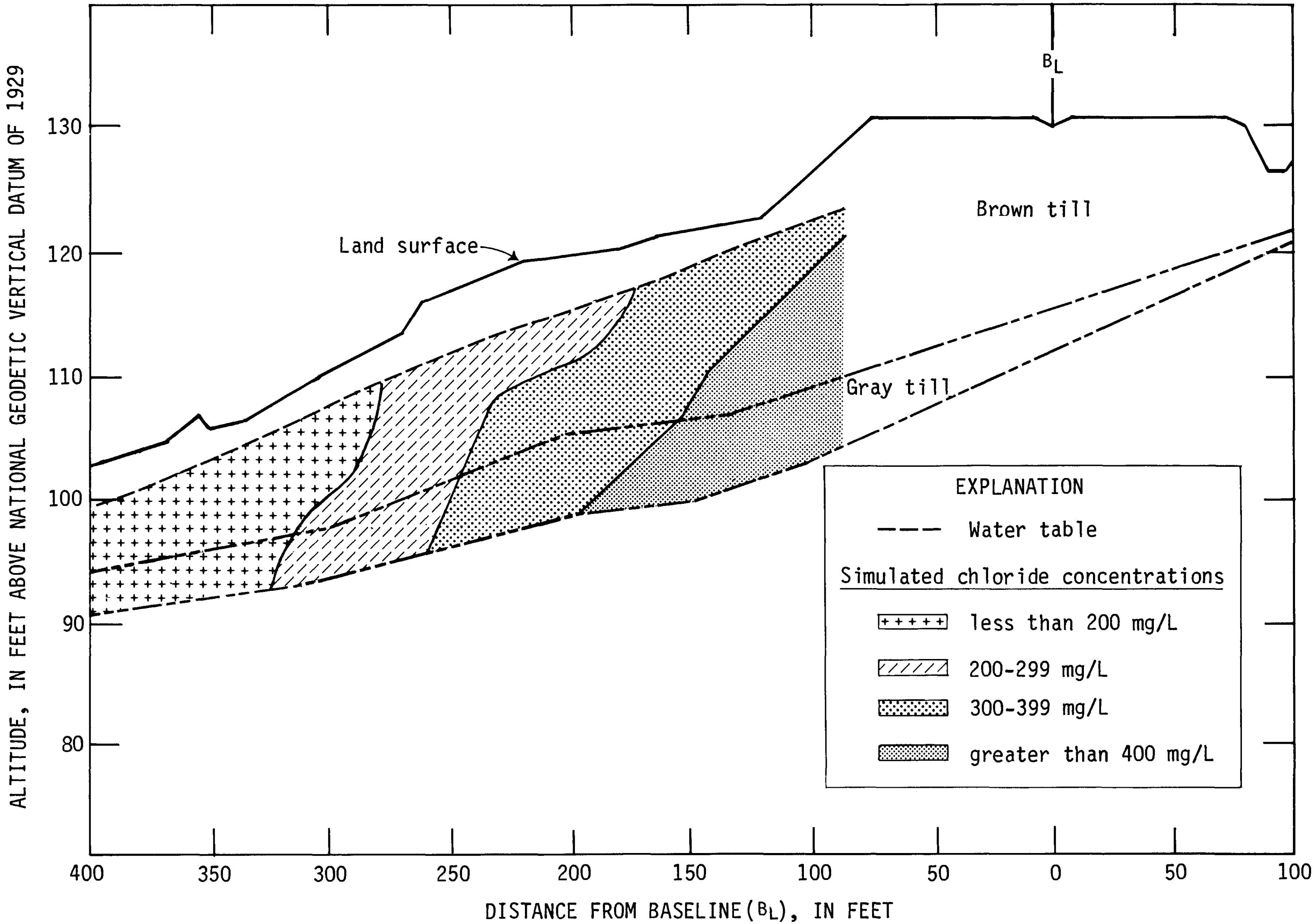


Figure 13.--Distribution of simulated chloride concentrations in a cross section of the Andover, Massachusetts, ground-water-monitoring site

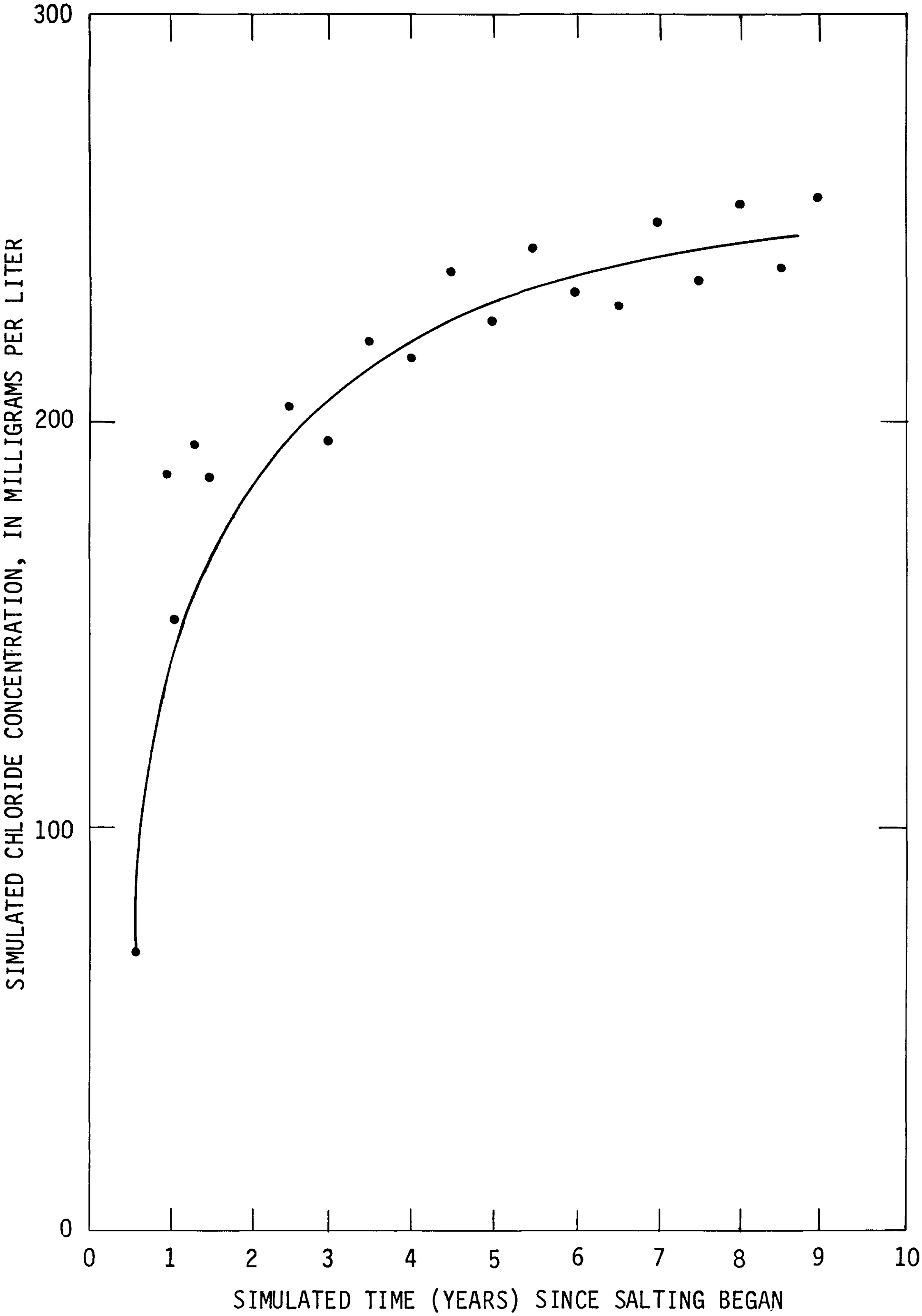


Figure 14.--Simulated chloride concentration versus time period simulated for selected observation well representing a location 9 feet below land surface and 135 feet from the edge of I-93 at the Andover, Massachusetts, ground-water-monitoring site

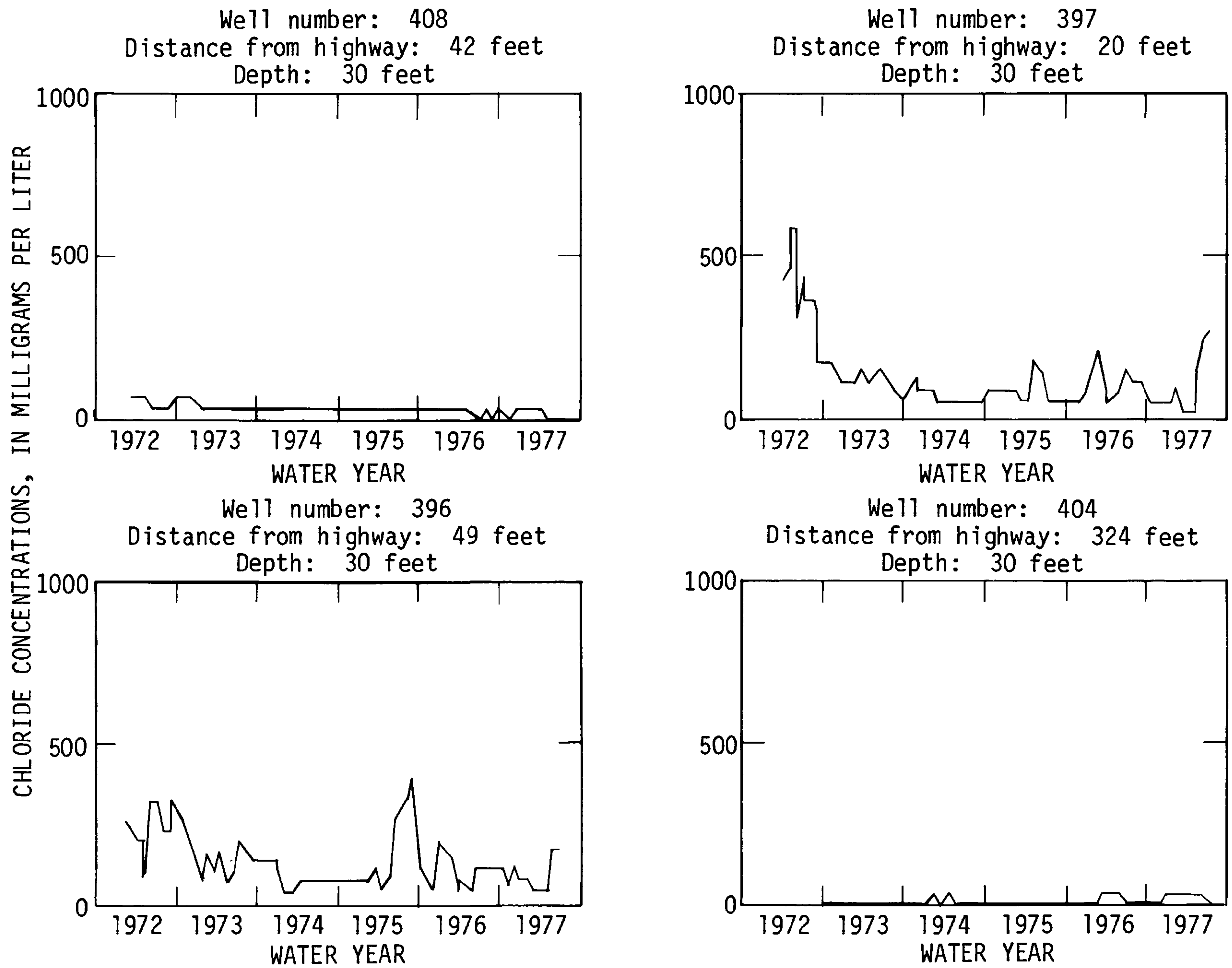


Figure 15.--Chloride concentrations in selected wells at the Chelmsford Massachusetts, ground-water-monitoring site

Because of the differences in site characteristics, storms, and location of wells in the ground-water-flow system, both increasing and decreasing trends can be illustrated for the same site for the same time period, as shown by the following examples:

Well 54 at Bolton (fig. 16), located in the median, shows a definite increasing trend in chloride concentrations, whereas during the same period, well 46, near the downgradient edge of the highway, shows a slight decreasing trend. The abrupt increase in chloride concentrations during the 1977 water year at Bolton is a result of increased highway runoff onto the roadfill bank during alteration of the breakdown lane and accompanying interruption of the highway drainage system.

West Newbury wells 114 and 116 (fig. 17) show increasing trends during 1974-77, when salt application, on an annual basis, was nearly the same. The only trend indicated in salt-application data for West Newbury is a general decrease for the 1972-75 period.

Salt application was nearly constant at the Andover site (fig. 18) during the 1974-77 period, yet a decreasing trend, an increasing trend, and relatively no change, took place in the chloride concentration of water from wells 476, 487, and 488, respectively.

Salt application and annual mean chloride concentrations in the ground water at the Needham site (fig. 19) were nearly the same for each year during the 1974-76 period. A 46 percent increase in salt application was reported for the 1977 season, compared with the 1976 season; however, little or no change was observed in average chloride concentration of well water except for the upgradient well (Needham 41) and one of the deeper downgradient wells (Needham 38).

Chloride concentrations in wells Canton 94 and 96 (fig. 20) show a slight decreasing trend between 1974 and 1976; although the highest salt-application rate during the same period was in 1975. The slight decreasing trend ended in 1977, although only a slight increase in salt-application rate was reported between 1976 and 1977.

Chloride concentration in water from well Wayland 7 had an increasing trend between 1973 and 1975 (fig. 21); although reported salt-application rates decreased from 1973 to 1974 and increased only slightly from 1974 to 1975.

Trends of chloride concentration in ground water caused by highway deicing salt can vary greatly, depending on well location. A single-well trend can be misleading, and, although nearly all wells sampled indicated contamination from highway deicing salt, quantitative cause and effect relations are obscured by irregularities in runoff and ground-water flow at all sites.

SALT BALANCE AND CHLORIDE BUDGET

The third segment of this study, to account for the quantity of salt applied to highways that is discharged by streams and discharged from or stored in ground-water bodies, was done at Boulder Brook in East Bolton, Mass.--the budget site.

The criteria for selecting the budget site included all those listed for stream- and ground-water-monitoring sites. Additional criteria include:

(1) The drainage basin is small and well defined, so that total precipitation on the basin can be readily determined;

(2) The highway crosses the basin so that surface water and most ground water flows about at right angles to the highway;

(3) Ground water does not flow out of the basin; and

(4) Permission is obtainable to construct and operate, for the 7-year period of the study, monitoring stations on the stream, upstream and downstream from the highway.

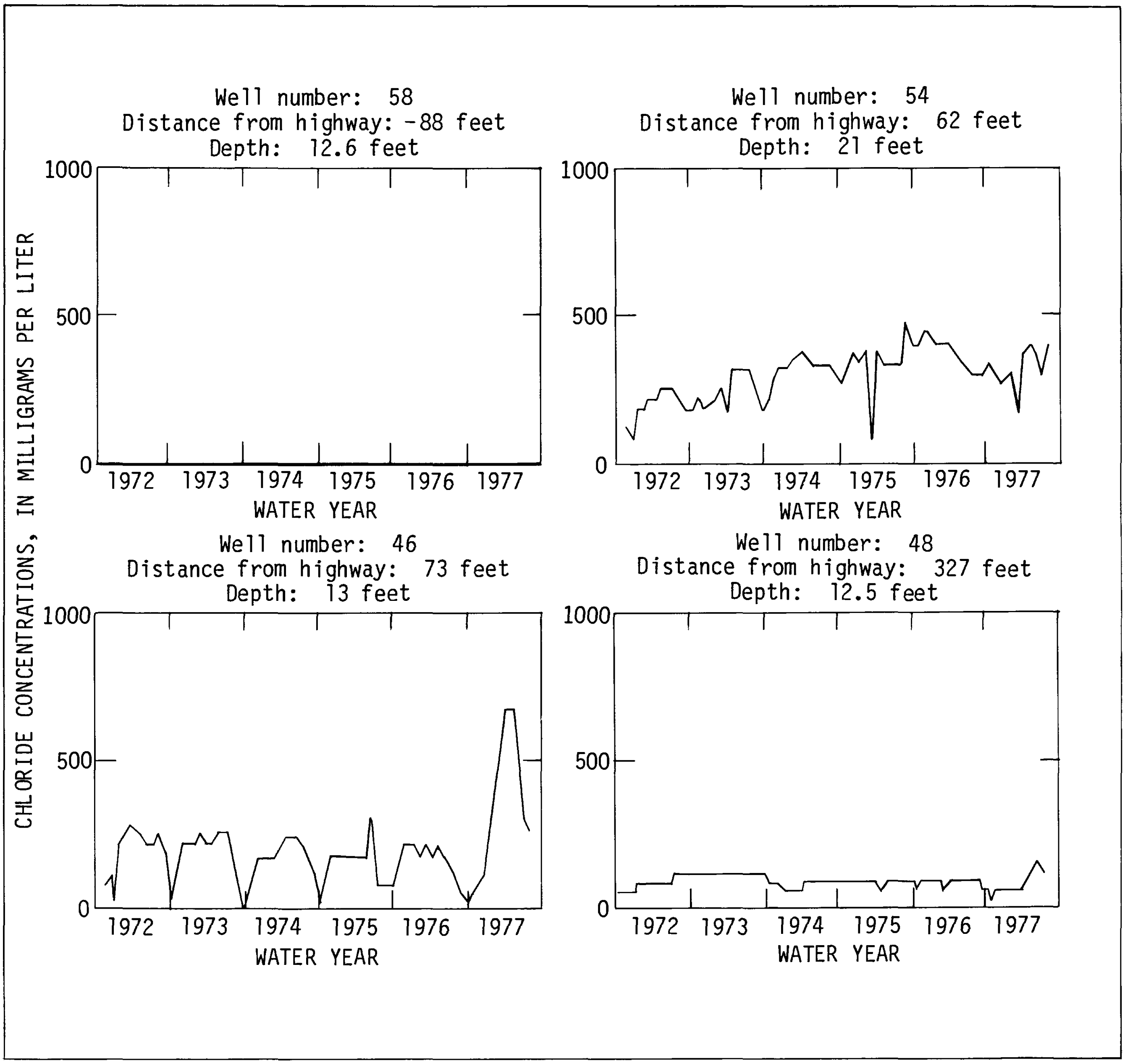


Figure 16.--Chloride concentrations in selected wells at the Bolton, Massachusetts, ground-water-monitoring site

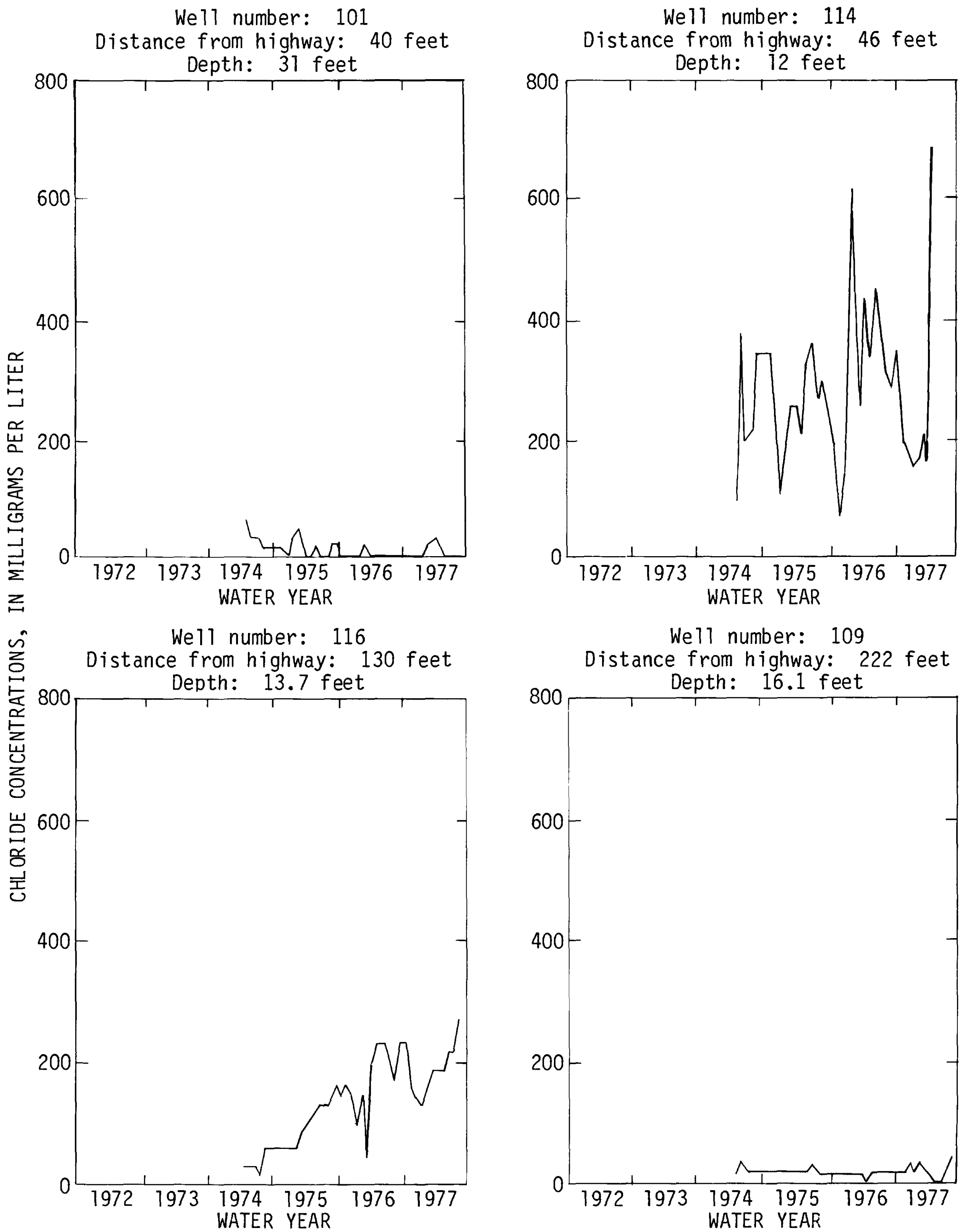


Figure 17.--Chloride concentrations in selected wells at the West Newbury, Massachusetts, ground-water-monitoring site

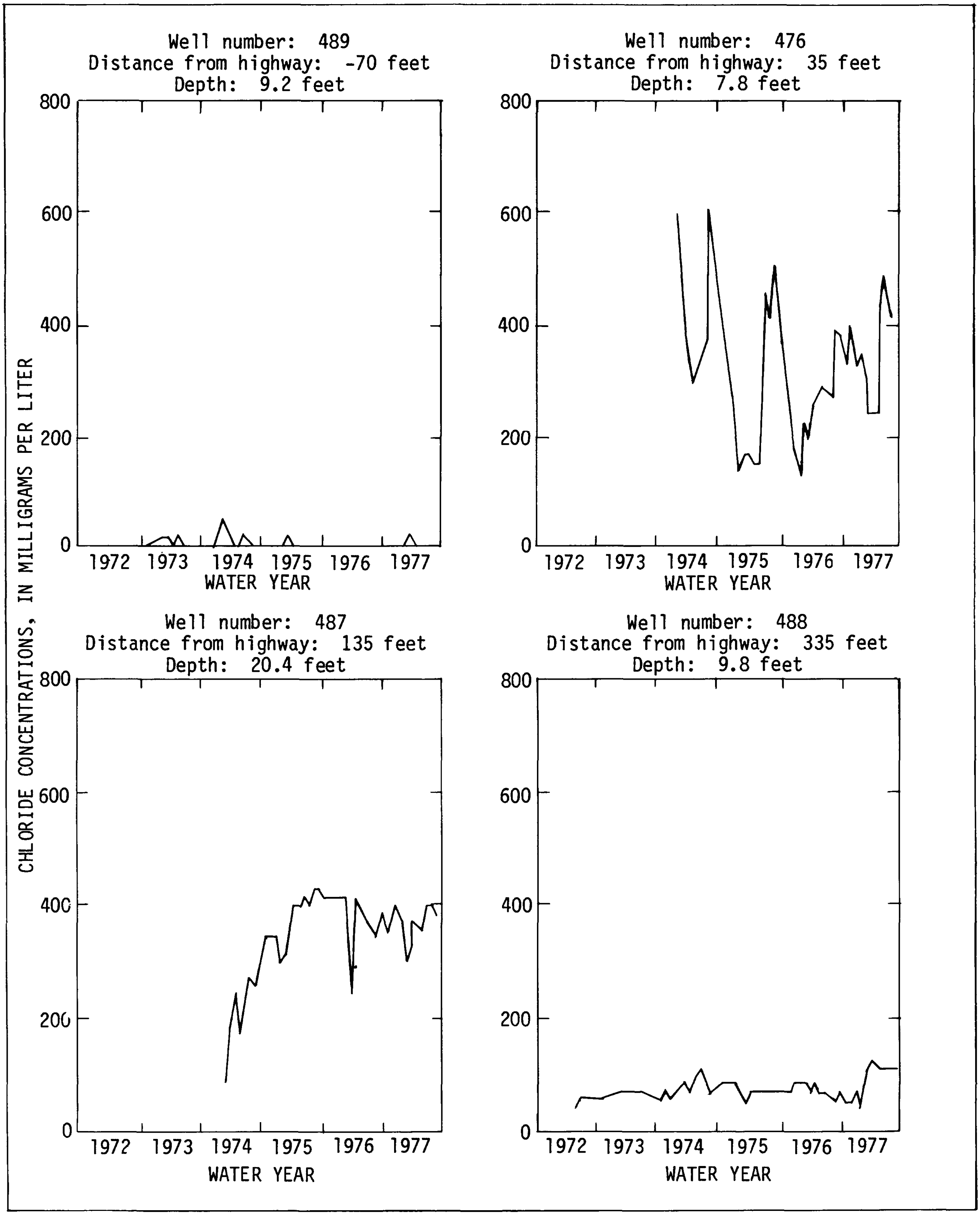


Figure 18.--Chloride concentrations in selected wells at the Andover, Massachusetts, ground-water-monitoring site

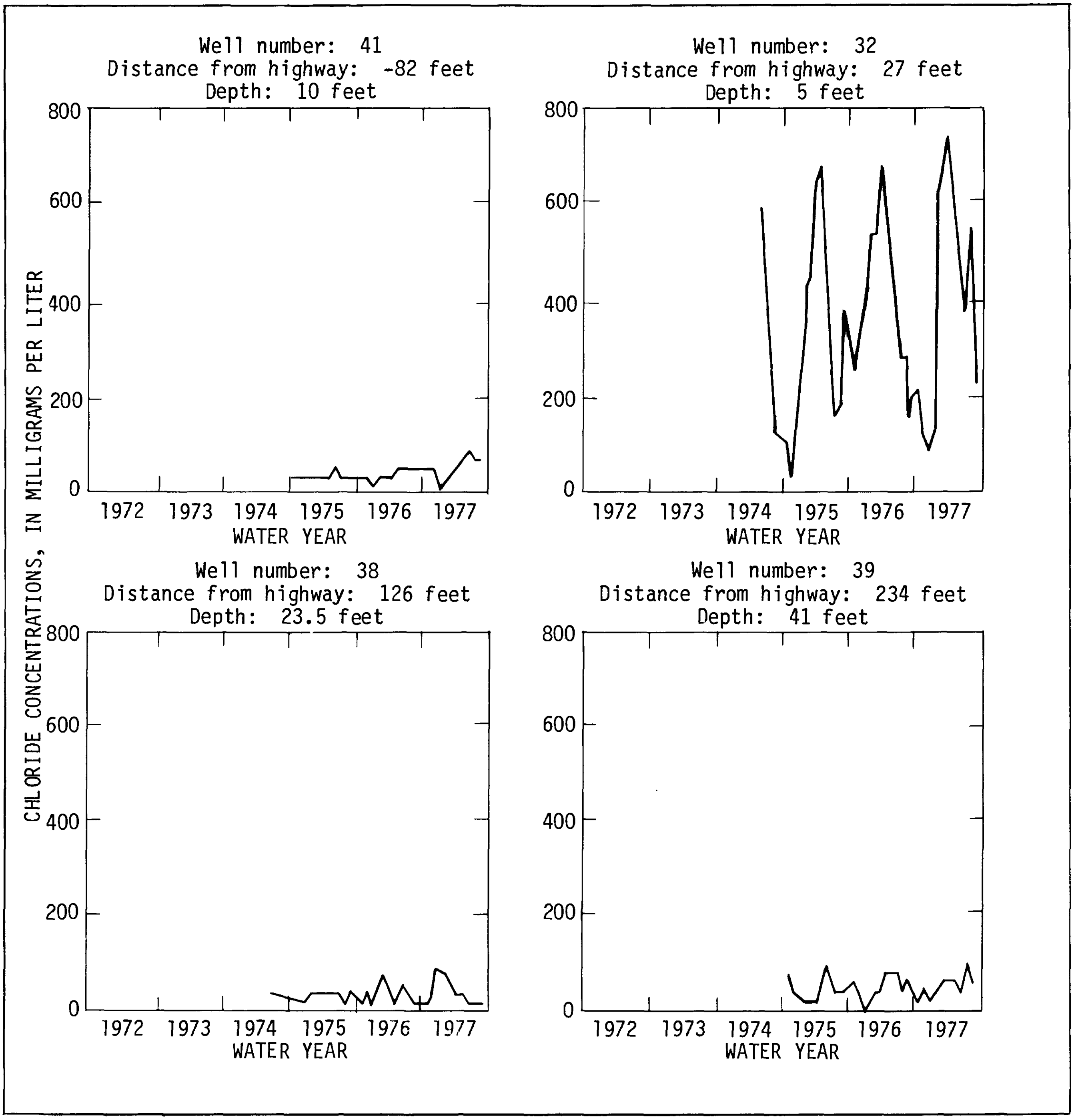


Figure 19.--Chloride concentrations in selected wells at the Needham, Massachusetts, ground-water-monitoring site

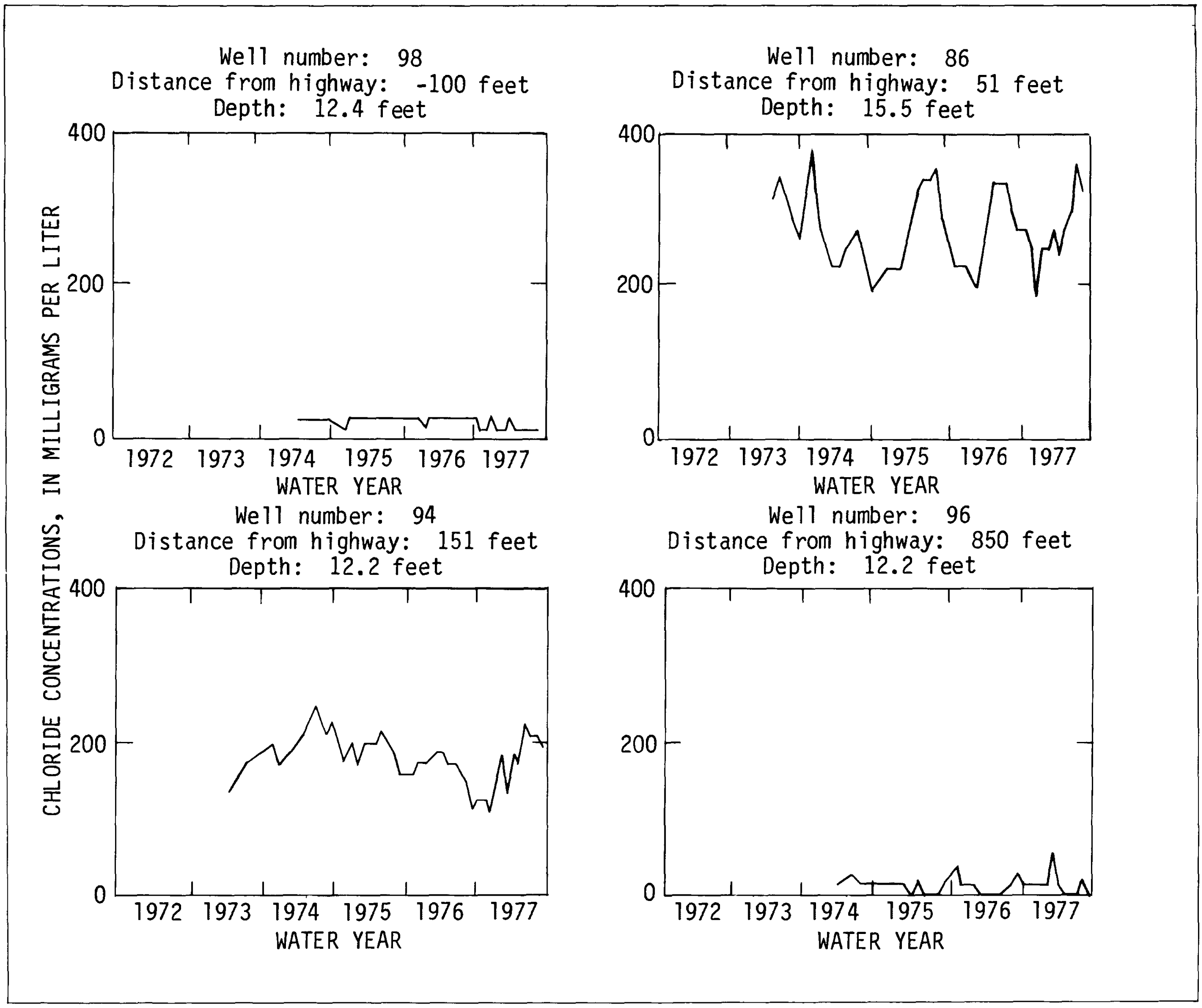


Figure 20.--Chloride concentrations in selected wells at the Canton, Massachusetts, ground-water-monitoring site

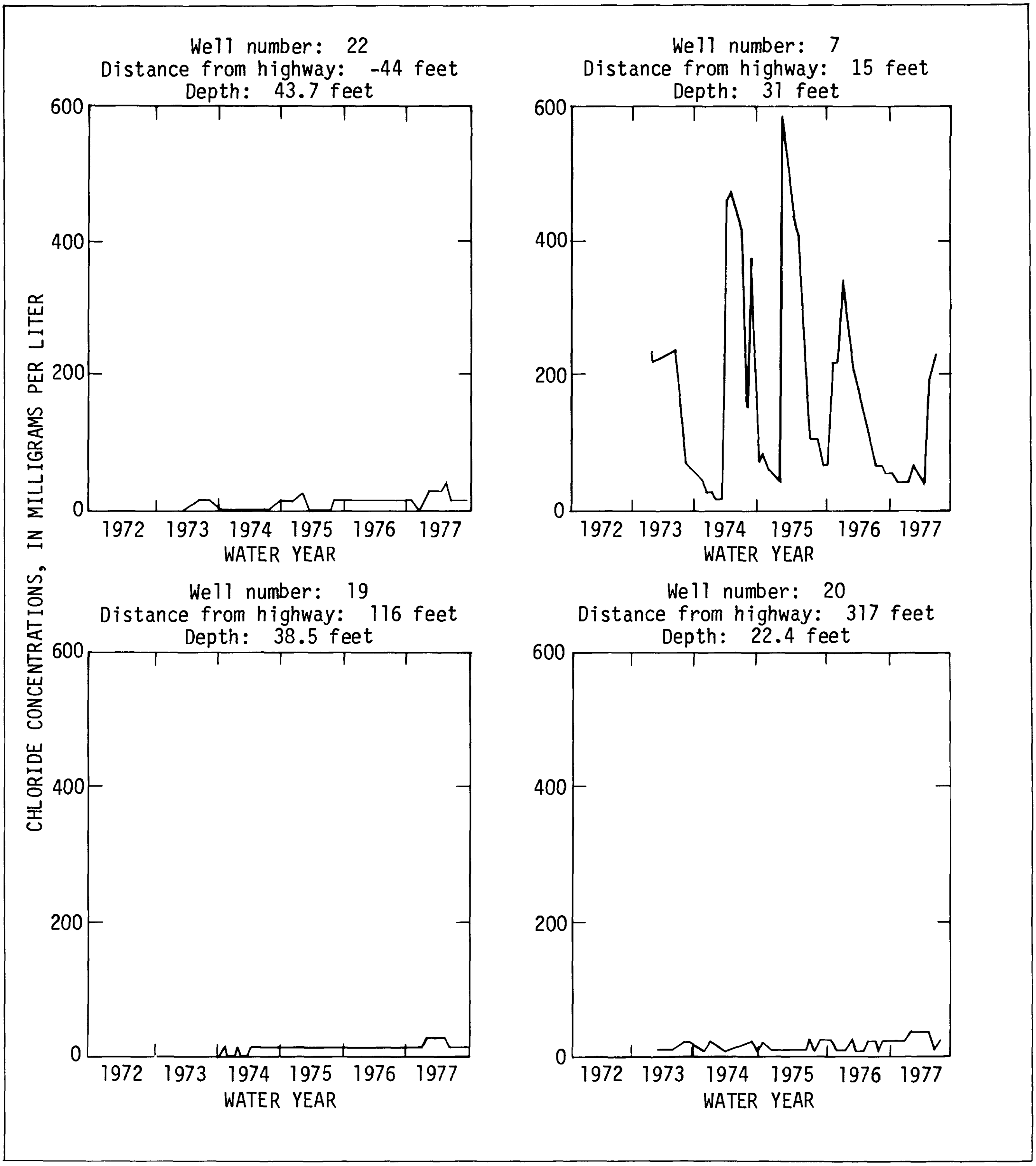


Figure 21.--Chloride concentrations in selected wells at the Wayland, Massachusetts, ground-water-monitoring site

Two monitoring sites on Boulder Brook, one upstream and one downstream from I-495, were selected for calculating a chloride budget. The upstream site was used to determine the influences of septic systems and highway salt upstream from I-495. The downstream site was used to monitor chloride concentrations for the entire basin. Salt loads due to deicing chemicals applied to I-495 were determined by differences between sites. Concentrations of sodium, calcium, and chloride at both sites are shown in figures 22-24, respectively.

The higher concentrations of sodium, calcium, and chloride in water from Boulder Brook downstream from I-495 are caused by deicing chemicals from the highway. Calcium is probably the principal cation in uncontaminated surface water in the Boulder Brook basin, and some of the increase in calcium concentration downstream from I-495 may result from cation exchange with sodium in the unsaturated zone near the edge of I-495 rather than from calcium chloride from I-495.

Chloride and Sodium Loads in Boulder Brook

Relations between specific conductance and chloride content were used to convert daily mean specific-conductance values to chloride concentrations. A similar method was used to obtain sodium concentrations.

Table 10 lists quantities of highway salt that were applied at the Bolton site in terms of sodium chloride, the chloride component, and the sodium component. Values are listed for both sites on Boulder Brook.

Percentages of applied chloride and sodium in stream loads are listed in table 10 and are used to calculate the fraction of applied sodium retained in the soil through sorption or ion exchange. Chloride is assumed to be conservative with respect to sorption or ion exchange; therefore, chloride loads are used to indicate the fraction of applied salt that discharges readily to a stream. However, part of the applied salt might have infiltrated the ground in areas such as the median, from which ground water moves a long distance before discharging to a stream. Thus, possibly part of the salt may not have been discharged to the stream during the period studied.

The differences in the average percentages of chloride (100 times chloride load divided by chloride applied) and sodium (100 times sodium load divided by sodium applied) represent the percentage of applied sodium retained by the soil.

Table 10.--Chloride and sodium applications to roads and stream loads of chloride and sodium in the Boulder Brook drainage basin near Bolton, Massachusetts

Water year	Highway salt (sodium chloride) applied (tons)	Chloride applied (tons)	Sodium applied (tons)	Chloride load, in tons, and (percent of applied)		Sodium load, in tons, and (percent of applied)	
		Boulder Brook upstream of I-495					
1972	28.8	17.5	11.3	29.8	(170)	16.6	(147)
1973	22.6	13.7	8.9	29.1	(212)	16.5	(185)
1974	18.6	11.3	7.3	18.5	(164)	10.5	(144)
1975	30.3	18.4	11.9	22.3	(121)	12.6	(106)
1976	23.2	14.1	9.1	22.9	(162)	12.9	(142)
1977	21.4	13.0	8.4	19.2	(148)	10.4	(124)
				Average =	(163)		(141)
		Boulder Brook downstream of I-495					
1972	147	89.0	57.6	68.0	(76)	32.9	(57)
1973	79.2	48.1	31.1	63.7	(132)	31.3	(101)
1974	83.5	50.7	32.8	41.5	(82)	20.5	(63)
1975	94.4	57.3	37.1	50.7	(88)	24.9	(67)
1976	108	65.5	42.4	67.8	(104)	33.5	(79)
1977	101	61.3	39.7	41.5	(68)	20.0	(50)
				Average =	(92)		(70)

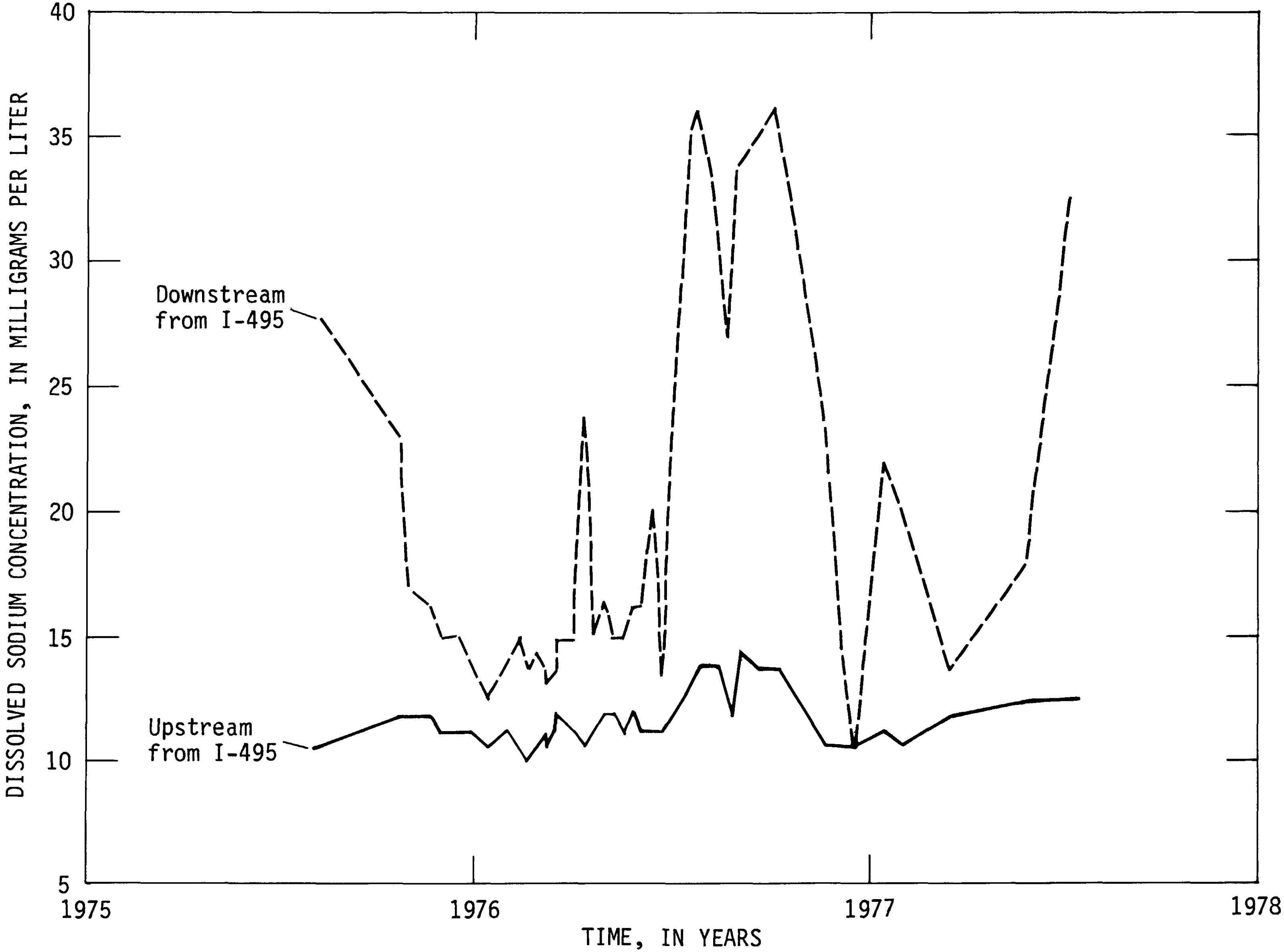


Figure 22.--Dissolved sodium concentrations in Boulder Brook, upstream and downstream from I-495 near Bolton, Massachusetts

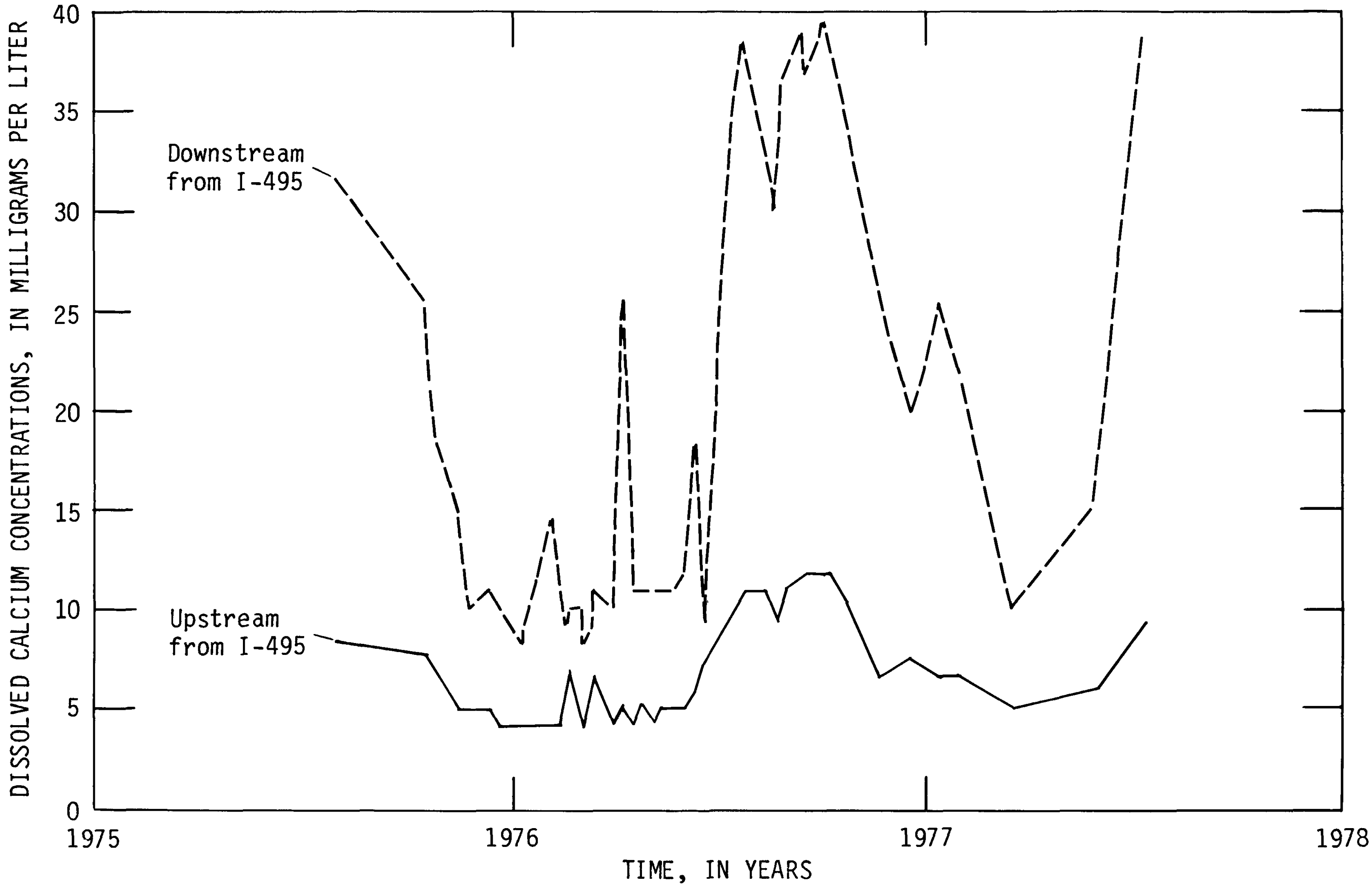


Figure 23.--Dissolved calcium concentrations in Boulder Brook, upstream and downstream from I-495 near Bolton, Massachusetts

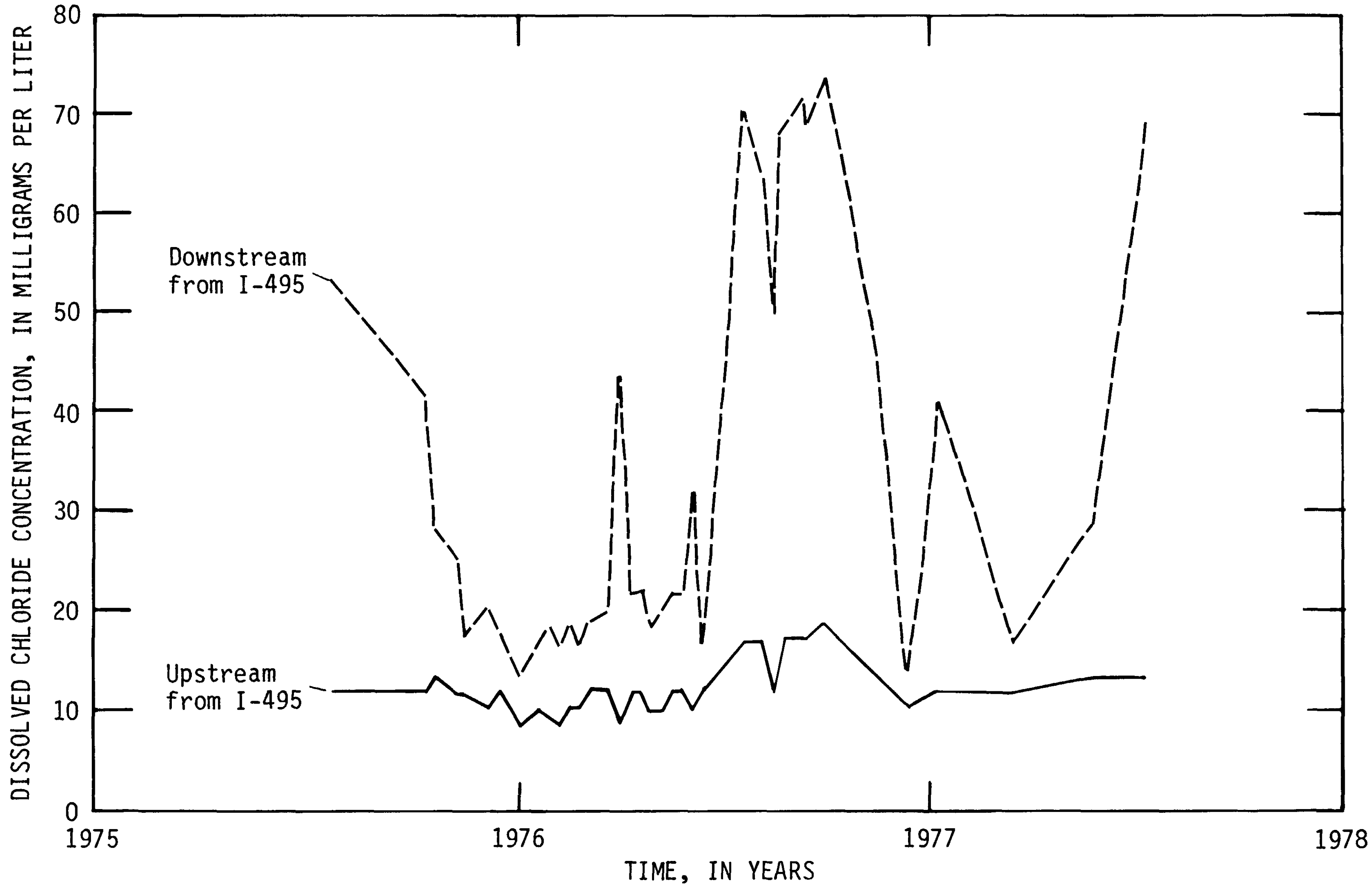


Figure 24.--Dissolved chloride concentrations in Boulder Brook, upstream and downstream from I-495 near Bolton, Massachusetts

Application and load data from the lower part of the Boulder Brook basin (between the two monitoring sites) are listed in table 11. For the lower basin, the average difference, 22 percent, between chloride and sodium in terms of stream load as a percentage of applied, is the same as that for the entire basin and for the upper basin. The percentage of applied salt discharged, however, is about 20 percent less. The lesser percentage being discharged in the lower basin indicates that either more salt is going into ground-water storage in the lower basin than in the upper basin or that salt-application data or load data are not accurate.

As no quantitative data for calcium chloride applications were available, they were ignored. Applications were few and probably did not greatly affect the calculations of sodium retained.

Table 11.--Chloride and sodium applications and stream loads of chloride and sodium between the two monitoring sites on Boulder Brook, East Bolton, Massachusetts

Water year	Applications to roads in lower Boulder Brook basin: Tons of sodium chloride	Tons of chloride	Tons of sodium	Load in stream, in tons, and (Load as percent of applied): Chloride		Sodium	
1972	118.0	71.7	46.5	38.2	(53)	16.3	(35)
1973	56.6	34.4	22.2	34.6	(101)	14.8	(67)
1974	64.9	39.4	25.5	23.0	(58)	10.0	(39)
1975	64.1	38.9	25.2	28.4	(73)	12.3	(49)
1976	84.8	51.5	33.3	44.9	(87)	20.6	(62)
1977	79.6	48.3	31.3	22.3	(46)	9.6	(31)
				Average =	(69.7)		(47.2)

Separation of Chloride Loads in Ground-Water Discharge and Direct Runoff to Boulder Brook

The percentage or relative fraction of salt applied to the highway that entered the ground and the relative fraction that ran overland directly to Boulder Brook were estimated by subtracting chloride load in ground-water discharge from chloride load in the stream, as follows:

1. Subtract streamflow at the monitoring site upstream from I-495 from streamflow at the monitoring site downstream from I-495 to obtain component of streamflow contributed by the lower basin (fig. 25, part B),
2. Separate ground-water discharge from the hydrograph of flow contributed by the lower basin to obtain an estimate of the volume of ground water contributed to the stream by the lower basin (fig. 25, part C),
3. Subtract chloride load at the monitoring site upstream from I-495 from chloride load at the monitoring site downstream from I-495 to obtain chloride load contributed by the lower basin,
4. Divide the lower basin daily chloride loads by the daily difference in flow between the upper and lower monitoring sites, using a factor to correct for units, to obtain daily chloride concentrations of water contributed by the lower basin (fig. 25, part D),
5. Estimate, considering precipitation, chloride concentrations of the ground- water discharge (fig. 25, part E), from the graph of chloride concentrations contributed by the lower basin,
6. Multiply daily ground-water discharges by daily ground water chloride concentrations to obtain daily ground-water-chloride loads. Sum these daily values to obtain annual ground-water-chloride loads due to the contribution from the lower basin,
7. The difference between chloride load computed for the downstream basin and ground-water discharge to the stream is assumed to be the annual contribution of direct surface runoff to the stream from the lower basin.

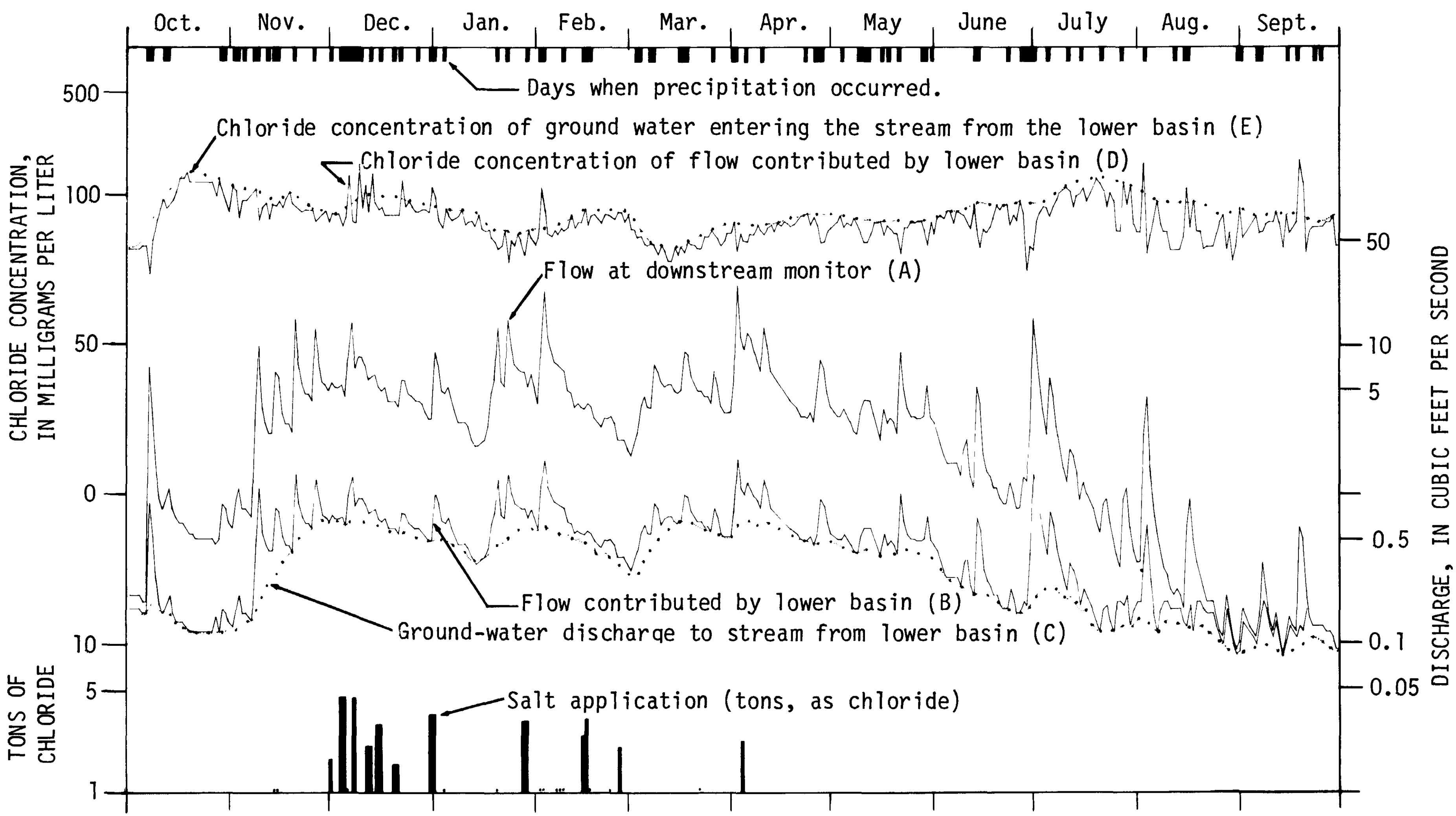


Figure 25.--Graphical separations of streamflows and of chloride concentrations in the Boulder Brook drainage basin at Bolton, Massachusetts, for the 1973 water year.

The chloride load and salt-application data (table 12) show that the preponderance of chloride applied to I-495 enters the ground and is subsequently discharged to the stream rather than running off directly to the stream.

Table 12.--Chloride loads in ground-water discharge and surface-water discharge at the Boulder Brook sites

Water year	1972	1973	1974	1975	1976
Chloride load at downstream monitor ----------------	68.0	63.7	41.5	50.7	67.8
Chloride load at upstream monitor-------------------	29.8	29.1	18.5	22.3	22.9
Chloride load from the lower basin------------------	38.2	34.6	23.0	28.4	44.9
Ground-water-chloride load from the lower basin -------	21.6	26.2	18.4	23.2	32.1
Surface-water-chloride load from the lower basin-------	16.6	8.4	4.6	5.2	12.8
Chloride applied in lower basin ---------------------	71.5	34.4	39.4	38.9	51.4
Percentage of applied chloride entering stream as overland runoff ------------------------------	23	24	12	13	25

Storage of Chloride in Ground Water Near the Boulder Brook Sites

The area between the two stream-monitoring sites on Boulder Brook was partitioned into rectangular areas, and an estimate of chloride content in ground water in each area was calculated. The contents were summed to estimate total chloride in storage in ground water between the monitoring sites, as follows:

Chloride in storage (tons) = volume of water in storage (ft^3) x chloride concentration of water (mg/L) x 3.12×10^{-8} tons of chloride/ft^3/mg/L

where:

Volume of water in storage = saturated thickness (ft) x area of rectangle (ft^2) x porosity

Chloride concentration = weighted average of chloride concentrations for each block determined from observation-well data

3.12×10^{-8} = factor to convert chloride concentration to tons of chloride per cubic foot per 1 mg/L of chloride.

Saturated thicknesses of the unconsolidated deposits in the budget area were calculated from altitudes of the water table determined from observation wells and altitudes of the bedrock surface determined from wells, highway borings, and bedrock outcrops. A porosity of 40 percent was assigned to the unconsolidated materials and is reasonable based on laboratory determinations of porosity of similar materials, as reported by Baker and others (1964, p. 31).

Calculation of chloride concentration is based on averaging chloride concentrations determined from water samples collected from observation wells screened at different depths in the aquifer from place to place in the budget area. Chloride-concentration data are not uniform throughout the area, and it was necessary to extrapolate data between well water having different chloride concentrations at different depths within the aquifer.

The quantity of chloride in storage was calculated for a time near the start of each water year during 1971-77 and the changes from year to year in amount of chloride in storage compared to salt application each year. Chloride storage and change in chloride-storage values are shown below:

Date	Tons of chloride in ground water	Annual change in chloride stored (tons)
Oct. 1971	39.2	--
Oct. 1972	48.0	+8.8
Oct. 1973	41.6	-6.4
Nov. 1974	36.0	-5.6
Oct. 1975	42.8	+6.8
Oct. 1976	50.0	+7.2
Aug. 1977	67.2	+8.6

In a quantitative sense, the values calculated for chloride storage probably provide only a rough index of the change in storage from year to year. Figure 26 shows the relation between quantity of highway salt (chloride) applied and estimated quantity of chloride storage in the ground water.

Chloride Budget

The calculation of a chloride budget for Boulder Brook between the two stream-monitoring sites is as follows:

Water year	Chloride applied (tons)	Direct runoff component of stream chloride load (tons)	Ground-water-discharge component of stream chloride load (tons)	Change in chloride stored in ground water[1] (tons)	Applied chloride not accounted for (tons)
1972	71.5	16.6	21.6	+8.8	24.5
1973	34.4	8.4	26.2	-6.4	6.2
1974	39.4	4.6	18.4	-5.6	22.0
1975	38.9	5.2	23.2	+6.8	3.7
1976	51.4	12.8	32.1	+7.2	-.7
Total	235.6	47.6	121.5	10.8	55.7

[1]Change from beginning to end of water year.

Approximately 24 percent of chloride applied in highway deicing chemicals was not accounted for by the chloride budget. The errors suspected in the calculation of chloride stored in ground-water reservoirs and in the application of chloride to I-495 are the most probable sources of the discrepancy.

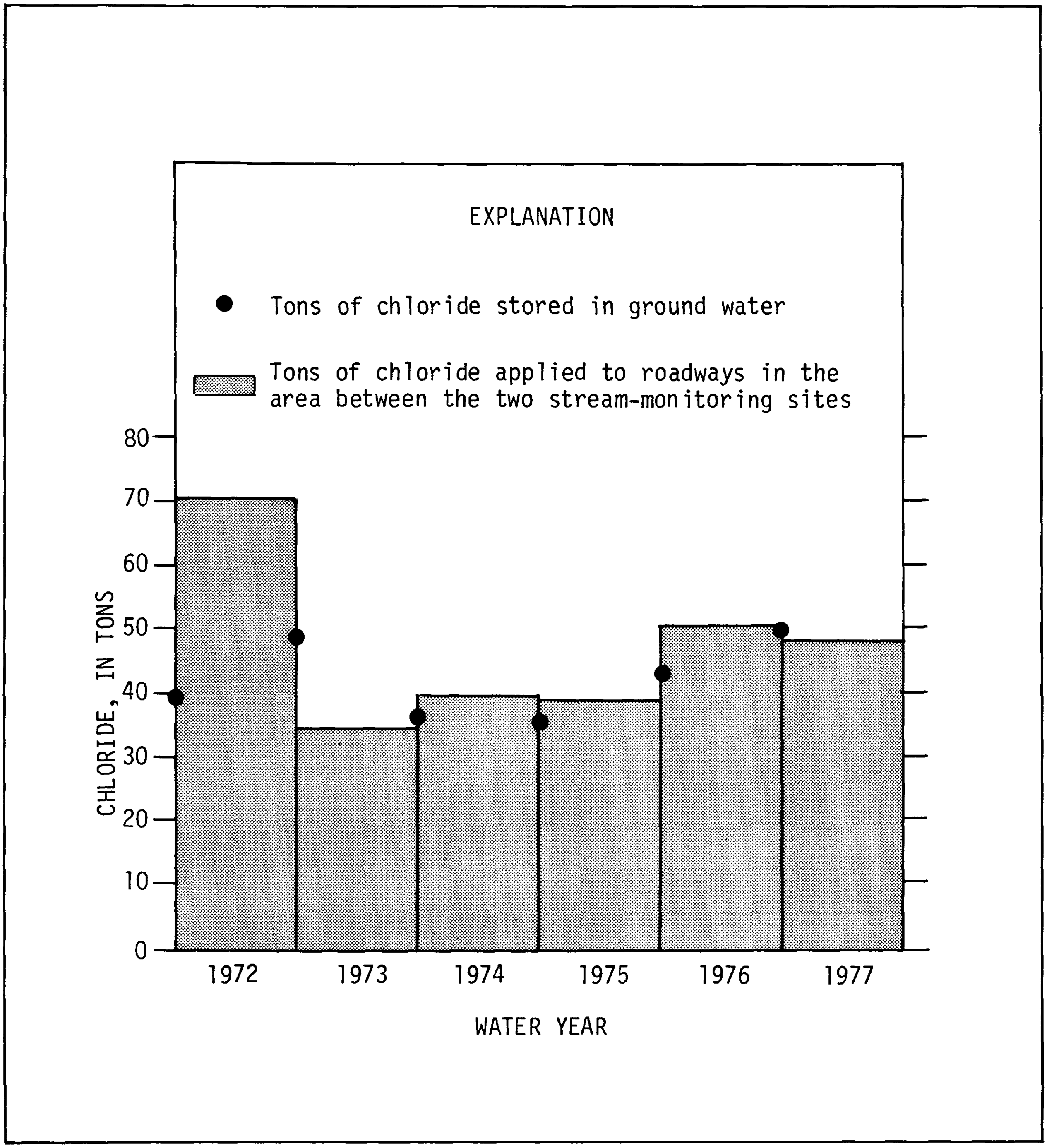


Figure 26.--Annual chloride applications and estimates of chloride stored in ground water between the two stream-monitoring sites on Boulder Brook near Bolton, Massachusetts

SUMMARY AND CONCLUSIONS

Annual mean chloride concentrations and annual mean sodium concentrations in streams were calculated from daily specific-conductance data and relations between chloride concentration and specific conductance, and sodium concentration and specific conductance. Multiple-regression analyses were done to obtain relations from which values of annual mean chloride concentrations and annual mean sodium concentrations can be estimated. Data for independent variables used in the regression analyses are easily obtained either from methods outlined within this report or from referenced publications. Variables are as described in table I. The equations obtained for estimating chloride and sodium concentrations in streams and associated standard errors of estimate are as follows:

$$\text{MEAN\_CL} = -0.94 + 1.22 \times \frac{\text{SALT\_APP}}{\text{ANAVFLOW}} + 0.06 \times \text{SLOPE}$$

Standard error of estimate = 3.3 mg/L.

$$\text{MEAN\_NA} = 5.13 + 0.481 \frac{\text{SALT\_APP}}{\text{ANAVFLOW}}$$

Standard error of estimate = 2.0 mg/L.

Equations for estimating maximum daily stream concentrations of chloride and sodium were obtained in a similar manner. The equations and associated standard errors of estimate are as follows:

$$\text{MAX\_CL-} = 26.1 + 2.1 \times \frac{\text{SALT\_APP}}{\text{ANAVFLOW}} - 3.2\ \text{STORAGE}$$

Standard error of estimate = 11.5 mg/L

$$\text{MAX\_NA+} = 11.0 + 1.02 \times \frac{\text{SALT\_APP}}{\text{ANAVFLOW}}$$

Standard error of estimate = 4.0 mg/L

Approximately 52 percent of the chloride applied to I-495 and some town roads between the monitoring sites on Boulder Brook entered the stream from the ground-water system. Approximately 20 percent of the applied chloride entered the stream as surface runoff, and about 5 percent was accounted for by the net change in chloride stored in the ground-water system. The remaining 24 percent of chloride applied to the roads between the monitoring sites was not accounted for in the calculations. Based on the proportions of sodium and chloride in salt applied to the roadways, the loads of chloride and sodium discharged in streamflow and the application of a small but not accurately determined quantity of calcium chloride, the amount of sodium retained in the soil was estimated to be 20 percent of the sodium applied.

Relating the concentrations of chloride in ground water near several highway systems to well location, salt application, and precipitation was more difficult than originally anticipated. Developing regression equations from which accurate estimates of chloride concentrations could be made was complicated by the following:

(1) Salt application-data not specific to section of roadway near monitoring wells. Averages were used that represented many miles of roadway which included a variety of road-surface conditions such as hills, flat stretches of roadway, ramps, curves, and interchanges; whereas, the monitoring site represented only one of these situations, generally a flat stretch.

(2) Salt application by different maintenance sections. In some places, crews from different maintenence sections salted the same stretches of roadway, resulting in some uncertainty with respect to quantities of salt spread on the stretch of roadway.

(3) Salt application by towns not well accounted for. Some of the data obtained from towns was based on records of purchase rather than records of application. In some circumstances, the amount purchased had to be reconstructed from the town highway superintendent's memory and fiscal data.

(4) Initial assumptions based on too few data. Well locations were chosen based on previous small-scale investigations during which interpretation of data indicated that salt entering the ground from highway runoff did so within 15 feet of the highway. Indications from this study are that highway runoff is widely dispersed in the vicinity of the edge of the highway based, at least partly, on the topography adjacent to the highway. Apparently, some of the snow-salt mixture plowed from the highway surface escapes the drainage system; whereas, some of the snow and ice melting on the road surface do not, causing the distribution of salty runoff to be variable.

(5) Consistency of chemical analyses. Throughout this project, the equipment and reagents used to determine chloride concentrations varied. The personnel assigned to the analysis of samples were of various backgrounds from inexperienced temporary personnel to chemists. The extent of analytical differences arising from differences in personnel assigned to this task is not known. During the first few years of data collection, many repeats of analysis were requested, sometimes resulting in greatly different analytical values. However, improved quality-assurance practices established by the laboratory resulted in accurate, reproducible values during the final years of the study.

(6) Quantity of data available for analysis. The planned network of wells was not completed until the early to middle part of the 1974 water year. Because much of the data analysis was based on annual averages, only 3 full years of data were available for study of a period common to all sites. The relationships sought could possibly have been obscured by 1 unusual year in 3.

(7) Variations in annual total annual salt application at some sites may not have been sufficient to cause a greater influence on chloride concentrations than the variations in melting and runoff during each salting season.

Despite the limitations represented by the items listed above, the regression analyses did indicate that, at nearly all of the ground-water-monitoring sites, the distance of a well from the highway's edge was not a significant factor in determining the chloride concentration in the wells within 100 feet of a highway. Variations in roadside topography are the most probable reason for the lack of correlation between chloride concentrations and distances of wells from roadways. This lack of relationship between chloride concentration and distance was supported by attempts to calibrate a two-dimensional solute-transport model for the Andover ground-water site. For this site, ground-water recharge had to be assigned chloride concentration values (100 mg/L) much above the background concentrations (less than 10 mg/L) at distances up to 170 feet from the edge of the roadway in order to make the model simulate observed data.

In general, values of annual mean chloride concentration, annual mean sodium concentration, annual chloride load, and annual sodium load in streams can be estimated with sufficient reliability to satisfy requirements of most environmental impact statements. Concentrations of chloride in ground water adjacent to (within a few hundred feet of) highways probably cannot be accurately related to salt application by statistical techniques which do not account for the wide variety of topographically induced surface runoff-patterns near the edge of the roadway. Nonstructural surface-drainage features such as variations in roadside topography influenced highway deicing chemical distribution in ground water within 300 feet of the highways to the extent that the effects of geology, salt application, precipitation, depth of well, and depth to water table could not be related closely to annual average or annual maximum chloride concentration in ground water.

Reasonably accurate chloride concentrations in ground water, as a result of highway deicing, have not been estimated during this study for several reasons, inadequate instrumentation among them. The characteristic of most importance, the distribution of chloride-containing recharge, was not recognized until data analysis was in progress. This characteristic must be adequately described before concentrations of chloride in ground water at any particular point can have much meaning. This problem might be overcome by extremely careful site selection and contour mapping of roadside areas. If the distribution of chloride-containing runoff from a highway can be described, then wells can be installed to determine the effects of chloride-containing recharge on the ground-water system.

Selecting sites for such study would be crucial and would have to represent highway drainage features. A decision to study highway-deicing impact in general or to study only areas that have a potential for water supply might make site selection easier. Because future highway design is to accommodate the deicing-chemical problem, sites, ideally, will be selected by joint parties of highway design engineers and hydrologists. Selecting sites mainly on the basis of geology was a weakness of this study. Highway drainage features were not determined until the data-analysis phase and were difficult to categorize.

Ideal sites would be located where highway runoff (that fraction escaping the storm sewers, etc.) is not channeled far from the edge of the roadway by ruts, pathways, or other features not part of the highway design. After selection of sites, wells could be located to represent the general topography. If the edge of the roadway is mostly steep sloped, wells installed in or near the steep-sloped part of the site would more nearly categorize the site. Wells could be located and constructed so that a flux of chloride could be measured by selecting a definable volume of earth materials and installing wells screened throughout their depth. The number of wells per site could be much less than the number used for this study and yet could yield information more closely related to the quantity of salt applied. The volume selected would need to be as close to the roadway as possible but not so close that deicing chemicals could be sprayed or splashed beyond the site. With the wells penetrating to bedrock and screened throughout the saturated zone, an average or integrated sample could be collected to represent the entire saturated thickness of materials. Because such wells would integrate throughout the vertical and wells would be located so that the volume of earth materials could be calculated, many of the problems of interpolating or extrapolating concentrations of chloride between or beyond screened intervals would be eliminated. Chloride content of the block (volume of earth materials) could be calculated on a regular basis and the rate of change of chloride contained in the block related to annual salt application.

A critical part of any study of highway-deicing impact on ground-water bodies would be to establish a procedure for strict accounting of salt applied in the future. Reliable data on salt application are necessary before an effective ground-water investigation.

REFERENCES CITED

Baker, J. A., Healy, H. G., and Hackett, O. M., 1964, Geology and ground-water conditions in the Wilmington-Reading area, Massachusetts: U.S. Geological Survey Water-Supply Paper 1694, 80 p.

Chute, N. E., 1966, Geology of the Norwood quadrangle, Norfolk and Suffolk Counties, Massachusetts: U.S. Geological Survey Bulletin 1163-B, 78 p.

Clapp, C. H., 1921, Geology of the igneous rocks of Essex County, Massachusetts: U.S. Geological Survey Bulletin 704, pp. 19 and 20, and map.

Emerson, B. K., 1917, Geology of Massachusetts and Rhode Island: U.S. Geological Survey Bulletin 597, 289 p.

Hansen, W. R., 1956, Geology and mineral resources of the Hudson and Maynard quadrangles, Massachusetts: U.S. Geological Survey Bulletin 1038, 104p.

Konikow, L. F., and Bredehoeft, J. D., 1978, Computer model of two-dimensional transport and dispersion in ground water: U.S. Geological Survey Techniques of Water Resources Investigations, chap. C2, book 7, 90 p.

LaForge, Laurence, 1932, Geology of the Boston area, Massachusetts: U.S. Geological Survey Bulletin 839, 105 p.

Lohman, S. W., and others, 1972, Definitions of selected ground-water terms--revisions and conceptual refinements: U.S. Geological Survey Water-Supply Paper 1988, 21 p.

Massachusetts Department of Public Works, 1976, Draft environmental impact report for the Snow and Ice Control Program: 398 p.

National Oceanic and Atmospheric Administration, 1971a, Climatological data: October, v. 83, no. 10.

_____1971b, Climatological data: November, v. 83, no. 11.

_____1971c, Climatological data: December, v. 83, no. 12.

_____1972, Climatological data, annual summary: v. 84, no. 13.

_____1973, Climatological data, annual summary: v. 85, no. 13.

_____1974, Climatological data, annual summary: v. 86, no. 13.

_____1975, Climatological data, annual summary: v. 87, no. 13.

_____1976, Climatological data, annual summary: v. 88, no. 13.

_____1977, Climatological data, annual summary: v. 89, no. 13.

Nelson, A. E., 1974, Surficial geologic map of the Natick quadrangle, Middlesex and Norfolk Counties, Massachusetts: U.S. Geological Survey Geologic Quadrangle Map GQ-1151.

_____1975, Bedrock geologic map of the Natick quadrangle, Middlesex and Norfolk Counties, Massachusetts: U.S. Geological Survey Geologic Quadrangle Map GQ-1208.

Ryder, R. B., Cervione, M. A., Jr., Thomas, C. E., Jr. and Thomas, M. P., 1970, Water resources inventory of Conneticut, part 4, southwestern coastal river basins: Conneticut Water Resources Bulletin No. 17., pp. 20 and 21.

Sammel, E. A., Baker, J. A., and Brackley, R. A., 1966, Water resources of the Ipswich River basin, Massachusetts: U.S. Geological Survey Water-Supply Paper 1826, pp. v-viii.

Simpson, G.S., Roe, Anne, and Lewontin, R.C., 1960, Quantitative zoology: New York, N.Y., Harcourt, Brace, and World, Inc., 440 pp.

Skougstad, M. W., Fishman, M. J., Friedman, L. C., Erdmann, D. E., and Duncan, S. S., eds., 1979, Methods for determining inorganic substance in water and fluvial sediments: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. A1, 626 p.

U.S. Water Resources Council, 1973, Essentials of ground water hydrology pertinent to water resources planning: Washington, D.C., 47 p.

Wandle, S. W., 1977, Estimating the magnitude and frequency of floods on natural-flow streams in Massachusetts: U.S. Geological Survey Water-Resources Investigations 77-39, 26 p.

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