GEOHYDROLOGY AND WATER QUALITY OF STRATIFIED-DRIFT AQUIFERS IN THE EXETER, LAMPREY, AND OYSTER RIVER BASINS, SOUTHEASTERN NEW HAMPSHIRE

By Richard B. Moore

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CONTENTS

PLATES

(Plates are in map jacket)

ILLUSTRATIONS

ILLUSTRATIONS--Continued

TABLES

CONVERSION FACTORS AND ABBREVIATIONS

For the convenience of readers who may prefer to use International System (SI) units rather than the inch-pound units used in this report, values may be converted by using the following factors.

Multiply inch-pound unit	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
gallon (gal)	3.785	liter (L)
million gallons (Mgal)	3,785	cubic meter (m^3)
	Flow	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per per square mile [(ft^3/s)/mi^2]	0.01093	cubic meter per second per square kilometer [(m^3/s)/km]
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Hydraulic Conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Transmissivity	
feet squared per day (ft^2/d)	0.09290	meters squared per day (m^2/d)

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

Geohydrology and Water Quality of Stratified-Drift Aquifers in the Exeter, Lamprey, and Oyster River Basins, Southeastern New Hampshire

By Richard B. Moore

ABSTRACT

A study was done by the U.S. Geological Survey, in cooperation with the State of New Hampshire Department of Environmental Services Water Resources Division, to describe the geohydrology and water quality of stratified-drift aquifers in the Exeter, Lamprey, and Oyster River basins in southeastern New Hampshire. Stratified-drift aquifers discontinously underlie 56 mi^2 of the Exeter, Lamprey, and Oyster River basins which have a total drainage area of 351 mi^2. Saturated thicknesses of stratified drift within these aquifers locally are as great as 100 feet thick, but generally are much less. Transmissivity values locally are greater than 3,000 ft^2/day but are generally much less.

Characteristics of stratified-drift materials that affect ground-water storage and movement are related to the original glaciofluvial environment in which they were deposited. Deglaciation of the western part of the study area occurred by a systematic process of stagnation-zone retreat that resulted in the deposition of eskers, kames, kame terraces, outwash, and outwash deltas. In the eastern part of the study area, where marine inundation occurred, the principal deposits are deltas formed at the inland marine limit and grounding-line deltas. Grounding-line deltas were formed during deglaciation at glacial-ice/ocean interfaces where meltwater entered the sea, and these are the most productive aquifers within the study area.

The geohydrology of stratified-drift aquifers was investigated by focusing on basic aquifer properties, including aquifer boundaries; recharge, discharge, and direction of ground-water flow; saturated thickness and storage; and transmissivity. Surficial geologic mapping assisted in the determination of aquifer boundaries. Data from more than 1,200 wells, test borings, and springs were collected, principally from areas of stratified drift, and stored in the U.S. Geological Survey's Ground Water Site Inventory (GWSI) data base. These data were then used to produce maps of water-table configuration, saturated thickness, and transmissivity of stratified drift. Seismic-refraction profiles were completed at 26 locations in the study area. These profiles aided in the construction of the water-table and saturated-thickness maps.

Two aquifer areas, West Epping and Newmarket Plains, were selected to evaluate the use of a superposition technique in conjunction with a digital-flow model. The results demonstrate that the amount of water that potentially is available is greatest in aquifers where induced infiltration from streams occurs. The sizes of the areas of contribution to wells estimated using the model results are 1.7 mi^2 for the West Epping aquifer and 0.38 mi^2 for the Newmarket Plains aquifer.

Water samples from 38 test wells and 2 springs were collected and analyzed to assess background water quality within the aquifers. Known areas of contamination were avoided, including three sites that are

on the National Priority List of hazardous-waste sites established by the U.S. Environmental Protection Agency. Apart from these problem areas, results of the sampling program show that water in the stratified-drift aquifer generally meets Environmental Protection Agency (EPA) drinking-water regulations and recommended limits, with some exceptions. One sample had a 280 mg / L chloride concentration and 12 samples had sodium concentrations that exceeded 20 mg / L (mainly from road salt); 5 samples had iron concentrations that exceeded 1,000 µg / L and 27 samples had manganese concentrations that exceeded 50 µg / L (of natural origin). Other evidence of possible degraded ground-water conditions include one sample with a chromium concentration of 50 µg / L, one sample with a mercury concentration of 4 µg / L, two samples with elevated arsenic concentrations of 14 and 11 µg / L, and one sample with detectable concentrations of volatile organic compounds.

INTRODUCTION

The population of southeastern New Hampshire increased by 30 percent between 1970 and 1980, and it is expected to increase rapidly in the foreseeable future (New Hampshire Office of State Planning, 1985). Economic development has been especially rapid in southeastern New Hampshire due to the area's proximity to metropolitan Boston. This growth has steadily increased demands for water and stressed the capacity of the existing municipal-water systems, which depend on aquifers as a primary source of water.The U.S. Geological Survey, in cooperation with the State of New Hampshire, has ongoing ground-water investigations in New Hampshire which provide detailed geohydrologic information necessary to ensure optimal use of existing water sources and for the development of new ones. The area covered by the present study includes the Exeter, Lamprey, and Oyster River basins and some intervening areas which flow directly into Great Bay (fig. 1). In this report for the sake of convenience, the Exeter River and its lower reach, the tidally influenced Squamscott River, are referred to as the Exeter River. Surface-water drainage basins were selected as the study units because they are a natural subdivision of the hydrologic system, and in southeastern New Hampshire, only a few stratified-drift aquifer extend across major ground-water divides.

Purpose and Scope

The purpose of this report is to (1) describe the hydrologic and geologic characteristics of the stratified-drift aquifers within the study area, including areal extent of the stratified-drift aquifers, ground-water levels, general directions of ground water flow, saturated thicknesses, and transmissivities; (2) present a technique for evaluating the hydrologic impact of ground-water development, and (3) assess the quality of the ground water in stratified-drift aquifers.

The study was generally limited to the collection, compilation, and evaluation of data from the stratified-drift aquifers in the study area. Two of the aquifers, West Epping and Newmarket Plains, were evaluated with a superposition modeling technique to illustrate how this method can be used to evaluate aquifer yields and estimate the configuration of contributing areas after 180 days of pumping.

Related Studies

Previous studies include a basic data report for wells and springs in southeastern New Hamphsire by Bradley and Petersen (1962) and the accompanying interpretive report on the ground-water resources by Bradley (1964). A reconnaissance map of the availability of ground-water in the Piscataqua and other coastal river basins was presented by Cotton (1977) on a map at a scale of 1:125,000. An advanced reconnaissance report of the Lamprey River basin (Cotton, 1987) also has recently been completed. These studies indicated that more information was necessary to improve understanding of the ground-water flow systems and the definition of aquifer boundaries and to evaluate ground-water quality.

Surficial geologic maps for parts of the study area are being produced as 7.5-minute quadrangle maps by the Cooperative Geologic Mapping (COGEOMAP) program (a program between various states and the U.S. Geological Survey). For New Hampshire, the New Hampshire Department of Environmental Services, Office of the State Geologist is the cooperator in this program. Three maps have already been published (Earl, 1983b; Gephart, 1985a and 1985b) and field work completed for the Sandown, Exeter, Epping, and Newmarket quadrangles.

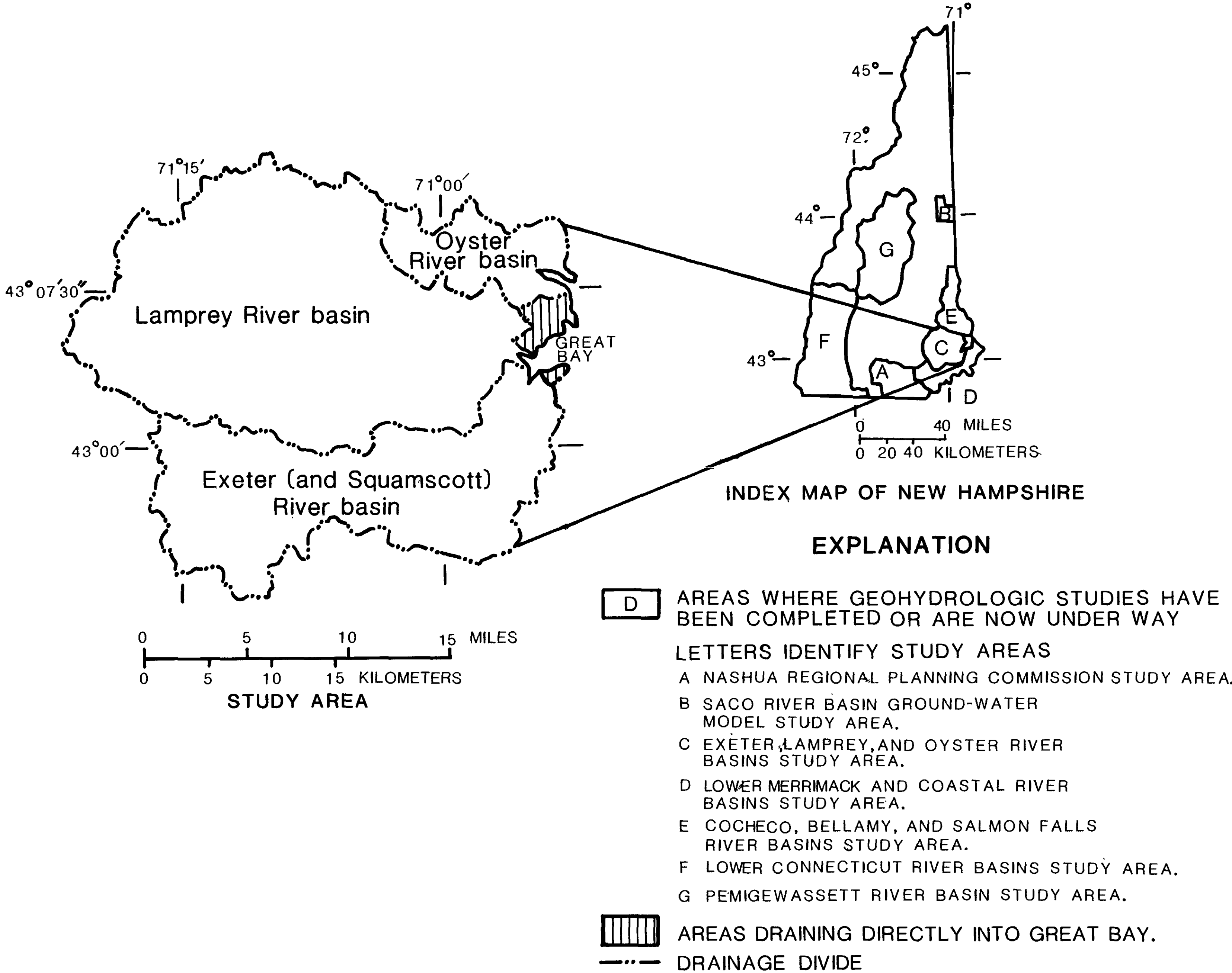


Figure 1.--Location of the Exeter, Lamprey, and Oyster River basins in southeastern New Hampshire.

Glacioestuarine silts and clays in southeastern New Hampshire have been and are being studied by Dr. Francis S. Birch and students at the University of New Hampshire (Birch, 1977; and F. S. Birch, Department of Earth Sciences, University of New Hampshire, written commun., 1987).

Approach and Methods

The following approach and methods were used in this study:

1) Areal extent of the stratified-drift aquifers was mapped with the aid of soils maps (U.S. Soil Conservation Service, 1973, and unpublished U.S. Soil Conservation Service data) and surficial geologic maps produced by the COGEOMAP program (1:24,000 scale). Some surficial geologic maps were also were constructed as part of this study.

2) Existing subsurface data on ground-water levels, saturated thickness, and stratigraphy of stratified-drift aquifers were compiled and data were reviewed for deficiencies. These data were obtained from published and unpublished sources of the U.S. Geological Survey and the New Hampshire Department of Environmental Services. Additional data were obtained from municipalities, local residents, well-drilling contractors, the New Hampshire Department of Public Works and Highways, and the University of New Hampshire. The location of wells, test borings, springs, and seismic lines were plotted on base maps, and their pertinent data were added to the GWSI (Ground Water Site Inventory) data base maintained by the U.S. Geological Survey. Each well, and test boring is cross referenced to a well-identification number, original driller, owner, and numerous other pertinent information.

3) Seismic-refraction profiling, a geophysical technique, was done at 27 locations in the study area to determine depths to the water table and to bedrock for use in determining aquifer saturated thickness. Locations of the profiles are shown on plates 1-4. A 12-channel, signal-enhancement seismograph was used to measure time-of-travel for a sound wave from a shot point to 12 geophone locations. Altitudes of geophones and shot points were determined by leveling to a common datum. The seismic data were interpreted with a Fortran computer-language program, developed by Scott and others (1972), that uses time-delay and ray-tracing methods. Data from nearby wells and test holes, where available, were used to verify the results of the computer program.

4) Test borings were made at 57 locations to better define the geometry, hydrologic characteristics, and stratigraphy of the stratified-drift aquifers. Their locations are shown on plates 1-4. Split-spoon samples of subsurface materials were collected at specific depths to evaluate the grain-size characteristics and identify the stratigraphic sequence of materials comprising the aquifers. Forty-three test borings were finished as observation wells with 2-inch polyvinyl chloride casing, and slotted well screen. Water levels were measured and samples were collected from these wells.

5) Data from items 2, 3, and 4 were used to construct maps showing the water-table configurations and saturated thicknesses of the stratified-drift aquifers.

6) Hydraulic conductivities of aquifer materials were estimated using grain-size-distribution data from 122 samples of stratified drift. Transmissivity values were estimated from well and test-boring logs by assigning hydraulic conductivity values to specific intervals, multiplying these values by the saturated thickness of the interval, and summing the results. Additional transmissivity values were obtained from reports by consultants or calculated from pump-test data. This information was then used to prepare maps showing the transmissivity distribution of the stratified-drift aquifers.

7) Two aquifers, West Epping and Newmarket, were selected to demonstrate an aquifer-evaluation technique based on the principal of superposition and the flow model developed by McDonald and Harbaugh (1984). This technique was used to estimate long-term aquifer yields and the size of the contributing areas that would develop around pumping centers. Aquifers selected for this analysis are examples of different types of local aquifer systems.

8) Flow-duration data from four streams in or near the study area were analyzed and used to investigate how unregulated streamflow is related to the areal percentage of coarse stratified drift in a basin. Streamflow estimates are important, especially under low-flow conditions, because they are important considerations in determining the yields of aquifers.

9) Samples of ground-water from 38 test wells and 2 springs were collected and analyzed. Standard characteristics (specific conductivity, pH, temperature) and concentrations of selected organic constituents were measured. The data provided by these analyses were used to assess the general quality of water from the stratified-drift aquifers.

Numbering System for Wells, Borings, and Springs

Local numbers assigned to wells, test borings, and springs consist of a two-letter town designation (table 1), a supplemental letter designation ("A" for borings done for hydrologic purposes with no casing set, "B" for borings done primarily for constructional purposes, "S" for springs, and "W" for all wells in which a casing was set), and a sequential number within each town. For example the first well in the town of Lee is LIW 1.

Acknowledgments

The author would like to thank the many State, Federal, and municipal officials, residents, well contractors, and consulting firms who provided data for this study. Included are personnel from: the Office of the State Geologist; the New Hampshire Water Resources Division; the University of New Hampshire; the Geologic Division of the U.S. Geological Survey; and the U.S. Soil Conservation Service. The author would also like to express his appreciation to all those who assisted in data collection, especially Timothy Fagan and Diana Morgan. Thanks go to Rick Chormann of the New Hampshire Water Resources Division for assisting in the development of computer programs to automatically transfer data from their computer data base to the Survey's data base.

GEOHYDROLOGIC SETTING

Three types of aquifer materials that occur in the study area are (1) stratified drift, which is a major source of ground water for towns and cities; (2) till, which locally can supply minor amounts of water for households; and (3) bedrock, which has a variable supply but provides many households with water.

Stratified Drift

Coarse stratified drift, the focus of this study, consists of stratified, sorted, dominantly coarse-grained sediments (sands and gravels) deposited by glacial meltwater at the time of deglaciation. Hydrologic characteristics of these sediments that affect ground-water storage and movement are related to the

Table 1.--*Two-letter town codes used as prefixes in the numbering system for wells, borings, and springs*

Town	Two-letter code	Town	Two-letter code
Barrington	BB	Hampstead	HD
Brentwood	BW	Hampton Falls	HF
Candia	CD	Kensington	KF
Chester	CL	Kingston	KT
Danville	DC	Lee	LI
Deerfield	DD	Madbury	MA
Dover	DJ	Newfields	NG
Durham	DP	Newmarket	NM
East Kingston	EA	Nottingham	NX
Epping	EP	Raymond	RB
Exeter	EX	Sandown	SD
Fremont	FM	Stratham	SS

glaciofluvial environment in which they were deposited. Stratified-drift deposits are composed of distinct layers of sediments with different grain-size distributions, sorted according to the depositional environment. For example, swiftly moving meltwater streams are apt to deposit coarse-grained sediments with large pore spaces between grains. If saturated, these materials generally form good aquifers--able to store and transmit ground water readily. As water slows, fine-grained materials including fine silts and clays are deposited in lakes, ponds, estuaries, and the ocean; these deposits do not transmit water freely.

The original environment of deposition affects the size and arrangement of voids or pore spaces between sediment particles, and these characteristics determine the capacity of the aquifer material to store and transmit ground water. Large, interconnected pore spaces readily transmit ground water and provide a large volume of ground-water storage. The ratio of total volume of pore space to the total volume of sediment is a measure of the space available for ground-water storage. A more useful measure of ground-water storage is specific yield--the ratio of the volume of water that can be drained by gravity to the total volume of the sediment. Total volume of pore space per total volume of sediment and specific yield are not equal because some water is held on the grain surfaces by tensional forces and will not drain by gravity. These characteristics are related to the original depositional environment of the sediments, and, thus, the term "stratified-drift aquifer" refers to several different types of aquifers, depending on the original mode of deposition.

The deglaciation process had a pronounced effect in determining the type of aquifer that was formed. Deglaciation of the western part of the study area is believed to have occurred by a systematic process of stagnation-zone retreat (Koteff and Pessl, 1981). During deglaciation, the active glacial-ice margin receded to the north leaving behind zones of stagnant ice in contact with the active ice margin. The stratified-drift aquifers found in this area are termed valley-fill aquifers and are composed of eskers, kames, kame terraces, outwash, and outwash deltas. Deglaciation of the eastern part of the study area was accompanied by marine inundation and glacial ice was in contact with the ocean. Aquifers there are different from the valley-fill aquifers to the west. They are exclusively deltaic deposits that subsequently have been modified by beach processes and now form topographic highs in the area. The aquifer index map, figure 2, shows the inland extent of marine inundation, as inferred from the areal distribution of glacioestuarine silts and clays. In the southern part of the study area (area 11 in fig. 2) the marine inundation continued further inland than the exposures of silts and clays indicate. In this area the glacioestuarine silts and clays are buried beneath outwash and beach deposits (Earl, 1983b).

Valley Fill

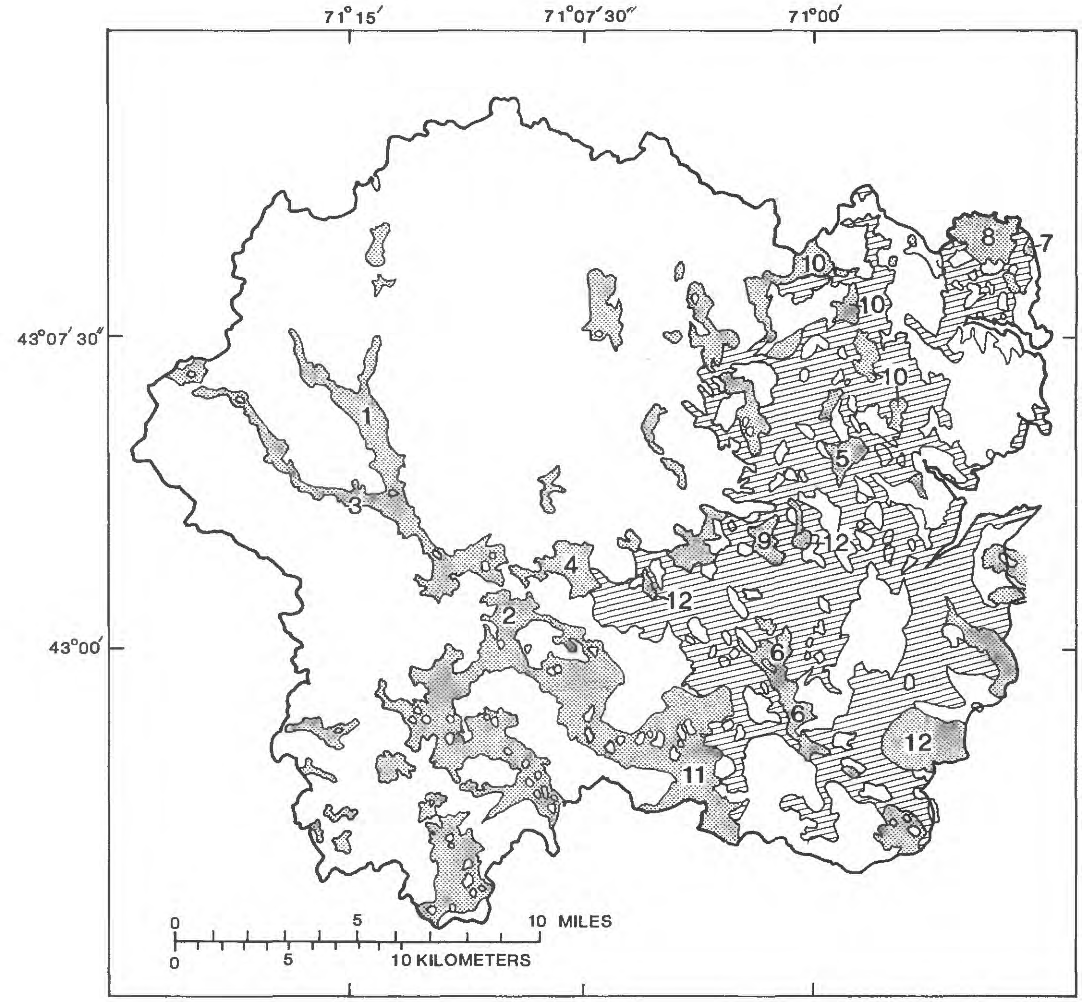
A block diagram showing the various types of deposits that comprise the valley-fill aquifers in the western upland part of the study area is shown in figure 3. These deposits are well represented in the area of the fairgrounds at Deerfield, discussed below and are referred to as the Deerfield valley-fill aquifer in this report.

Eskers are long ridges of sand and gravel deposited in the meltwater channels within the zone of ice stagnation during deglaciation. Examples of eskers are found near the fairgrounds at Deerfield (location 1, figs. 2, 3 and 4), and in Raymond, N.H. (location 2, fig. 2). These eskers have been extensively mined for sand and gravel. The esker near the fairgrounds at Deerfield is among the oldest of the stratified-drift deposits at that locality and was deposited at a time when stagnant glacial ice surrounded the area. As the ice melted from around the esker, outwash deposits were deposited on the flanks. These outwash deposits are deltaic in places (fig. 5) where meltwater streams entered shallow-ponded water. Areas where the stagnant ice persisted the longest contain kettle holes. These depressions either never fully filled in or exist where blocks of ice were buried and subsequent melting of the ice resulted in collapse.

The kame terraces located near the Deerfield Fairground probably were formed early in the sequence, perhaps at the same time as the nearby esker. Another excellent example of a kame terrace is located in the western part of Raymond (location 2, fig. 2). A geologic section through the Deerfield valley-fill aquifer (fig. 6) shows stratigraphic relations among the various units.

Glacioestuarine Deltas

Stratified-drift aquifers found in the eastern part of the study area, where marine inundation occurred, formed as deltas in a glacioestuarine environment.



EXPLANATION

[4] STRATIFIED-DRIFT AQUIFERS

GLACIOESTUARINE SILTS AND CLAYS

NUMBERS IDENTIFY LOCATIONS OF DEPOSITS

1, Valley fill in fairgrounds at Deerfield
2, Esker in Raymond
3, Kame terrace in Raymond
4, Shoreline delta at West Epping
5-8, Grounding-line delta:
  5, at Newmarket Plains
  6, studied by Earl (1983a)
  7, at Back Bay
  8, at Pudding Hill
9, Shoreline delta near Camp Hedding in Epping
10, Other grounding-line deltas
11, Deposits in which the water table was difficult to map
12, Deposits with stratified-drift aquifer material buried beneath glacioestuarine silts and clays

—— BOUNDARY OF STUDY AREA

—— BOUNDARY OF STRATIFIED-DRIFT AQUIFER OR GLACIOESTUARINE SILTS AND CLAYS

Figure 2.--Location of stratified-drift aquifers and glacioestuarine silts and clays.

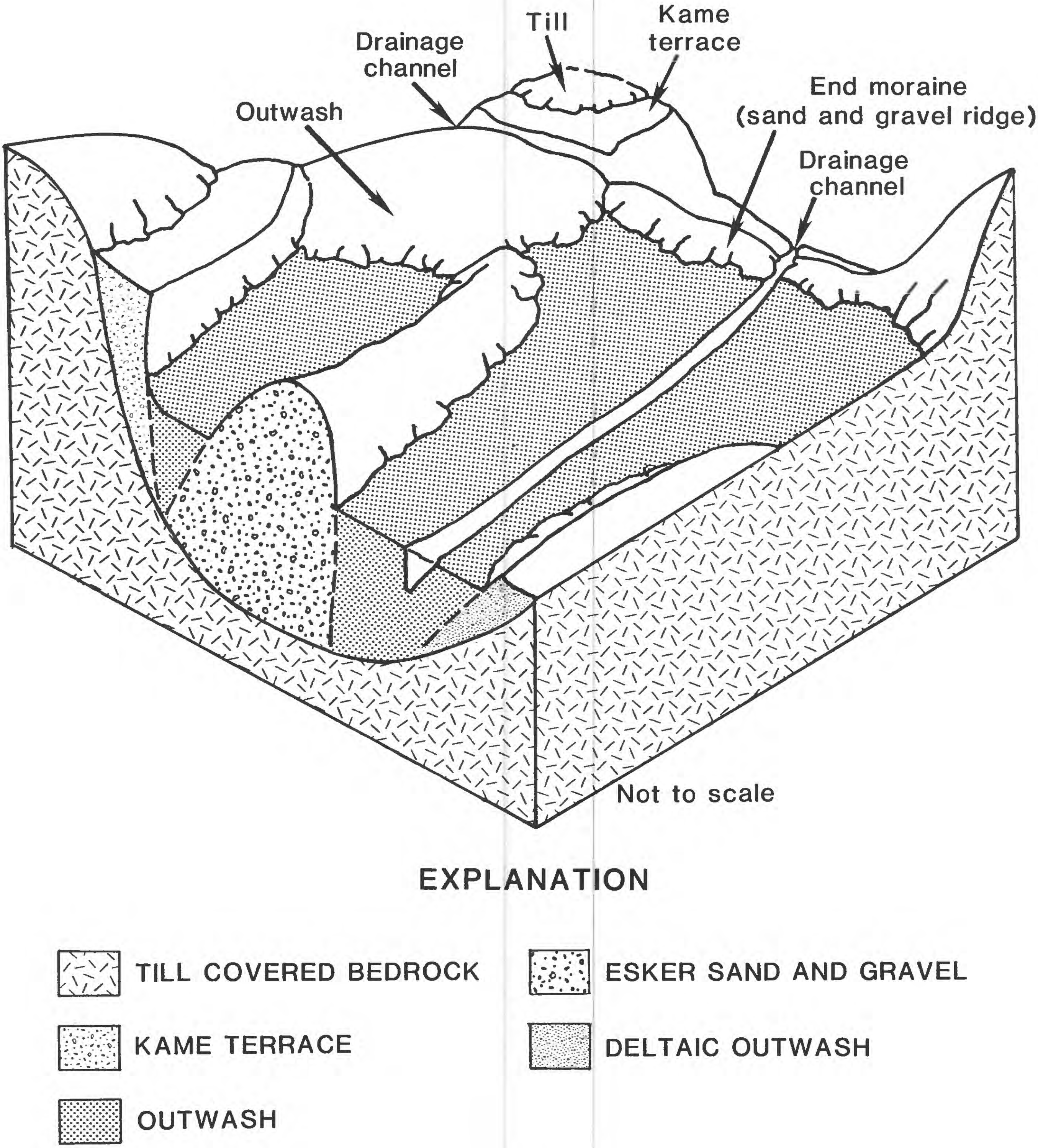
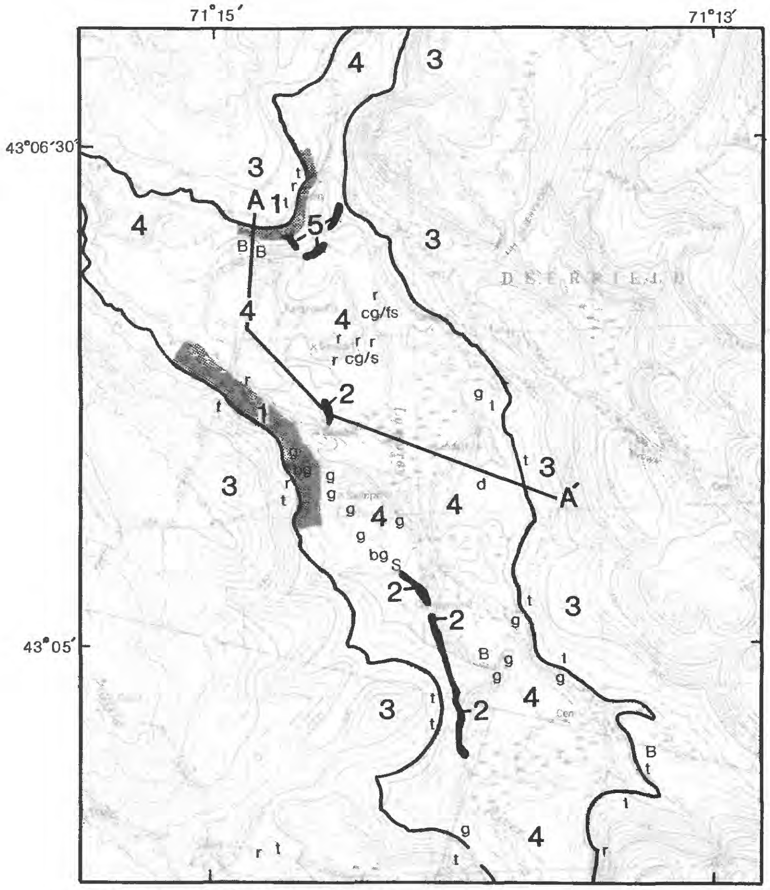


Figure 3.--Valley-fill deposits at the Deerfield Fairgrounds.



Base from U.S. Geological Survey
Candia, NH, 1969, and
Mt. Pawtuckaway, NH,
1981, 1:24,000

0 .5 1 MILE
0 .5 1 KILOMETER
CONTOUR INTERVAL 10 FEET
NATIONAL GEODETIC VERTICAL
DATUM OF 1929

EXPLANATION

A–A′ LINE OF GEOLOGIC SECTION

4 NUMBERS IDENTIFY GEOLOGIC FEATURES.
1, Kame Terraces
2, Esker ridges
3, Till and bedrock
4, Outwash
5, End moraine - ridge of sand and gravel

bg FIELD OBSERVATION LOCATION:
g, Sand and gravel
bg, Sand and boulder gravel
d, Deltaic outwash
t, Till
r, Bedrock
cg/s, Sand with cobbles over sand
cg/fs, Sand with cobbles over fine sand
B, Large boulders on land surface or in stream bed

—— AQUIFER BOUNDARY

Figure 4.--Deerfield valley-fill aquifer.

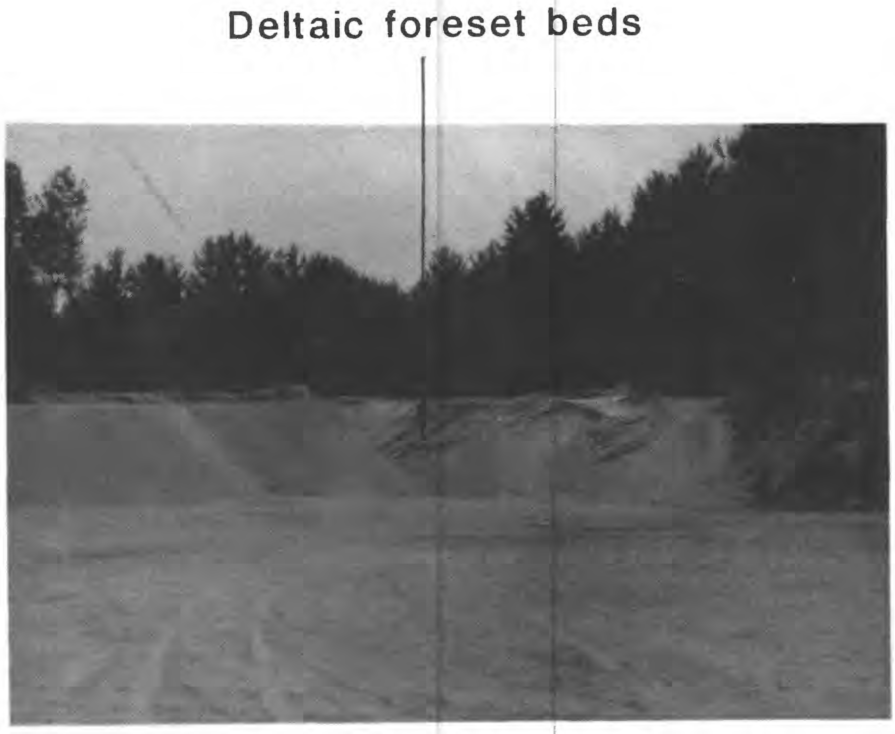


Figure 5.--Deltaic foreset beds within the Deerfield valley-fill aquifer.

These deltas formed during deglaciation at either the marine limit (not in contact with the glacial ice) or at grounding lines, which are glacial-ice/ocean interfaces.

Shoreline Deltas

The delta at West Epping (location 4, fig. 2) is an example of the type of aquifer formed at the marine limit and it is referred to as the West Epping aquifer in this report. It was formed where meltwater, following the path of what is now Pawtuckaway Brook, entered the ocean. The delta probably did not form in contact with glacial ice, because the source-end of the delta abuts the valley wall. Typically this type of aquifer tends to be fine grained and has a lower hydraulic conductivity than do the grounding-line deltaic aquifers to the east because deposition occurred at a greater distance from the glacial ice. A geologic section through the area (fig. 7) illustrates that the delta built out to the southeast, prograding seaward over glacioestuarine silts and clays. The delta was subsequently eroded by the Lamprey River, which removed some material and now flows across the aquifer.

Another example of this type of delta is found in the area of Camp Hedding in Epping (location 9, fig. 2). The flat, sandy deposit near the entrance to Camp Hedding seems to be the seaward margin of a delta. Much of the area is composed of sand overlying clay presumably where deltaic foreset beds prograded out over prexisting glacioestuarine deposits. The Lamprey River also eroded this delta and removed a large amount of material from the source end. The delta probably also has been extensively modified by beach processes.

In Kingston, Brentwood, and the eastern part of Fremont, sediment-laden meltwater entered the estuary system during deglaciation, blanketed the lowlands with sand and gravel and covered the estuarine silts and clays (Earl, 1983a). Thicknesses of the sand and gravel differ considerably--from less than 2 feet to more than 50 feet. Reworking of sediments by beach processes probably contributed to the spread of sands and gravels over the area. Deposition probably occurred at a late stage when sea level was dropping relative to the land and shoreline deposition was gradually moving eastward.

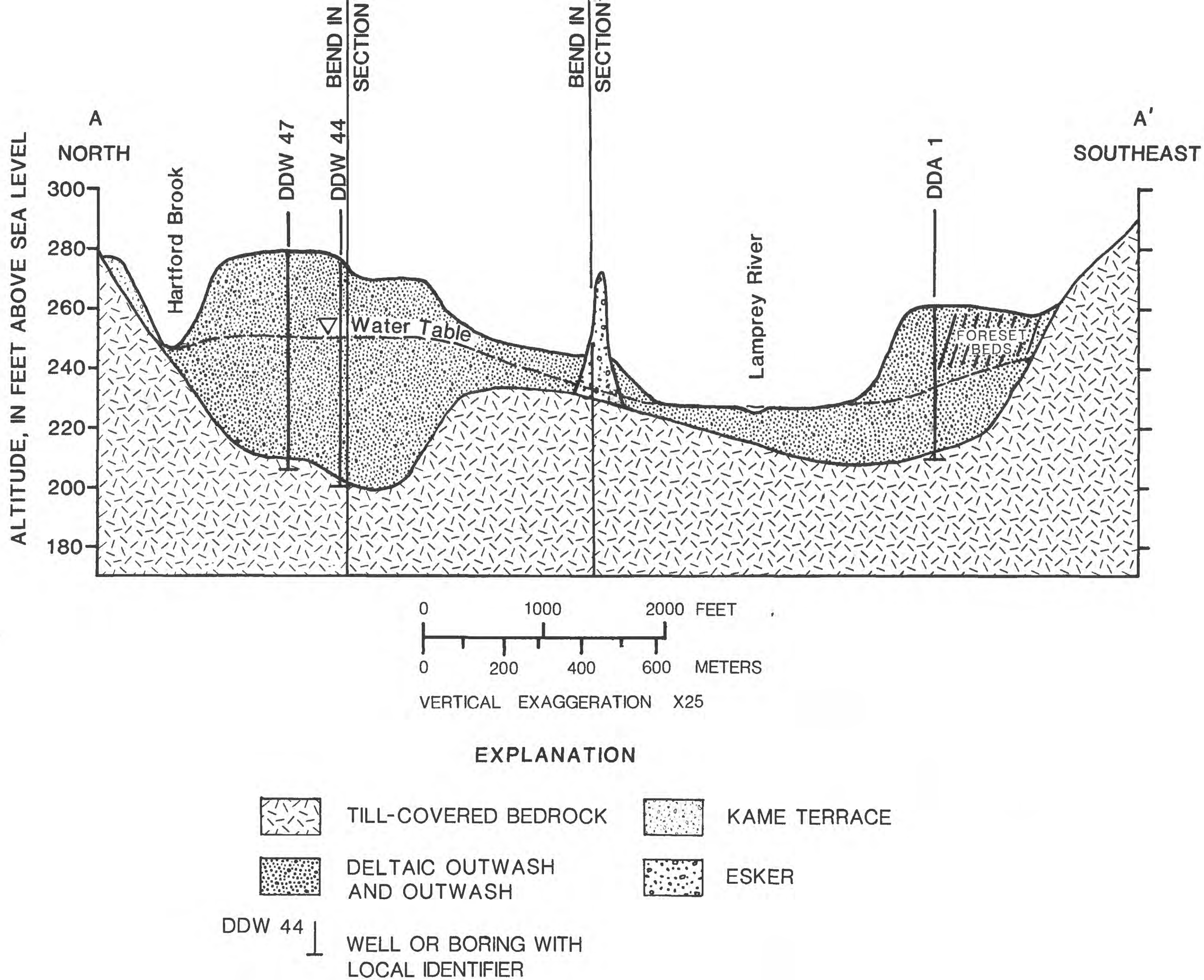


Figure 6.--Deerfield valley-fill aquifer, location shown in figure 4 and plate 1.

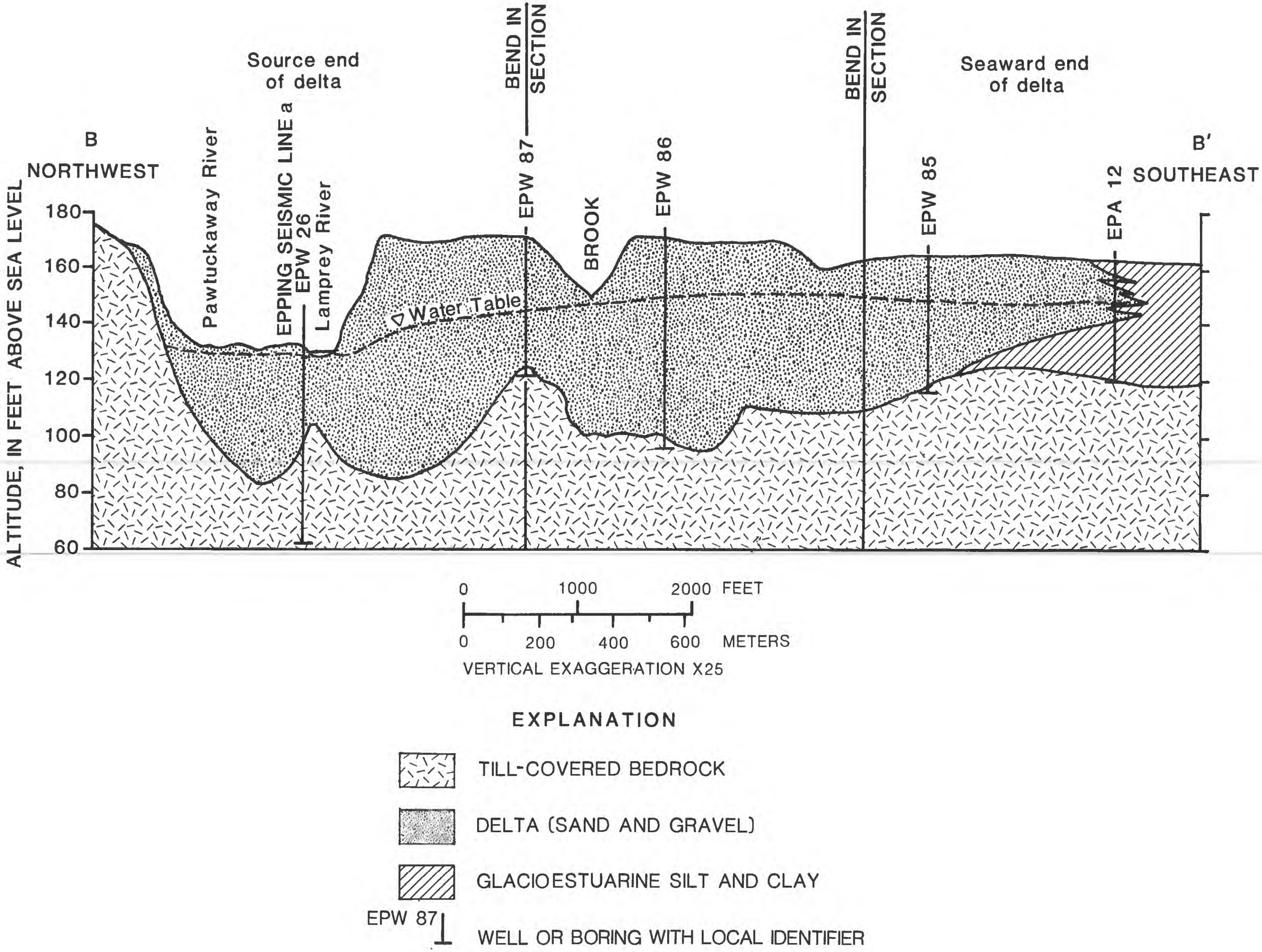


Figure 7.--West Epping aquifer, location shown in plates 3 and 4.

Grounding-line deltas

Grounding-line deltas were formed where glacial meltwater entered the ocean at the glacial-ice/ocean interface. This interface, or grounding line, moved from east to west through what is now the study area during the period of deglaciation. Active glacial ice was mostly removed by calving, and marine transgression occurred as a result.

Grounding-line deltas are the most productive aquifers within the study area. They generally are coarser grained and more permeable than deltas formed at the marine limit because of the high energy of the original glaciofluvial environment in which they were deposited. The grounding-line deltas also are thicker locally than the other aquifers in the study area. In addition, they are more numerous than the deltas formed at the marine limit, and more of them are being used for municipal water supplies.

Grounding-line deltas are found throughout the area of marine inundation and are identified in figure 2 (locations 5-8 and 10). These are slightly older deposits than the deltas formed at the marine limit because they were deposited while glacial ice still partly covered the eastern half of the study area. Some geologists have argued that these deposits are not deltas but kames deposited as the ice retreated on land (Goldthwait and others, 1951; Tuttle, 1952). The view that these deposits were formed as deltas at the glacial-ice/ocean interface was first proposed by Katz and Kieth (1917) and later supported by Moore (1978, 1982), Hensley (1978), Thompson (1982), Earl (1983a), and Koteff (Carl Koteff, U.S. Geological Survey, personal commun., 1986).

Grounding-line deltas may have formed as the result of deposition of material fed by meltwater from the top of the glacier or fed by meltwater from below the glacier (fig. 8). Recent work indicates that the highest of the deltas have tops (that is, topset-foreset contacts) that fall on a single plane (Carl Koteff, U.S. Geological Survey, personal commun., 1986). This could have occurred only if the deltas were built up to the sea level of that time, in which case meltwater would have been supplied to the top of the delta at sea level. However, another possibility is that the deltas could have been fed initially by meltwater from below and later been fed from above as the glacial ice thinned (that is, going from method A to B in figure 8).

The Newmarket deposit (location 5, fig. 2 and pl. 2) is a good example of grounding-line deltaic aquifer and it is referred to as the Newmarket Plains aquifer in this report. Deltaic foreset beds indicate a southern direction of meltwater flow during deposition, and the ice-contact side of this delta is to the northwest (figs. 9 and 10). The top of this delta falls well below the plane corresponding to sea level during deglaciation. For some unknown reason, it never built up to sea level or if it did subsequent beach erosion has lowered it considerably.

Till

Till is an unsorted mixture of clay, silt, sand, gravel, and rock fragments, deposited directly by glacial ice. In the study area, it is discontinuous on the bedrock surface and is generally thin. The type of till commonly encountered during the course of this investigation consists of an upper, brownish, presumably oxidized till, underlain by a compact, grayish till. The thickest sequences of till are composed of lodgement till in drumlins. In the eastern half of the study area, most drumlins overlie bedrock of the Eliot Formation (Bradley and Petersen, 1962; Novotny, 1969; Birch, 1980), which, according to the Interim Geologic Map of New Hampshire (Lyons and others, 1986) is Ordovician(?) to Precambrian in age.

The till aquifer generally is considered to be a minor source of ground water because of its low transmissivity. Large-diameter dug wells in till can provide modest amounts of water for household needs, but water-level fluctuations within till can be quite large, making these wells much less reliable during dry seasons. Ablation tills containing lenses of stratified material are the most productive till deposits. Because sorted stratified drift and ablation tills may grade into one another, the distinction between the two material types may not always be clear cut.

Bedrock

The Exeter, Lamprey, and Oyster River basins are underlain mainly by metamorphic rocks of Ordovician(?) to Precambrian age that were originally deposited as sediments (Lyons and others, 1986). These are intruded by lesser amounts of granite, diorite, granodiorite, and gabbro of Ordovician age (Lyons and others, 1986). A circular complex of intrusive rocks of Cretaceous age forms the Pawtuckaway Mountains in the west-central part of the study area. The structure of the metamorphic rock strikes

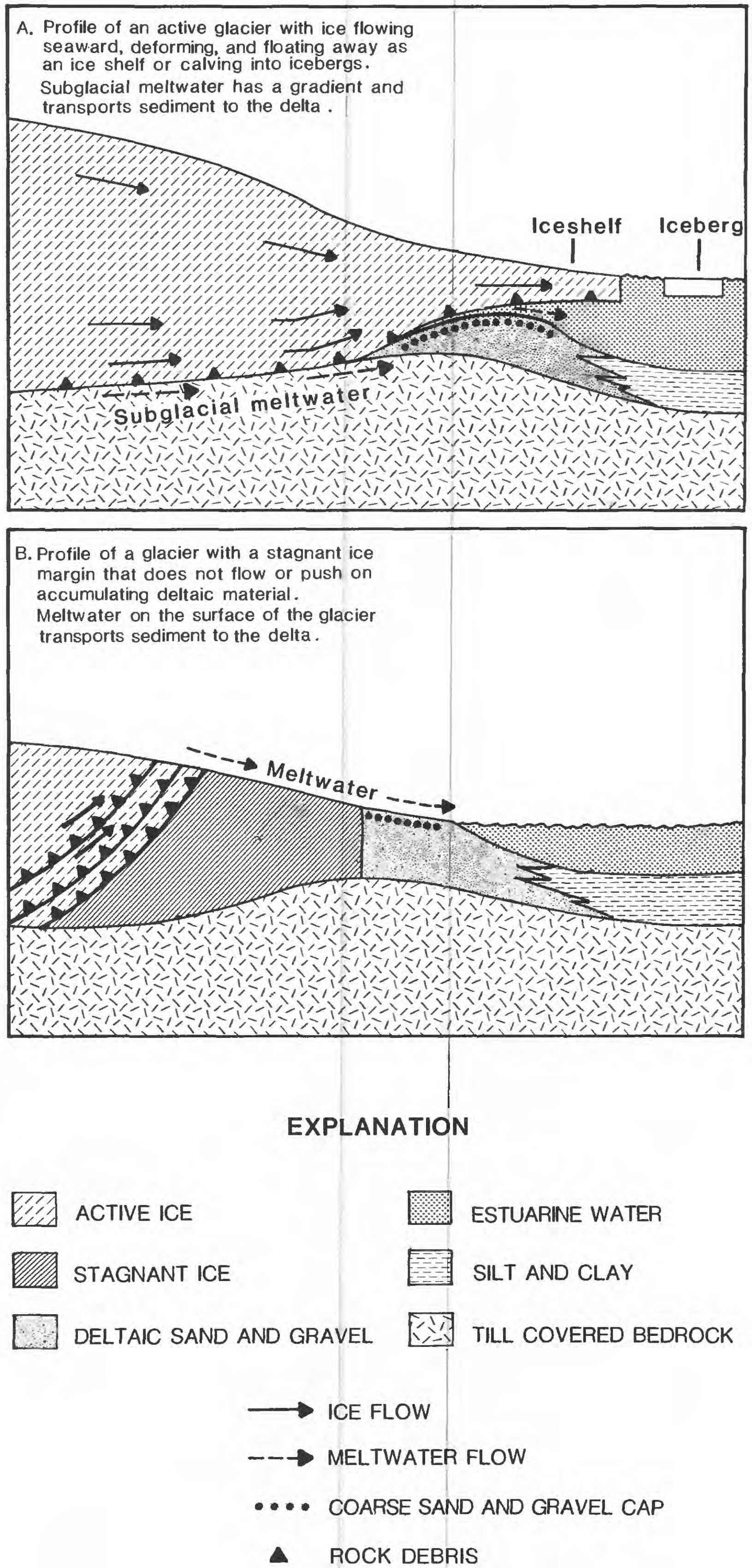


Figure 8.--Two possible models for the deposition of grounding-line deltas formed at the contact of glacial ice and the ocean.

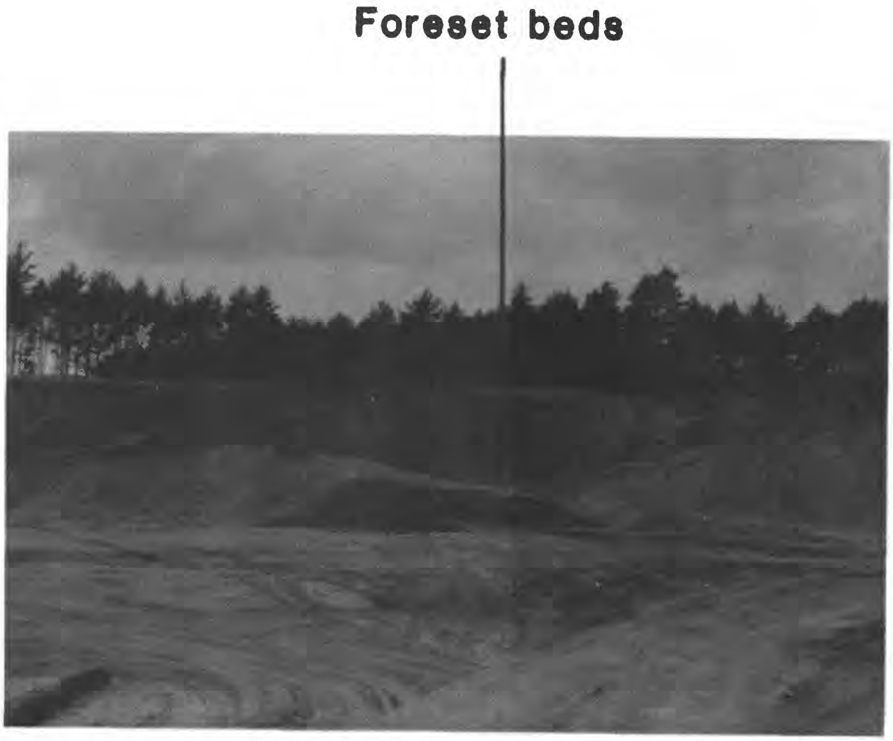


Figure 9.--Deltaic foreset beds within the Newmarket Plains aquifer.

predominantly northeast-southwest, and major faults in the study area are oriented parallel to this regional northeast-southwest strike of the bedrock; lesser faults cut across the bedrock structural grain.

Ground water available to wells fills fractures within these rocks. The capacity of the bedrock to store and transmit ground water is limited by the number, size, and degree of interconnection of fractures. Wells that penetrate bedrock commonly yield small supplies of water generally adequate for individual households. In areas where the bedrock is extensively fractured, higher yields may be obtained. Six municipalities in New Hampshire, all outside the study area, have wells in crystalline bedrock that yield 0.5 Mgal/d (million gallons per day) or more (U.S. Geological Survey, 1985).

GEOHYDROLOGY OF STRATIFIED-DRIFT AQUIFERS

The geohydrology of the stratified-drift aquifers was described by identifying (1) aquifer boundaries; (2) direction of ground-water flow from recharge to discharge areas; (3) aquifer thickness and storage; and (4) aquifer transmissivity. Data sources in this investigation include surficial geologic maps, records of wells and test borings and seismic-refraction profiles. Results of the geohydrologic investigation are presented on plates 1-8.

Delineation of Aquifer Boundaries and Water Table

The stratified-drift aquifers in the study area are comprised of coarse-grained sand and gravel deposited by glacial meltwaters as valley-fill deposits and glacioestuarine deltas.

Lateral aquifer boundaries correspond to the extent of the coarse-grained deposits delineated on surficial geologic maps. Bottom aquifer boundaries are determined from well logs and geophysical data.

Areal Extent of Stratified-Drift Aquifers

The areal extent of coarse-grained stratified-drift aquifers is shown on plates 1-4 and in figure 2. Also shown are the locations of glacioestuarine silts and

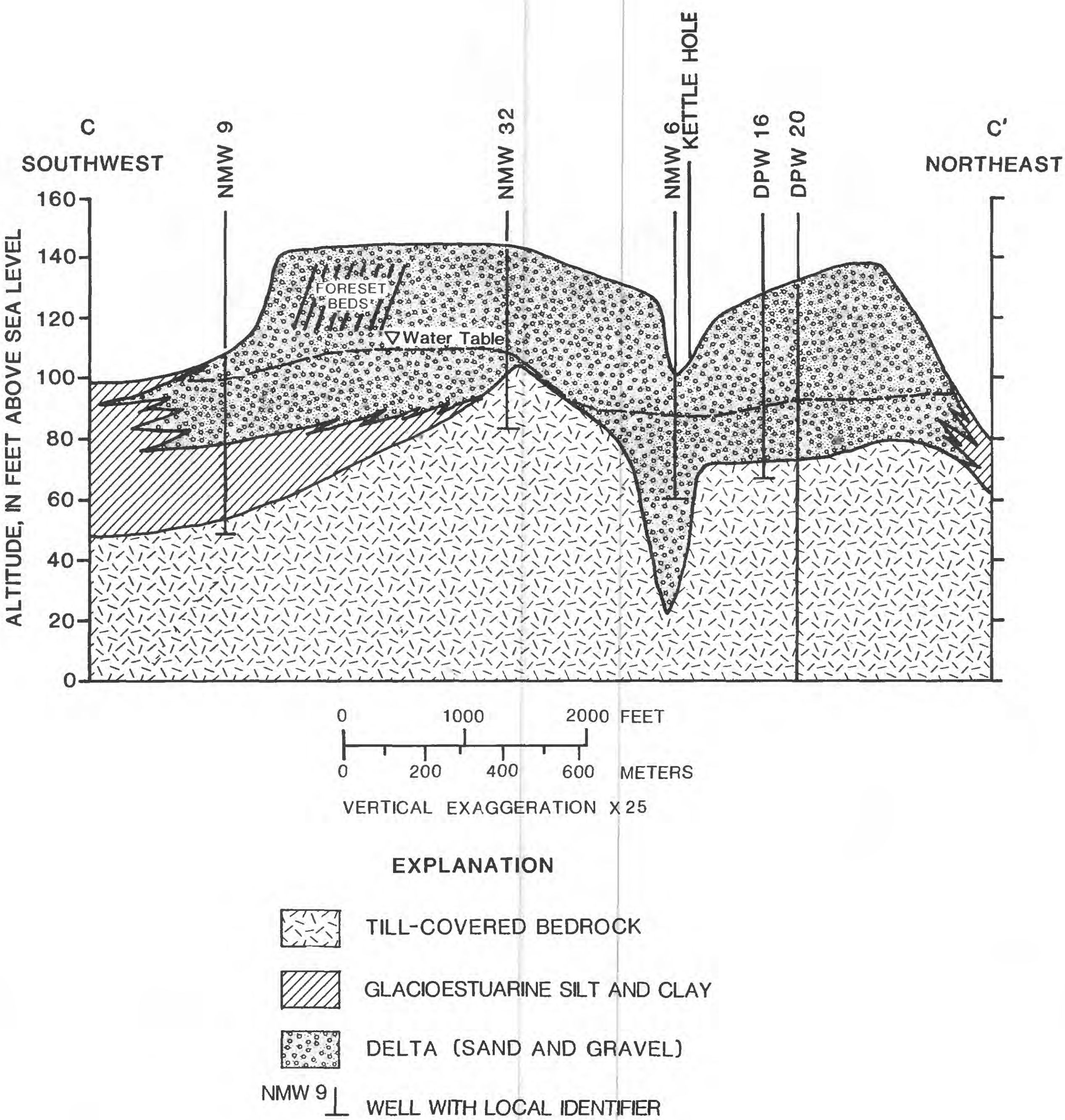


Figure 10.--Geologic section through the Newmarket Plains aquifer, location shown in plate 2.

clays. Coarse-grained aquifer material underlies some areas of silt and clay, as indicated on plate 4 and in figure 2. The same conditions may exist elsewhere within the study area. Although the silts and clays themselves cannot supply enough water to wells even for domestic purposes, the buried coarse-grained material locally is an important aquifer.

A major source of data for delineating aquifer boundaries and the extent of the silts and clays was 1:24,000-scale, surficial-geologic maps being produced by the COGEOMAP program. These surficial geologic maps are Candia (Gephart, 1985a); Derry (Gephart, 1985b); Kingston (Earl, 1983a); Epping, Exeter, Newmarket, and Sandown (Gregory Gephart, Office of the New Hampshire State Geologist, written commun. 1986). The remainder of the study area was specifically mapped as part of this study and includes parts of the Barrington, N.H.; Dover West, N.H.-Me.; Gossville, N.H.; and Northwood, N.H., quadrangles; and all of the Mt. Pawtuckaway, N.H., quadrangle. Only aquifer boundaries are shown on the maps produced specifically for this study.

The aquifer-boundary maps shown on plates 1-4 are simplified surficial geologic maps. These maps show the areal extent of the stratified-drift deposits that contain sufficient saturated permeable material to yield significant quantities of water to wells and springs. Surficial geologic maps show several additional features not included on the aquifer-boundary maps. One such feature, swamp deposits, can conceal aquifer boundaries.

Most aquifer boundaries delineated in plates 1-4 are shown as solid lines. The explanation for the plates identifies solid lines as "approximately located" because the boundary locations, which they represent, can not be assured with the accuracy a solid line would otherwise indicate. A solid line contact on a 1:24,000-scale U.S. Geological Survey map implies a ±80-foot horizontal accuracy. In most areas, especially in the upland western part of the study area where there is significant vertical relief, the solid-line boundaries probably are plotted with nearly this accuracy. Delineating surficial-geologic contacts and aquifer boundaries is more difficult in the eastern part of the study area where marine inundation occurred, because the topography is gently rolling and less indicative of changes in relief at aquifer boundaries. Delineation of aquifer boundaries within the area of marine inundation potentially is prone to greater error than those in the uplands.

Stratigraphic position of lithologic units and altitude of water table

Ground Water site inventory

Locations where inventoried subsurface data exists for wells, bore holes, and springs are plotted on plates 1-4. Pertinent information for more than 1,200 locations have been added to the U.S. Geological Survey computerized GWSI (Ground Water Site Inventory) data base and the data base has been checked for accuracy. As part of this process, a set of computer programs was developed to transfer automatically New Hampshire Water Well Board data on recently completed wells, stored in their computer data base, to the GWSI data base. Data on more than 400 new wells within the study area were transferred by this process.

The data assembled in the GWSI data base were used to produce the plates that accompany this report. The following sections of this report present the methods employed in plate production. Data also can be transferred automatically to the State of New Hampshire's GIS (Geographic Information System) data base and the data analyzed relative to other geographic features. Applications of the U.S. Geological Survey GWSI data base are discussed by Mercer and Morgan (1981).

Seismic Refraction

Seismic-refraction profiles were completed at 26 locations within the study area to determine depths to the water table and bedrock (pl. 1-4). A 12-channel, signal-enhancement seismograph was used to record the arrival times of compressional waves generated by a sound source. The data were collected according to procedures described by Haeni (1986). Interpretive results, made by use of a computer program (Scott and others, 1972), are given in figures 11-16. Estimated depths were generally in good agreement with observations from data for nearby wells, outcrops, springs and brooks, as well as with shallow auger-hole data collected during the refraction surveys.

Seismic velocities estimated for the materials under investigation and used in the seismic interpretations are 900 to 1,500 ft/s for unsaturated stratified drift, about 5,000 ft/s for saturated stratified drift, and about 10,000 to 14,000 ft/s for bedrock.

The altitude of the land surface, in figures 11-16, in feet above sea level, was determined by leveling the geophone locations and tieing that information to sea level datum using nearby U.S. Geological Survey benchmarks, altitudes of road crossings, or an altimeter. Altitudes of the land surface shown in the figures where benchmarks were not available are only accurate to within a few feet. This accuracy is thought to be acceptable, considering the errors involved in determining depths to water table and depths to bedrock.

The estimated altitude of the water table within unconsolidated deposits, as determined by interpretation of the seismic-refraction profiles, is shown in figures 11-16. The altitudes are accurate to within a few feet and represent the water table at the time the seismic-refraction data were collected. The seismic-refraction profiles located on plates 1 and 3 were run in the fall of 1984, and the profiles located on plates 2 and 4 were run in the summer of 1985. Epping line b, shown on both plate 3 and plate 4, was run in the fall of 1984.

The estimated altitude of the top of the bedrock is shown in figures 11-16. Accuracy of the altitude of the bedrock surface is not as good as that of the water table, because errors in the interpretation are cumulative. If the water table altitude, estimated by the interpretation of the seismic refraction data, is erroneously high, the estimated position of the bedrock will be low by an even greater margin. Additional error will result if the relief of the bedrock surface differs considerably over distances less than the 50-foot geophone spacing used in profiling, or if a thick layer of till overlies the bedrock. A thick layer of till would cause problems with the interpreted depth to bedrock if the seismic velocity in the till is faster than that in saturated stratified drift. On the other hand, if velocities in the till are slow, approaching that of stratified drift, depth-to-bedrock estimates are valid but thickness of stratified drift would be overestimated. Accuracy of the altitude of the bedrock surface probably averages plus or minus 10 percent of the depth to bedrock but may be greater in some places.

Recharge, Discharge, and Direction of Ground-Water Flow

Ground-water recharge is the water that is added to the saturated zone of an aquifer. Recharge originates as rain or snowmelt and can be determined as the difference between total precipitation and the amount that runs off as overland flow and the amount that is lost to evapotranspiration. Vegetation and soil permeability affect the quantity of recharge to aquifers. Sandy soil covered by mature forests can absorb up to about 1 inch of rainfall per hour; silty, clayey soil may absorb less than 0.1 inch per hour (Heath, 1983). In a 3-month period, August through October 1977, Hill (1979, p.87) estimated that one third of the rainfall that fell on the surface of the Newmarket Plains aquifer, located in the east-central part of the study area (fig. 2), actually reached the water table. The Newmarket Plains aquifer, a grounding-line delta (fig. 9 and 10) composed of sand and gravel, has been modified in places by the mining of sand and gravel. How these sand-and-gravel-mining operations affect aquifer recharge is uncertain. Recharge may be increased by exposing unsaturated sands and gravels to direct infiltration of precipitation or it may be decreased because of increased evaporation from a shallow water table. In other parts of the northeast, recharge to stratified-drift aquifers has been estimated to be as high as one-half of the annual precipitation (MacNish and Randall, 1982; Pluhowski and Kantrowitz, 1964).

Recharge to the stratified-drift aquifers also comes from the adjacent till-covered bedrock uplands. Morrissey (1983) estimated that the average annual lateral inflow of ground water from upland areas to a stratified-drift aquifer in Maine is 0.5 $(ft^3/s)/mi^2$ (cubic feet per second per square mile). Flow from the adjacent till uplands probably varies throughout the year, increasing in the spring and decreasing during dry summer periods.

Ground-water recharge through permeable streambeds occurs where streams that drain the upland areas cross stratified-drift aquifers (Randall, 1978). An excellent example of this is an aquifer located at Freezes Pond in Deerfield (pl. 1), where a small stream enters the aquifer outcrop area at its northwestern boundary. During summer periods when the water table falls below the water level in the stream, flow from this stream rapidly discharges into the aquifer until, at a certain point downstream, flow ceases and the streambed is dry.

Ground-water discharge includes natural discharge from the aquifers through seepage to streams, lakes, and wetlands, ground-water evapotranspiration, and artifical discharge through pumping.

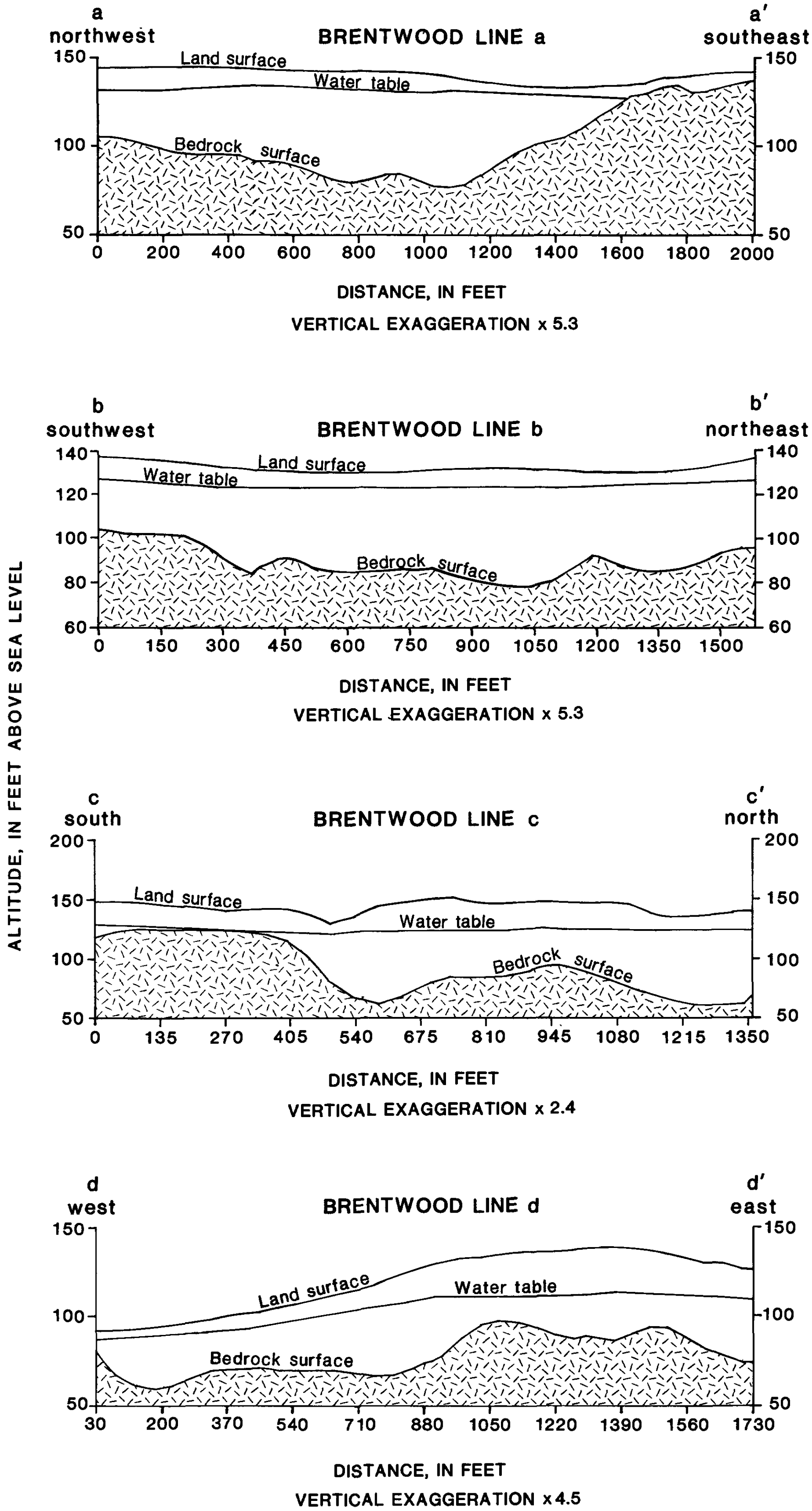


Figure 11.--Seismic-refraction cross sections, Brentwood lines a through d; locations shown in plate 4.

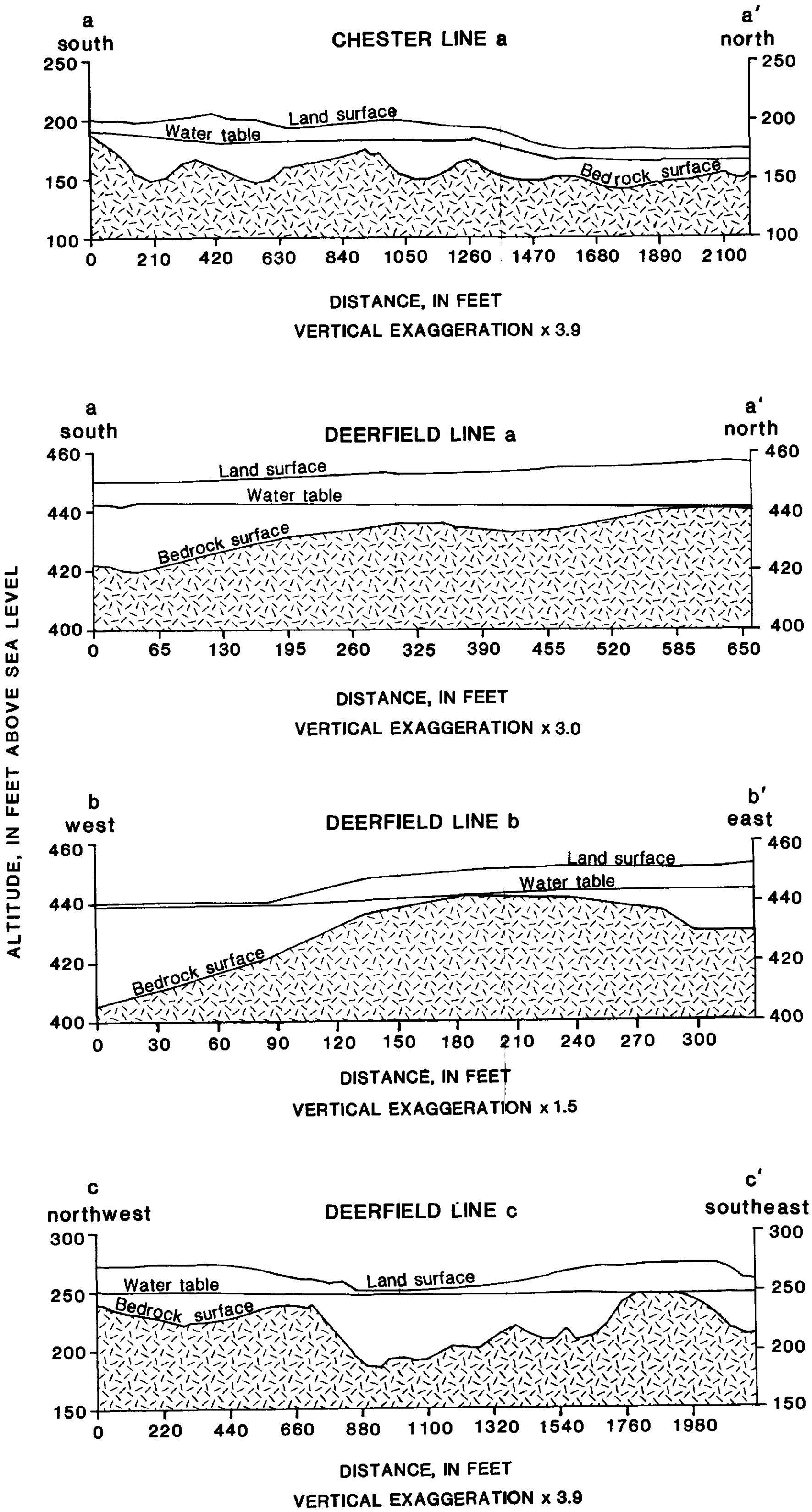


Figure 12.--Seismic-refraction cross sections, Chester line a, location shown in plate 3; Deerfield lines a through c, locations shown in plate 1.

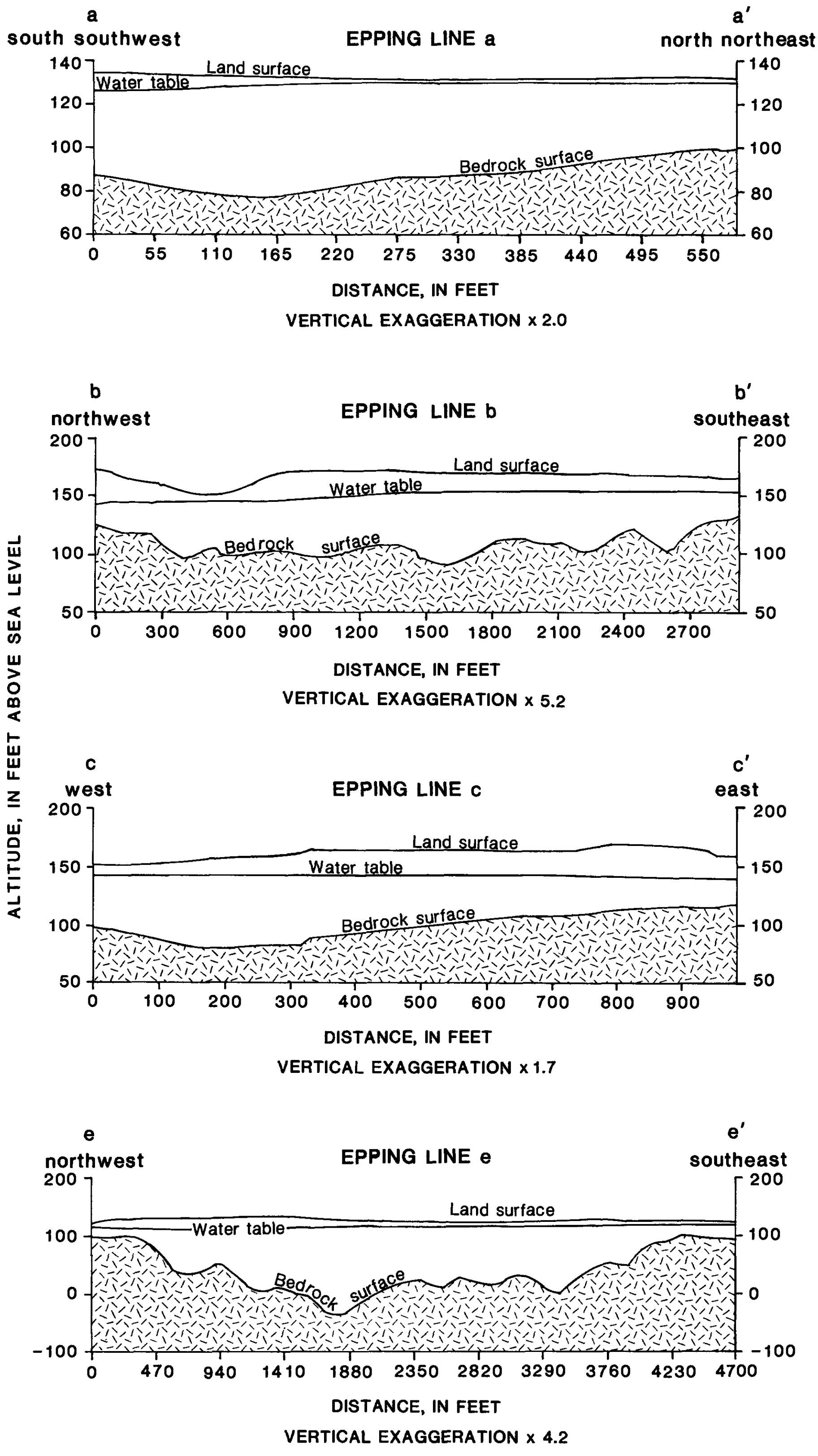


Figure 13.--Seismic-refraction cross sections, Epping lines a, b, c, and e; locations shown in plates 3 and 4.

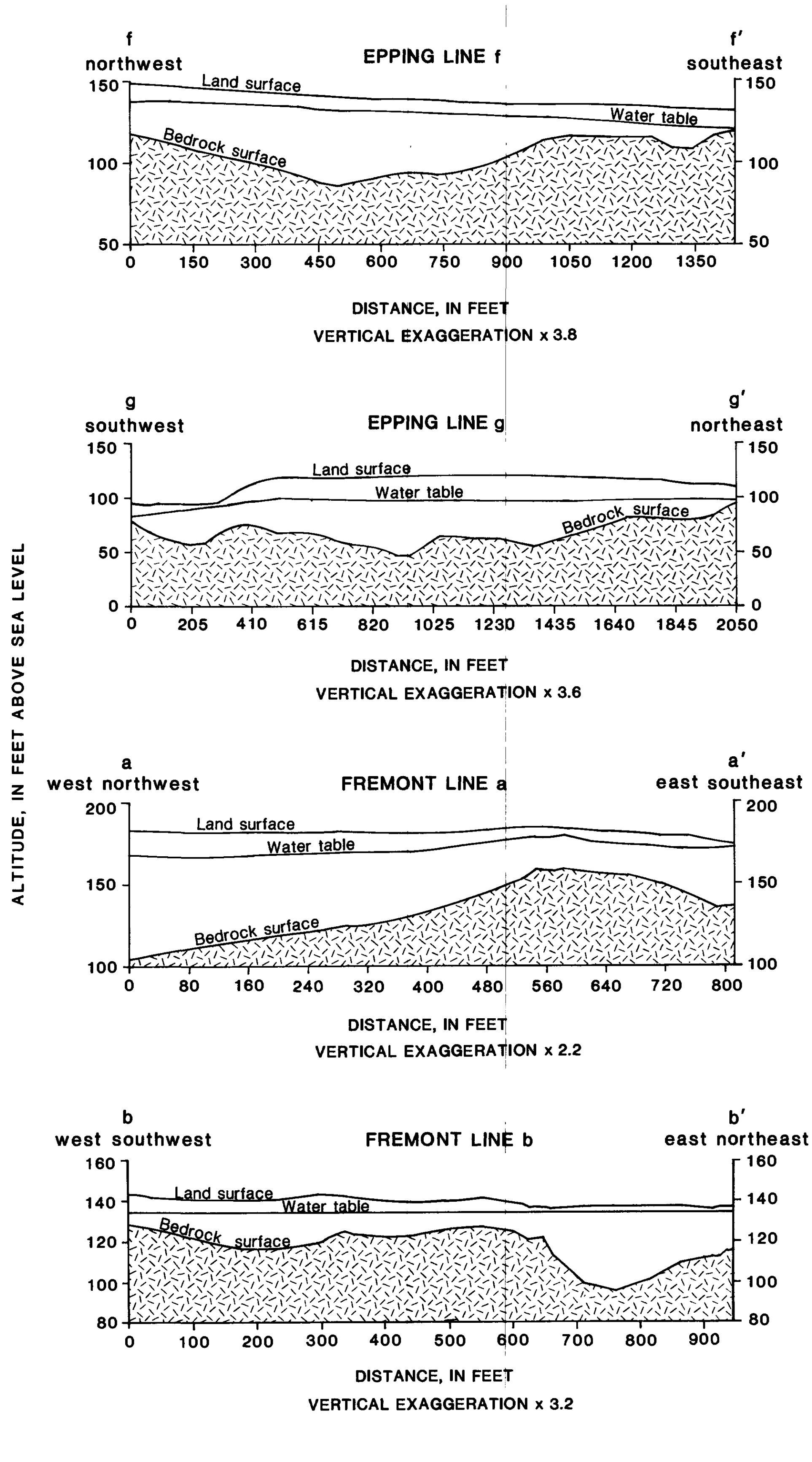


Figure 14.--Seismic-refraction cross sections, Epping lines f and g, Fremont line a and b; locations shown in plates 2, 3 and 4.

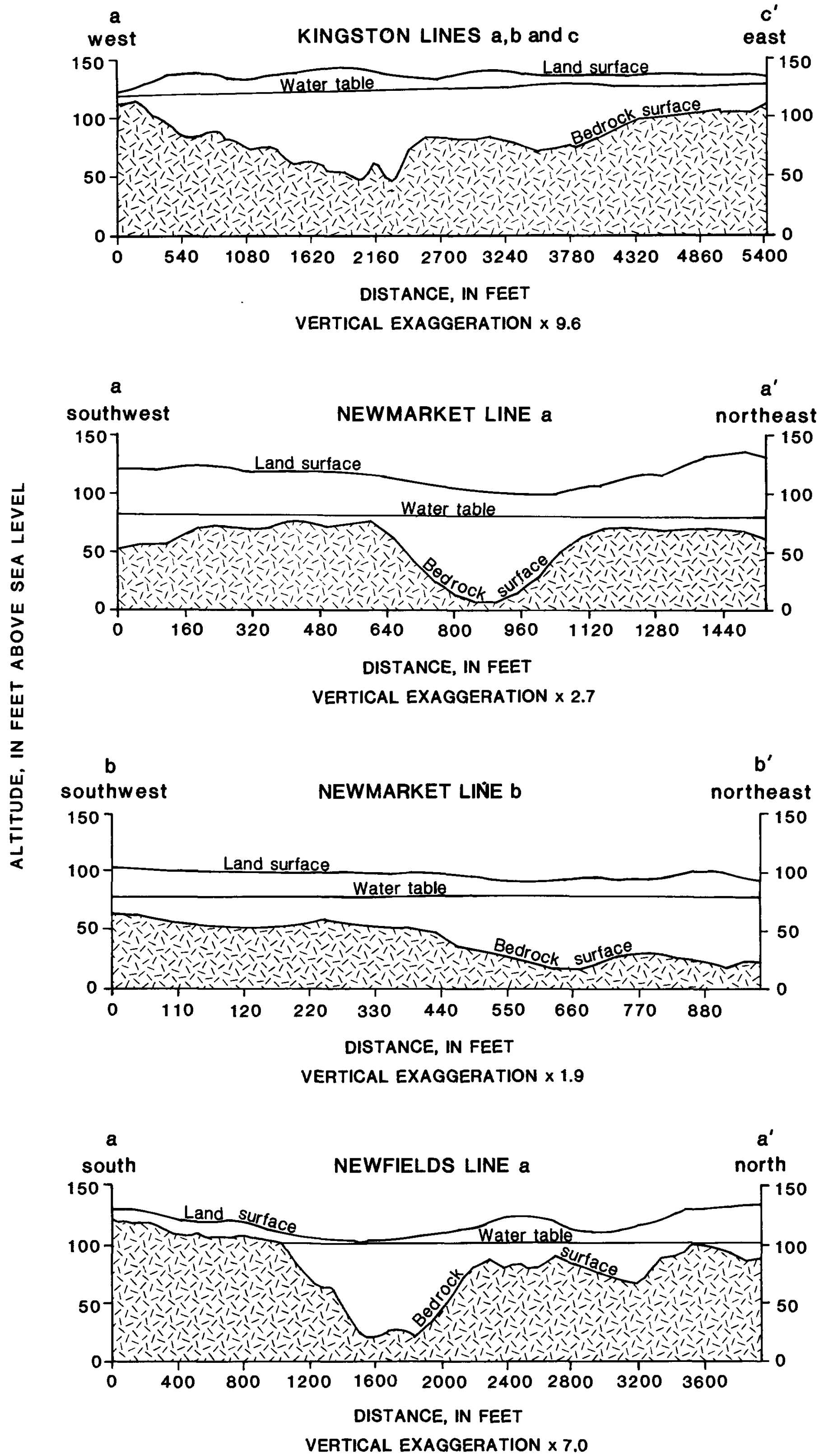


Figure 15.--Seismic-refraction cross sections, Kingston lines a, b, and c combined, locations shown in plate 4; Newmarket lines a and b, locations shown in plate 2; Newfields line a, location shown in plate 4.

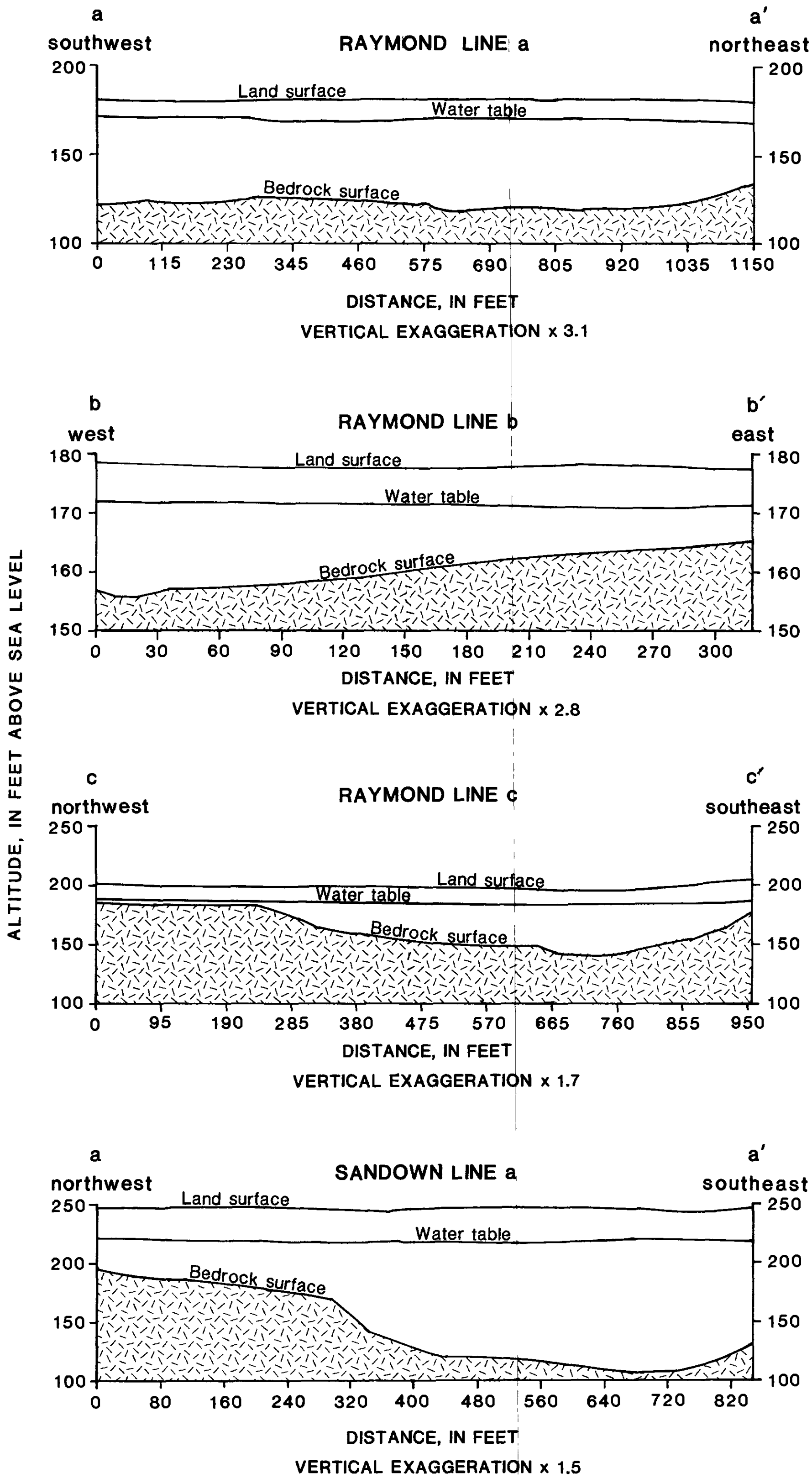


Figure 16.--Seismic-refraction cross sections, Raymond lines a through c, Sandown line a; locations shown in plate 3.

Artificial sources of recharge or discharge to an aquifer complicate the construction of water-table maps that are intended to represent natural conditions. Major withdrawals of ground water that affect the direction of ground-water flow occur in several aquifers in the study area. Also, artificial recharge is occurring in the Pudding Hill aquifer (pl. 2 and fig. 2.). The city of Dover pumps water from the Bellamy River and directs the water to recharge basins excavated in the aquifer; this recharge raises the water table in the aquifer beneath and near the basins. This additional water is later removed by two production wells that tap the aquifer. Data used to construct the water-table map at Pudding Hill (pl. 2) were collected prior to the installation of both large municipal-supply wells and before the practice of artificial recharge was begun.

Water Levels

Periodic water-level measurements have been made by the U.S. Geological Survey at 67 wells in the study area. During this study, water levels in 38 test wells were measured (usually once a month) from the time the test well was completed until May 1986. In the late 1970s and into 1980, water levels at 10 other wells were measured monthly (Cotton, 1986) and, in the mid 1950s, 18 other wells were measured (Bradley and Petersen, 1962)--one of them daily. In addition to this, well LIW 1 (fig. 17) in Lee has been measured monthly from 1953 to present. Figure 17 gives two examples of hydrographs of these wells. Data from these 67 wells show that natural water-level fluctuations in the coarse-grained stratified-drift aquifers are at most only about 10 feet and are usually less than 5 feet. From this, it is concluded that a 10-foot contour interval for water-table altitudes under nonpumping conditions in the coarse-grained, stratified-drift aquifer is reasonable. Water levels in wells constructed in till tend to have larger fluctuations than those in coarse-grained stratified drift.

The altitude of the water-table within the stratified-drift aquifers is shown on plates 1-4. Water-table contours were drawn to represent water levels during the summer season. Arrows drawn at right angles to the contour lines are shown to indicate the direction of the horizontal component of ground-water flow.

Directions of ground-water flow and the maps of the water-table surface are based on data derived from (1) altitudes of streams, ponds, and rivers as shown on U.S. Geological Survey 1:24,000-scale topographic maps; (2) well records in the GWSI data base; (3) geophysical seismic-refraction profiles (figs. 11-16); and (4) geophysical seismic profiles completed by the University of New Hampshire (Birch and Bowring, 1977; Birch, 1980; Hensley, 1978; Moore, 1978; and Hill, 1979).

Water-level altitudes were mapped for unconfined aquifers within the stratified drift but not for confined aquifers. The altitude of the water table is controlled locally by the stratigraphy, which differs from place to place and is difficult to map. Accordingly, in areas where outwash and beach sands and gravels overlie glacioestuarine silts and clays, such as those identified in figure 2, the water table is very difficult to contour. In these areas the low hydraulic conductivity of the silts and clays impedes the downward percolation of water and raises the water table unpredictably. These conditions prevail mainly in Kingston, Brentwood, and the eastern part of Fremont.

Water-table contours generally indicate natural sources of recharge and discharge to aquifers. A water-table contour that crosses a gaining stream forms a "V", the pointed end of which points upstream. This indicates that water is flowing from the aquifer to the stream. At times, in some locations, the opposite occurs. This is especially true where small tributary streams enter stratified-drift areas along steep till slopes and during dry periods when the water table is low. In these situations, a water-table contour would form a "V" that points downstream as it crosses the stream, indicating that water is flowing from the stream to the aquifer.

Aquifer Characteristics

Thickness and storage

The saturated thickness of an unconfined, stratified-drift aquifer is the vertical distance between the water table and the bottom of the aquifer. For many stratified-drift aquifers, the bottom is the contact between the stratified-drift deposits and till or bedrock. For other aquifers, the bottom is the contact between upper coarse-grained deposits and underlying fine-grained deposits. (However, thickness of underlying fine-grained stratified drift commonly is unknown, so that the thickness contours shown on plates 5-8 include underlying fine-grained deposits.) The

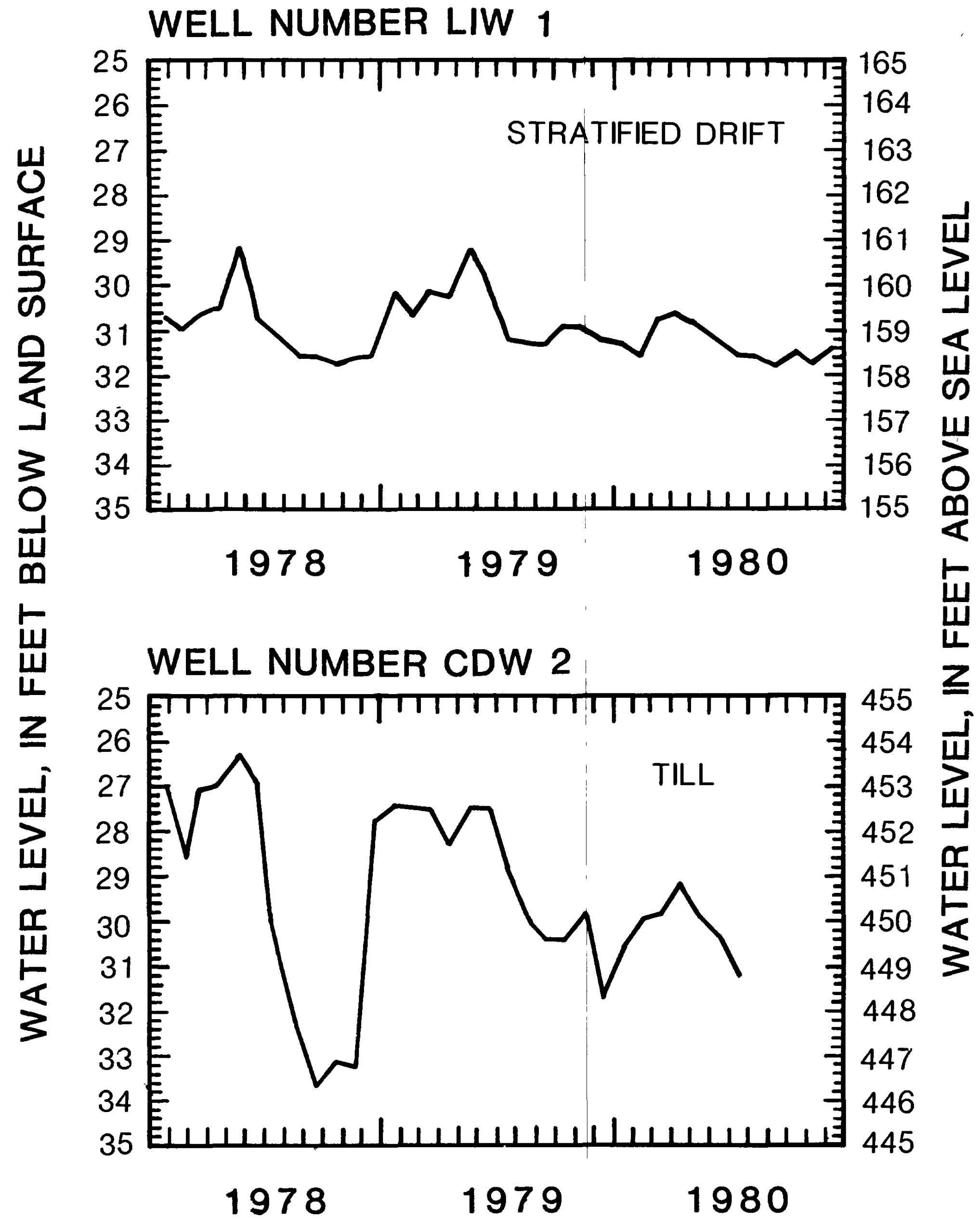


Figure 17.--Two examples of water-level hydrographs.

saturated thickness and specific yield of an aquifer determine the amount of ground water it has in storage.

The storage coefficient of an aquifer is defined as the volume of water the aquifer releases or takes into storage per unit surface area of the aquifer per unit change in head (Theis, 1938). The storage coefficient of an unconfined aquifer essentially is equal to specific yield--the amount of water that can be obtained by gravity drainage from a unit volume of the aquifer. Laboratory tests done on 13 unconsolidated samples from southern New Hampshire that ranged from fine-grained lacustrine sands to coarse-grained sands and gravels indicate that specific yields range from 0.14 to 0.34 with an average of 0.26 (Weigle and Kranes, 1966). A value of 0.2 commonly is used to estimate specific yield in stratified-drift aquifers in New England.

Saturated-thickness maps can be used to estimate the total amount of ground water stored in an aquifer. The volume of an aquifer can be approximated by summing the products of the areas between successive pairs of saturated-thickness contours multiplied by the average saturated thickness for each interval. The actual volume of ground water stored in the aquifer can then be estimated by multiplying the saturated volume by the storage coefficient.

Saturated-thickness maps shown on plates 5-8 were prepared using data from surficial geologic maps, seismic-refraction profiles, test drilling, and the GWSI data base. A 20-foot contour interval was used to show saturated thicknesses of stratified drift, which range in thickness from 0 to greater than 140 feet. The entire saturated thickness may not be aquifer material. Layers of saturated silts and clays that lie above, below, or interfinger with the aquifer are included in the saturated thicknesses depicted.

Information from surficial geologic maps was used to construct the saturated-thickness maps. The contacts between stratified drift and till mark the edge of the stratified-drift aquifers and represent zero saturated thickness. Locations of bedrock outcrops within aquifer areas indicate points of zero saturated thickness; areas adjacent to the outcrops were assumed to be thinly saturated unless evidence to the contrary was available.

Seismic profiles show the depths to the water table and depths to bedrock, but they usually do not show depth to till deposits unless the till is thick and has a seismic velocity that is significantly faster than that of saturated stratified drift. For the purpose of constructing the maps presented in this study, till was assumed to be thin (less than 10 feet thick) unless there was evidence to the contrary. Sources of seismic-refraction profiles included (1) seismic lines done as part of this investigation (figs. 11-16); (2) seismic lines run by the University of New Hampshire (Hensley, 1978; Moore, 1978; Hill, 1979; Birch, 1980); and (3) seismic lines run for the U.S. Army Corp of Engineers (Anderson-Nichols and Co., Inc., 1980).

In some areas, saturated thickness was determined from test-boring data. Subsurface materials were also collected with a split-spoon sampling device which is lowered down through the hollow stem of the auger and pounded into earth material. In this manner, water-table altitudes, stratigraphic logs and samples, usually collected every 5 feet, were obtained. Figure 18 shows the split-spoon sampling device and a sample of saturated, coarse-grained sand. Values for saturated thickness are the distances from points where the test borings first encountered the the water table down to the top of the till or, in some cases, where till was not encountered, down to the top of the bedrock.

Well and test-hole data stored in the GWSI data base were the final source of information used in the construction of the saturated-thickness maps (pls. 5-8). A problem with these data is that many sites lack information on both the depth to the bottom of the stratified drift and depth to the water table. For example, wells penetrating bedrock usually provide information concerning the bottom of the stratified drift but not depth to the water table. Conversely, shallow dug wells usually provide information concerning the depth to water table but not the depth to the bottom of the stratified drift. In such areas where depth to water table was unavailable the water-table altitude was obtained from the water-table maps (pls. 1-4). Depths to the bottom of stratified-drift deposits were assumed to be indicated by one of the following factors, in the priority shown.

1) Depth to top of till, if known. Till has not been found to overlie stratified drift anywhere in the study area.;

2) Depth to top of bedrock, if known;

3) Length of well casing minus ten feet, if the well is known to penetrate bedrock. Depth to bedrock is assumed to be about 10 feet above the bottom of the casing. This general rule of thumb applies to wells

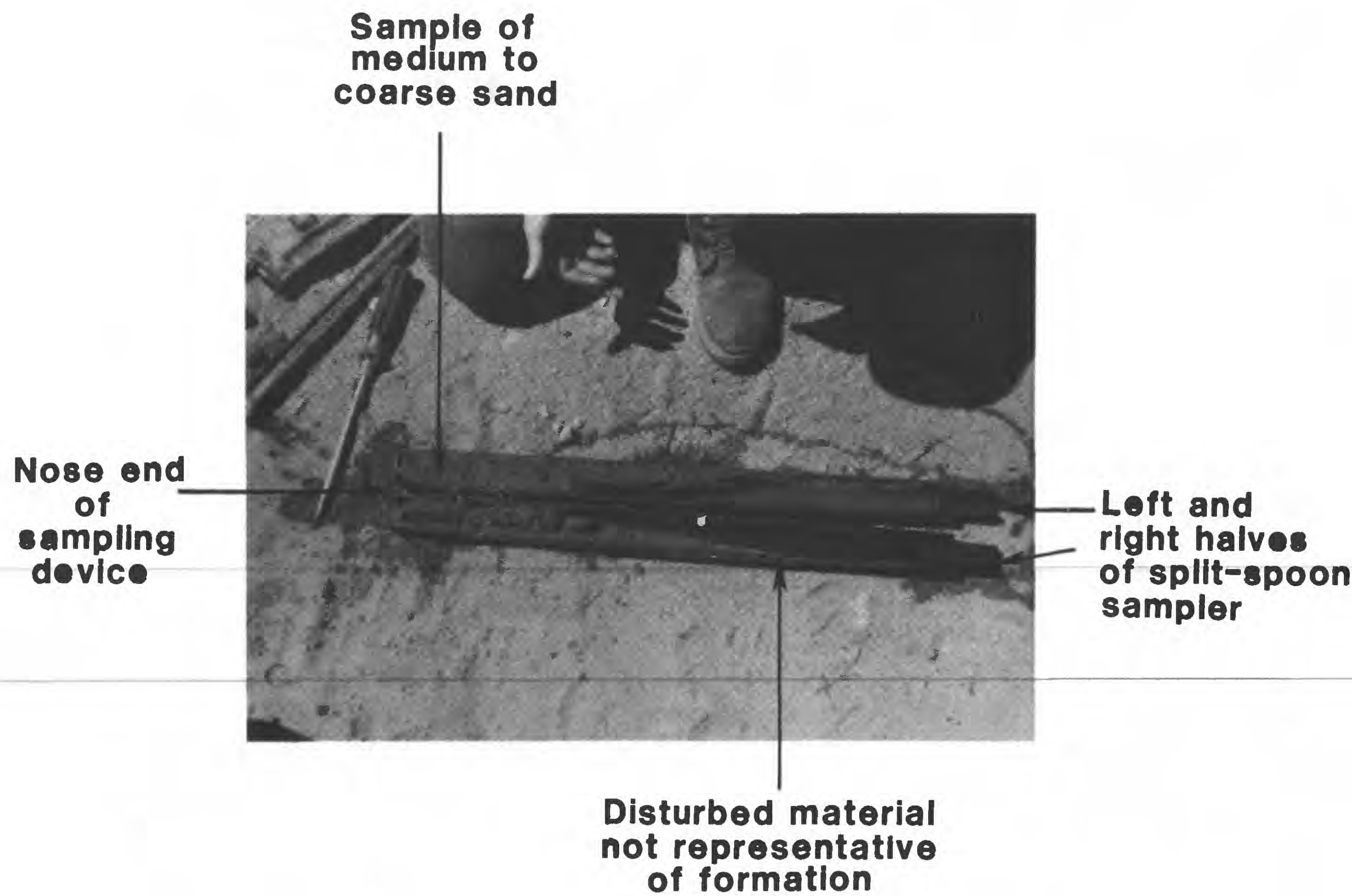


Figure 18.--Split-spoon sampling device and lithologic sample.

that penetrate crystalline bedrock in New Hampshire.

If a well penetrated stratified drift, and bedrock was not encountered, the depth to refusal was taken to be equal to or less than depth to the bottom of the stratified drift. Saturated thickness was then assumed to be greater than or equal to the difference between the water-table depth and the refusal depth. If a well penetrated stratified drift, and neither bedrock nor refusal was encountered, the bottom of the well was assumed to be above the bottom of the stratified drift. Saturated thickness was assumed to be greater than the difference between the water-table depth and the depth to the bottom of the well.

Using data from the sources described above, saturated-thickness contours were determined and plotted on plates 5-8. For most areas, the results are reasonable. However, the area in Nottingham that indicates the presence of thick deposits (fig. 2 and pl. 6) may be questionable. Contours in that area are based on drillers' logs that included depths to bedrock but only limited information on the thickness of the stratified drift.

Relation of aquifer thickness to a hydrogeologic setting

Areas where the saturated thickness of stratified-drift is greater than 40 feet and less than 80 feet and where it is greater than 80 feet are shown in figure 19. The areas of greatest thickness, indicated in this figure and on plates 5-8, are located where the surface of the bedrock has been the most deeply eroded. Short valleys less than a few miles long have been eroded into the bedrock and generally do not lead anywhere. An exception is the valley under Pudding Hill (fig. 2) which can be traced for about 8 miles (Hensley, 1978). The presence of these short valleys are unexplained by the normal erosional process of streams open to the atmosphere but must have resulted from erosion by glacial ice and perhaps subglacial meltwater. Erosion occurred in these valleys at altitudes lower than any bedrock-controlled base level.

A comparison of the locations of these short stretches of buried valleys to the underlying bedrock types (fig. 19) illustrates a striking relation between the presence of thick, saturated stratified drift and areas either underlain by the metasediments of the Eliot Formation or the contact between the Eliot Formation and the Ordovician Exeter Diorite. This suggests that bedrock controls the location of these short buried valleys. Adjacent to the valleys, topographic highs in the land surface associated with the Eliot Formation probably temporarily stabilized the glacier-ocean interface in these areas during deglaciation. Because pressure gradients within the glacial ice were greatest in the vicinity of this interface, active glacial ice and subglacial meltwater is likely to have at least partly eroded these valleys. Geohydrologically, a setting quite different from a typical system of interconnected buried valleys was created. Instead of looking down valley when prospecting for "new" aquifers, such aquifers may be located perpendicular to the valley axis, along the previous glacial ice/ocean interface where other short-buried valleys and deltaic aquifers are found.

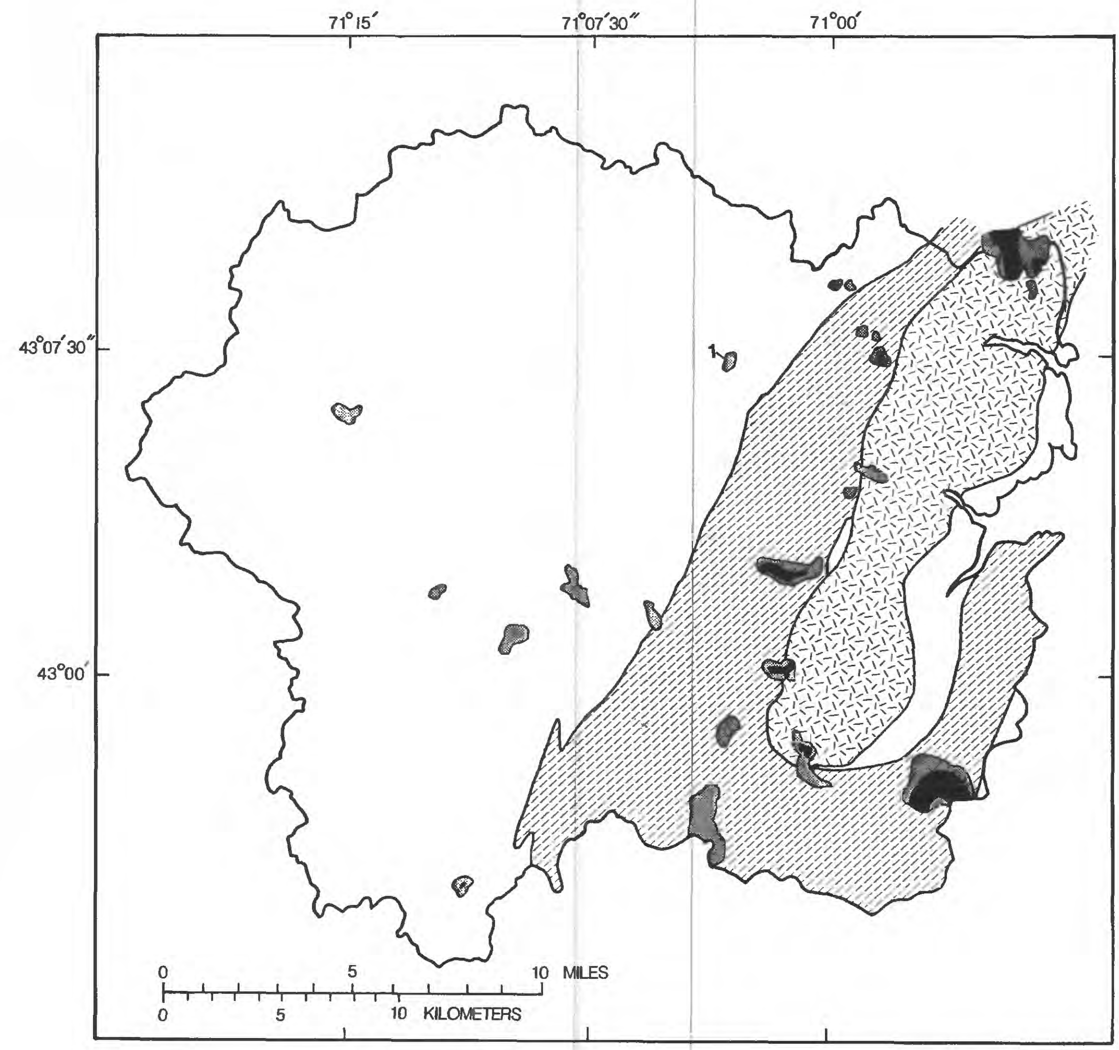
Transmissivity

Aquifer transmissivity is defined as the rate at which water is transmitted through a unit width of the aquifer under a unit hydraulic gradient (Heath, 1983). The transmissivity (T) of an aquifer is equal to the horizontal hydraulic conductivity (K) of the aquifer multiplied by its saturated thickness (b); thus, T = Kb. In this report, transmissivity is expressed in units of feet squared per day.

Hydraulic conductivities were estimated from the geologic logs for each test well using grain-size distribution data for 122 samples obtained during drilling. Hydraulic conductivities of these samples were determined by using a empirical relation developed by Olney (1983), where the effective size (D_{10} in phi units) is used to predict the hydraulic conductivity (K in ft/d):

$$K = 2{,}100\,(10)^{-0.655D_{10}} \qquad (1)$$

Effective size is defined as the grain-size diameter where 10 percent of the sample is of smaller grains and 90 percent is of larger grains. It is an important parameter because the finer part of a sample has a profound effect on resistance to ground-water flow due to the attraction of water molecules to particle surfaces (Hazen, 1892). The effective size for the 122 samples was determined directly from cumulative grain-size distribution curves as determined by sieve analysis. When compared to other methods currently in use for estimating hydraulic conductivity from grain-size distributions (including Masch and Denny, 1966; Bedenger, 1961; Krumbein and Monk, 1942),



EXPLANATION

AREAS OF STRATIFIED-DRIFT AQUIFER

- GREATER THAN 40 FEET AND LESS THAN 80 FEET THICK
- GREATER THAN 80 FEET THICK

UNDERLYING BEDROCK

- ELIOT FORMATION (ORDOVICIAN (?) TO PRECAMBRIAN (Lyons and others, 1986))
- EXETER DIORITE (ORDOVICIAN (Lyons and others, 1986))
- UNDIFFERENTIATED

- BOUNDARY OF STUDY AREA
- GEOLOGIC CONTACT
- SATURATED STRATIFIED-DRIFT THICKNESS CONTOUR
- 1 LOCATION IN NOTTINGHAM WHERE THICKNESS CONTOURS ARE QUESTIONABLE

Figure 19.--Relation between saturated thickness of stratified drift and underlying bedrock formations.

the estimated conductivity falls within the range of values estimated by the other methods.

Estimates of horizontal hydraulic conductivity from the 122 samples were then used to estimate horizontal hydraulic conductivities of comparable materials described in the remaining parts of the stratigraphic logs of the test wells. Transmissivities for each test hole were calculated by multiplying the horizontal hydraulic conductivity times the saturated thickness of the corresponding interval of the stratigraphic log and summing the products.

Only 70 calculated values of transmissivity for sites within the study area are known. In a few cases, transmissivities were reported by consultants or were estimated from results of aquifer tests. Estimates of transmissivity calculated from logs of drillers, who generally do not determine grain-size distributions, were considered to be unreliable and were not used. Two test wells for which grain-size distributions were determined were adjacent to wells where aquifer tests were conducted. Transmissivities computed by grain-size distributions at these wells were within ±40 percent of values computed using the aquifer-test data. The transmissivities shown on plates 5-8 are based on saturated thicknesses and estimates of hydraulic conductivity and rely mainly on data collected specifically for this study. Geologic and drillers' logs were examined during this process, and saturated silts and clays were excluded from the transmissivity estimates because their contribution to transmissivity is assumed to be negligible.

Factors other than effective grain sizes of materials affect aquifer transmissivities. Transmissivity can be extremely variable over short distances because of the heterogeneous nature of stratified-drift deposits. Because of the uncertainties associated with estimates of transmissivity the values shown on plates 5-8 should be considered generalized estimates.

Estimation of Aquifer Yield and Recharge Contributing Area

Two deltaic aquifers were selected to estimate aquifer yields and the size of contributing areas using a technique based on the principal of superposition. The aquifers are located at West Epping and Newmarket Plains (fig. 2) and were selected because they represent different types of geohydrologic settings. The aquifer at West Epping was formed at the marine limit and is now traversed by the hydraulically connected Lamprey River. The aquifer at Newmarket Plains was formed at a grounding line and is not hydraulically connected to a surface-water body.

Transient simulations of a two-dimensional finite-difference model (McDonald and Harbaugh, 1984) were used to simulate drawdowns that would occur in the aquifers in response to pumping of production wells. These drawdowns were subtracted from previously determined water-table altitudes (pl. 1-4) by use of the principle of superposition to estimate the water-table surface that would result from pumping. Ground-water flow directions and areas contributing flow to the pumping wells were determined from the estimated water-table surface, and the estimated aquifer yield was determined from the water budget calculated by the transient simulations. In the model, recharge from the Lamprey River to the West Epping aquifer was simulated as flow through a confining layer that represented the river bed.

Principle of Superposition

The principle of superposition is based upon the fact that, if a composite problem in a system is governed by linear equations, solutions to individual parts of the problem can be added together to solve the composite problem (Reilly and others 1984). Because the individual parts of a problem commonly can be formulated in relatively simple terms, the overall solution to the problem becomes attainable. The major consideration in using this tool is that the response of the system under investigation must be governed, or at least approximated, by linear equations.

Application of the superposition technique to the West Epping and Newmarket Plains aquifers is based on the assumption that the drawdown in a real aquifer can be approximated by the drawdown calculated for a simpler hypothetical aquifer that has characteristics similar to the real aquifer but with a flat water table and no recharge (except induced infiltration from the river). Drawdowns calculated from the hypothetical aquifer, after 180 days of pumping, are then subtracted from the water-table altitudes of the real aquifer to predict its water-table configuration after 180 days of pumping. Similar concepts, using image wells, a simple system with a flat water table, and no recharge, to predict the response of stratified-drift aquifers to pumping stresses have been described by Mazzaferro and others, (1979) and Toppin, (1986). In these earlier studies, a pumping period of 180 days with no recharge also was used because that length of time approximates the growing season during which evapotranspiration is high and recharge to the aquifers is assumed to be small. It is also assumed that recharge to the aquifer during the rest of the year is sufficient to allow continuous pumping at the assumed pumping rate.

Assumptions

Assumptions relative to the use of two-dimensional finite-difference models and the application of superposition in this study are:

(1) The aquifer characteristics of transmissivity, saturated thickness, and the water-table configuration shown on the plates that accompany this report and streambed characteristics are assumed to be a reasonable representation of the natural system.

(2) A three-dimensional ground-water-flow system can be approximated by flow in two dimensions. Although this is not entirely valid, in models under discussion, this assumption is believed to contribute significant errors only in the immediate vicinity of the pumped wells, and near the rivers, where a significant vertical component of ground-water flow exists. Potential errors from this source are believed to be small compared to the uncertainty involved in estimating transmissivity.

(3) Ground-water flow in two dimensions (that is, map view) can be approximated by a process of discretization, whereby the aquifer area is divided into discrete blocks or cells in which all hydraulic properties are constant. Each block is represented by a single thickness, by a single hydraulic conductivity, and by a single storage coefficient. This is one way in which the digital models are superior to the analytical image-well models used by Mazzaferro and others (1979) and by Toppin (1986). With analytical image-well models the hydraulic properties of an aquifer are assigned a uniform average value; in numerical models, aquifer properties can be varied spatially to represent field conditions more accurately. In the numerical models used in this study, a 100-foot uniform grid spacing was used. Assignment of single aquifer thickness and hydraulic conductivity to an individual grid cell may be viewed as a possible source of error because it generalizes distributed aquifer properties. However, given the size of the model areas, 100-foot spacings tend to minimize this error and are considered appropriate.

If changes in ground-water conditions with respect to time are important, time also must be discretized. For example, during extended pumping periods, the water table declines continuously. This condition is approximated in the models by a series of time steps. The effects of 180 days of pumping were simulated with 20 discrete time steps of 9 days each. Approximations of the water-table configuration after the first 9 days of pumping, were used as the initial configuration for the second 9 days, and so forth. Errors associated with this technique are minor and the use of smaller time increments does not significantly improve the results.

(4) Despite the discretization of space and time, exact solutions to the simplified systems are not possible. Instead, approximate solutions are obtained through an iterative process. The model repeatedly solves the set of governing equations until the maximum change in hydraulic head between successive iterations is less than some tolerance level. Tolerance was set at 0.001 foot in the models; potential errors associated with this source are insignificant compared to other factors.

(5) The response of the ground-water-flow system can be approximated by linear equations. For natural unconfined systems, this is not strictly true because changes in saturated thickness that result from water-table fluctuations affect transmissivity and may cause nonlinear responses. However, in the model, changes in transmissivity resulting from lowering of the water table in response to pumping are accounted for and the nonlinear system is approximated by a series of linear equations.

Changes in transmissivity caused by the natural fluctuation of the water table during the growing season are not accounted for. The maps shown in the plates 1-4 represent average summer altitudes of the water table. Drawdown values calculated and superimposed on these altitudes are not adjusted for seasonal lowering of the water table. Errors from this source, however, are thought to be small because seasonal changes in the water-table altitudes are small relative to the saturated thickness.

River Infiltration

Estimates of the amount of water available to an aquifer that is in good hydraulic connection with a river require information on how much water flows in and can be obtained from the river. This requires a knowledge of the range in flows. The quantity of water available as induced recharge depends on the natural flow in the river and on how much flow is needed during pumping. To assist in this determination, flow-duration curves that consider the percentage of stratified drift that underlies an upstream drainage area have been used by the U.S. Geological Survey in Connecticut and Massachusetts. Flow-duration curves indicate the percentage of time a given streamflow is equaled or exceeded. V. A . de Lima (U.S. Geological Survey, written commun., 1987) has found that the curves developed by Thomas (1966) for Connecticut can be applied to streamflows in the Nashua River basin in northern Massachusetts.

The technique that uses selected flow and basin characteristics to estimate unregulated streamflows in southeastern New Hampshire is discussed below.

(1) Streamflow data from southeastern New Hampshire were evaluated and compared to data from Connecticut to see if relations, similar to the one between streamflow and basin geology that Thomas (1966) found in Connecticut, also exist in the study area. Thomas used data from Connecticut to create the family of curves shown in figure 20 that relate daily mean flow per unit area, percentage of time daily flow is equaled or exceeded, and percentage of the basin covered by coarse stratified drift. These Connecticut-based curves were then used with data from southeastern New Hampshire to determine if they could estimate low streamflows for the study area accurately. Similar curves for New Hampshire could not be developed and used because of insufficient long-term natural streamflow data at sites with differing basin characteristics.

(2) Flow and basin-characteristic data were collected from four basins in southeastern New Hampshire; Lamprey River, Oyster River, Mohawk River, and Dudley Brook. The data included 57 value pairs--daily discharge per unit area versus percentage of time discharge is equaled or exceeded--and represented flow durations that ranged from 75 to 99.7 percent. Basin characteristics used in the analysis included drainage area and percentage of coarse-grained stratified drift. These are summarized in table 2.

(3) An attempt was made to determine, by regression analysis, a relation between daily discharge per square mile for the four gaged basins in southeastern New Hampshire and the percentage of time discharge is equaled or exceeded, using observed flow-duration values that range from 75 to 99.7 percent. For the regression analysis, a R^2 (coefficient of determination) was determined and used to judge how well the regression describes, or fits, the observed data. A value of R^2 that approaches 1.000 indicates that values calculated by the regression equation are apt to approximate the observed data. In this case R^2 was determined to be 0.395 indicating that a simple regression equation based on drainage area and percentage of time discharge is equaled or exceeded is apt to be inaccurate for estimating streamflows at ungaged

Table 2.--*Characteristics of four basins in southeastern New Hampshire*
[mi^2, square miles.]

Drainage Basin	Drainage Area (mi^2)	Percentage of area underlain by: Coarse-grained stratified drift	Fine-grained stratified drift
Lamprey River	183	10.2	7.2
Oyster River	12.1	13.8	11.2
Mohawk River	8.87	1.5	0.0
Dudley Brook	4.97	5.7	63.8

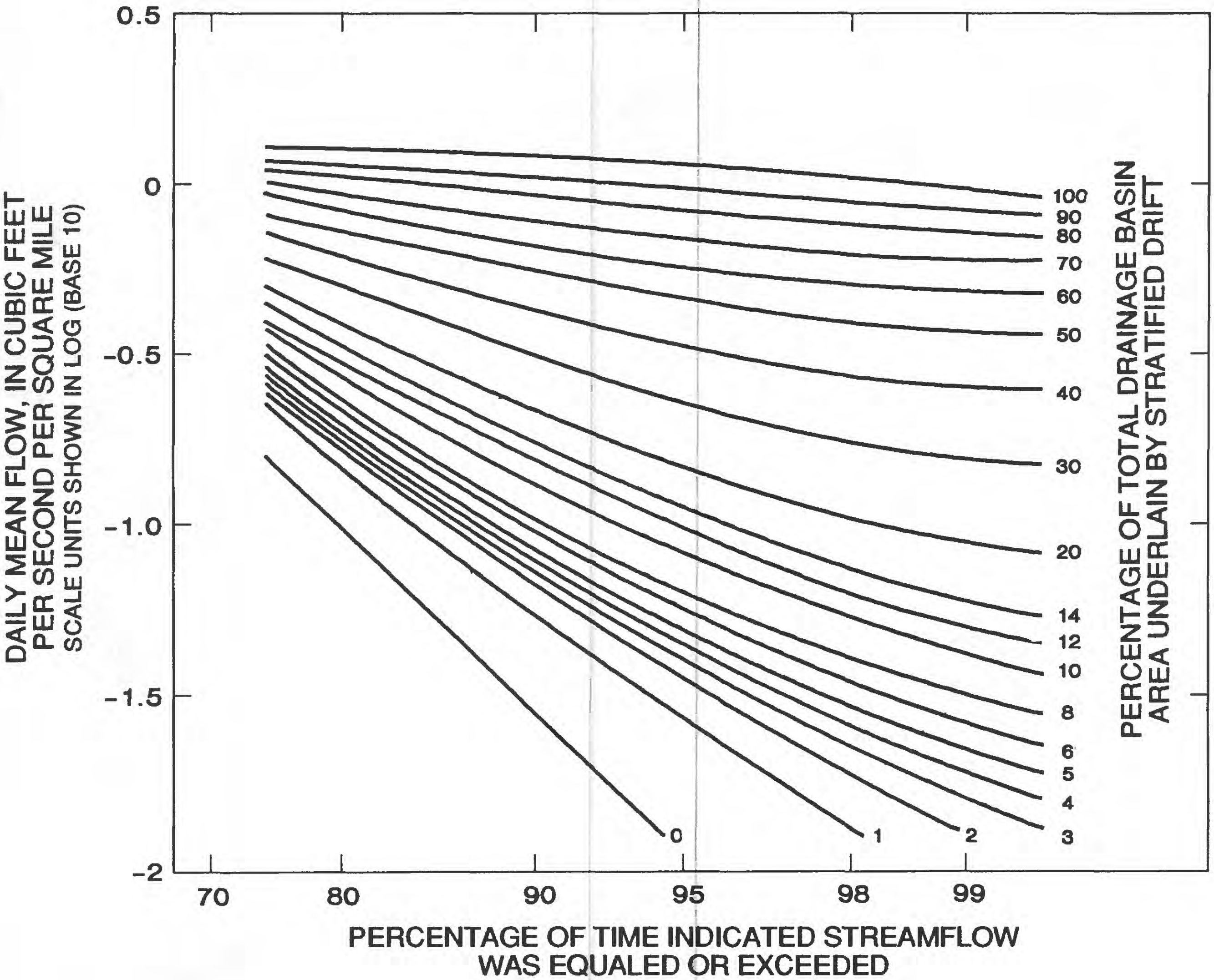


Figure 20.--Curves used to estimate unregulated streamflow in Connecticut, (modified from Thomas, 1966).

sites. This suggests that additional variables should be evaluated.

(4) A regression equation was developed that relates daily discharge per square mile of drainage area to the percentage of time discharge is equaled or exceeded and percentage of basin underlain by coarse-grained stratified drift. This is done by relating BSENH (daily discharge, per square mile, in southeastern New Hampshire) to BCONN (estimated daily discharge, per square mile, from Connecticut curves). BCONN is obtained from the relationship between daily flow, flow-duration percentage, and coarse-grained stratified-drift percentage discussed by Thomas (1966). The relation for determining BCONN is based on data from 23 basins in Connecticut and from one basin on Long Island and is shown, in part, in figure 20. The use of only the percentage of coarse-grained stratified drift for the New Hampshire basins is reasonable because the Connecticut relation is based on coarse-grained materials. Lacustrine (fine-grained) material was present in one of the 23 Connecticut basins used to develop the original relation but was not used to calculate percentage of stratified drift. The New Hampshire data, when restricted to percentage of coarse-grained stratified drift and used in the Connecticut relation yield a regression equation with a R^2 of 0.791:

$$BSENH = 1.24\ BCONN - 0.15 \qquad (2)$$

where: BSENH = Daily discharge in $(ft^3/s)/mi^2$, in southeastern New Hampshire, expressed as a logarithm (base 10);

BCONN = Daily discharge in $(ft^3/s)/mi^2$, based on flow duration and percentage of coarse-grained stratified drift in New Hampshire and the Connecticut (Thomas, 1966) curves, expressed as a logarithm.

The R^2 value of 0.791 indicates a relatively good correlation and strongly suggests that, in both New Hampshire and Connecticut, the coarse-grained stratified drift in a basin is a key characteristic to consider when attempting to estimate low streamflow.

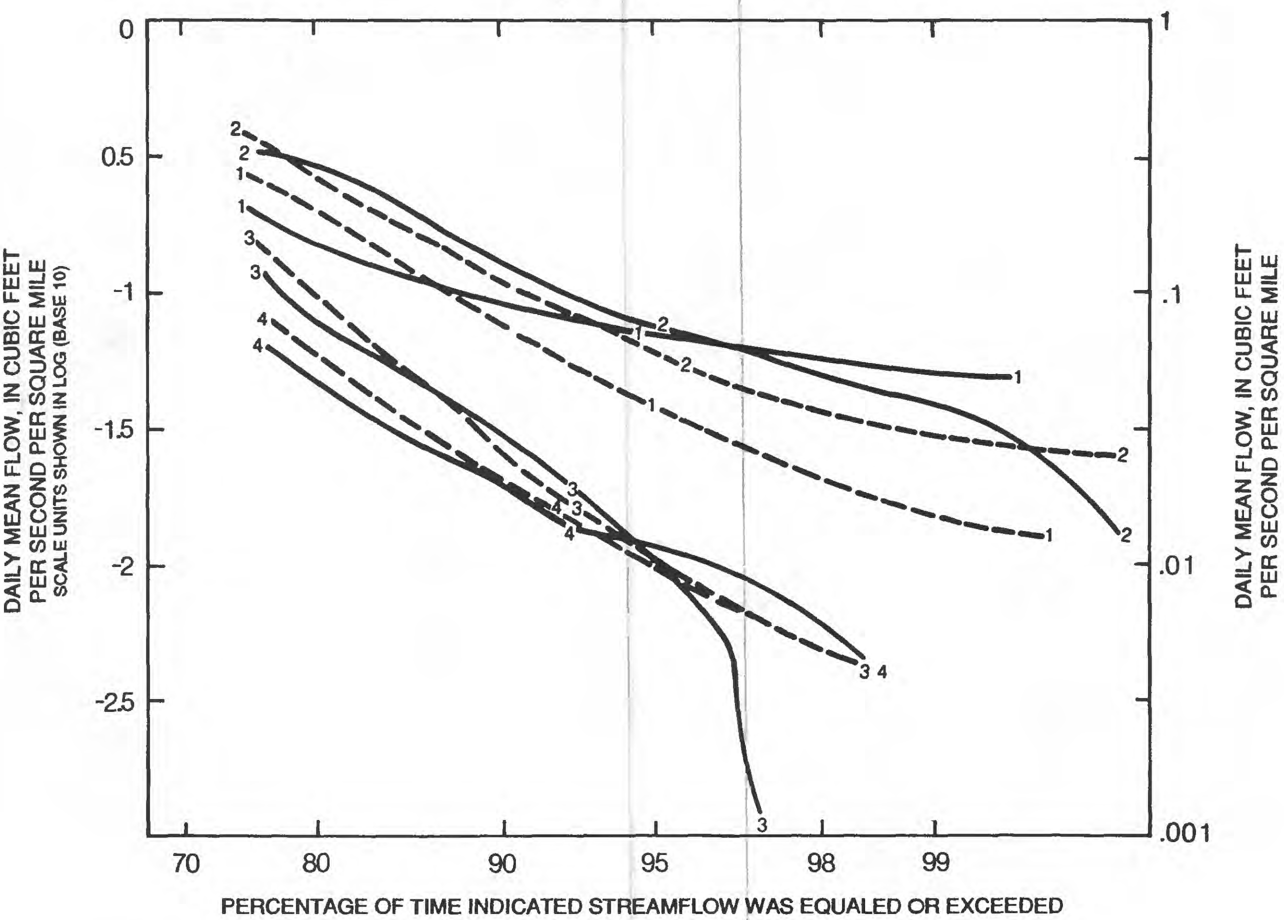
Equation (2) can be used to estimate low streamflows at ungaged sites in southeastern New Hampshire but its application is approximate and should be limited to basins with characteristics similar to the four basins used in the analysis. This includes percentages of coarse-grained stratified drift that range from 1.5 to 13.8. A comparison of observed data to values estimated by regression equation (2) show they match fairly well except at Mohawk Brook for flow durations less than 96 percent and at Oyster River for flow durations less than 94 percent (fig. 21).

Additional research is needed to develop improved regional equations that can be used with a wider range of basin characteristics and that consider other factors such as percentage of the basins covered by fine-stratified drift. Also, to improve low streamflow estimates, more long-term natural streamflow data at sites with differing basin characteristics are needed.

Application of Estimating Technique

West Epping aquifer

The delta at West Epping, formed at the marine limit during deglaciation and now dissected by the Lamprey River was selected for evaluation by the superposition technique because it represents an aquifer in good hydrologic contact with a river. The location of the delta is shown in figure 2 and its boundaries are shown in figure 22. The model area is represented as a finite-difference grid comprised of 75 rows and 71 columns with cell dimensions of 100 by 100 feet. The dark line in figure 22 encloses the area of active cells. The line also represents a so-called "no-flow" boundary which, in all but the southeastern corner, is an approximation (to the nearest 100 feet) of the contact between till and stratified drift. In the southeastern corner, the "no-flow" boundary represents the contact between the aquifer and glacioestuarine silts and clays. Although termed a "no-flow" boundary some flow does, in fact, occur along this margin as ground water does move from the till hillsides into the aquifer. In a superposition model the no-flow boundary assumes that pumping will not create additional flow across the boundary. This assumption is justified, especially in the transient simulations, because drawdowns produced by pumping are negligible at the boundaries. Natural flow from the till has already effected the initial water table on which drawdowns are superimposed. The initial water table is shown on figure 22. Most of the ground water in the aquifer discharges to the Lamprey River except for flow in the southeastern



EXPLANATION

—— 2 —— FLOW - DURATION CURVES DETERMINED FOR GAGED RIVERS.

— — 2 — — FLOW - DURATION CURVES ESTIMATED BY REGRESSION ANALYSIS

NUMBERS IDENTIFY THE RIVER:

1, OYSTER RIVER
2, LAMPREY RIVER
3, MOHAWK BROOK
4, DUDLEY BROOK

Figure 21.--Flow-duration curves (real and estimated) for streams in southeastern New Hampshire.

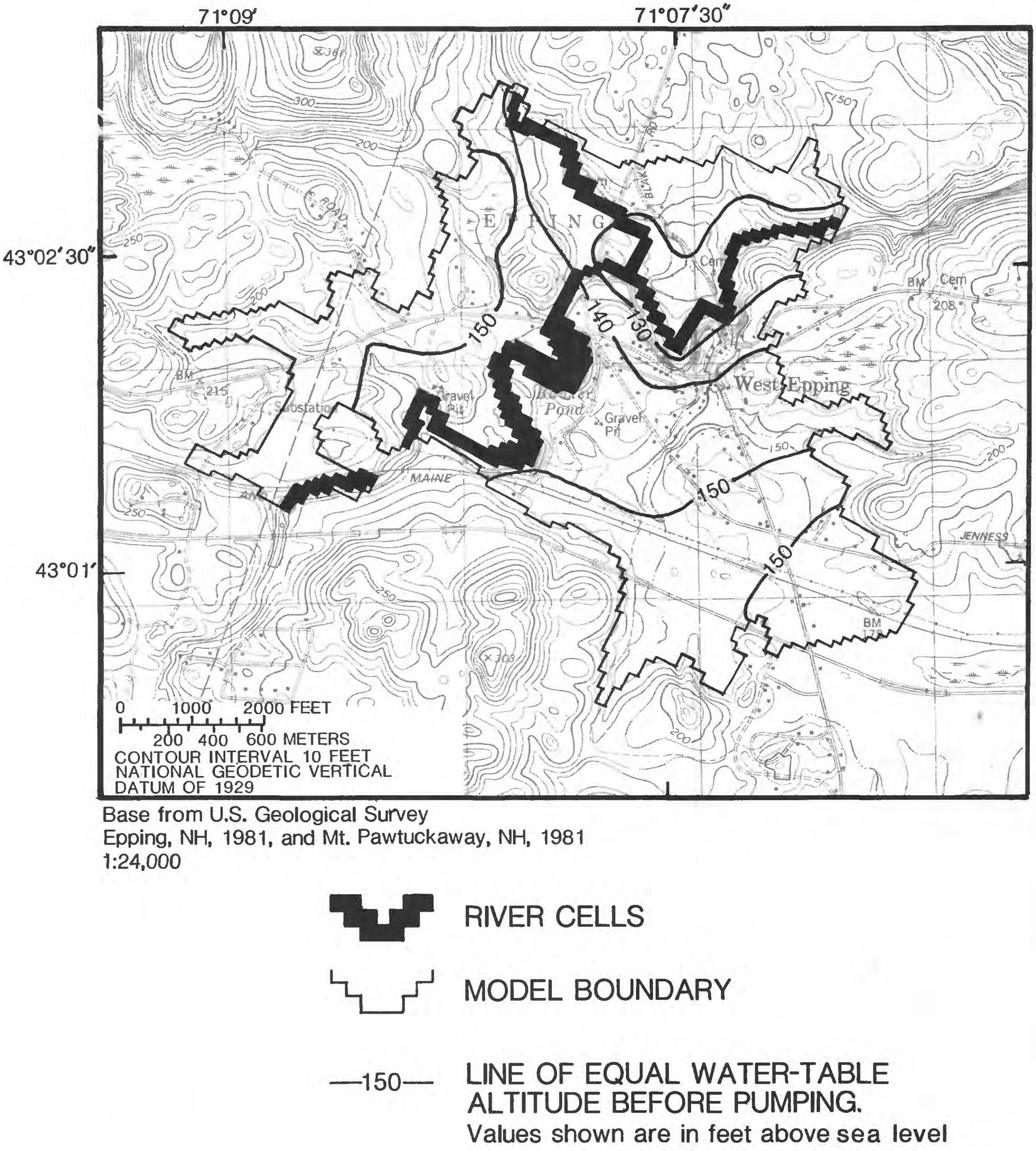


Figure 22.--Initial water-table configuration for the model simulation of the West Epping aquifer.

corner of the aquifer which drains to the Piscassic River (pl. 4).

The Lamprey River is in good hydraulic connection with the West Epping aquifer. Cells in the model where the river is simulated are shown in figure 22. The river cells are assumed to be entirely covered by the river, and stream depth is assumed to be 3 feet. Hydraulic conductivity of the streambed material is assumed to be 2 ft/d (feet per day), and the thickness of this material is assumed to be 2 feet. A hydraulic conductivity of 2 ft/d was selected because this rate has been calculated for a similar hydrogeologic setting for Gulf Brook in the Nashua River basin, Massachusetts (V. A. de Lima, U.S. Geological Survey, written commun., 1987).

The amount of water potentially available to wells through induced infiltration from the Lamprey River was estimated from basin characteristics and the equations discussed previously. Above the downstream end of the aquifer, the Lamprey River has a drainage area of 100.8 mi^2, 10.8 percent of which is underlalin by coarse stratified drift. A discharge of 3.8 ft^3/s that is exceeded 95 percent of the time and a discharge of 1.5 ft^3/s that is exceeded 99 percent of the time were calculated for the Lamprey River as it exits from the aquifer area in West Epping. The difference of 2.3 ft^3/s is the quantity of water that potentially could be withdrawn from the stream by induced infiltration 95 percent of the time and still maintain a streamflow of 1.5 ft^3/s, equivalent to the 99-percent duration flow. A 2.3 ft^3/s (or 1.5 Mgal/d) reduction in streamflow is assumed during model simulation. Other streamflow-management options can be accommodated by the model.

Aquifer thickness and transmissivity values were obtained from data on the plates (5-8) that accompany this report. Model cells located between contour lines were assigned the average value of the two contours. For example, between the 0- and 20-foot thickness contour lines, all cells were assigned an aquifer thickness of 10 feet. Model thickness in the southeastern corner of the aquifer was decreased to account for underlying silts and clays that are part of the total thickness of saturated stratified-drift materials. Altitudes of the initial water table and bottom of the aquifer, and average hydraulic conductivity values at each cell are required as part of the input data for the computer program (McDonald and Harbaugh, 1984) that was used. In applying the superposition technique the water table is set at an initial altitude of zero throughout the aquifer, and an altitude of zero also is assigned to the river surface. Altitude of the bottom of the aquifer is assigned a value that is equal to the negative of the saturated thickness at each cell. Average hydraulic conductivity at each cell is calculated by dividing transmissivity by saturated thickness. An aquifer storage coefficient of 0.2, typical of unconfined stratified-drift aquifers, is used for the entire aquifer.

Four wells were introduced to the model and pumped at varying rates until the desired value of 2.3 ft^3/s was supplied by the stream. Four wells were needed because the model cells containing the pumping wells went dry if fewer were used. The locations of the wells and resultant drawdowns are shown in figure 23. The combined pumping rate of the four wells was 2.0 Mgal/d and, at this rate, streamflow was reduced by 2.3 ft^3/s or 1.5 Mgal/d. The difference, 0.5 Mgal/d, is the rate at which ground water was being removed from storage at the end of the simulation. At that time, 26 percent of the water being supplied to the wells comes from storage, and about 11 percent of the available aquifer storage was used.

Figure 24 shows the result of superimposing the drawdowns calculated by the model and shown in figure 23 on the initial water-table altitudes shown in figure 22. The shaded area in figure 24 is the contributing recharge area for the wells after 180 days of pumping. Where the shaded areas reach the till/aquifer boundary the area of contribution is assumed to continue into the till. The areas of drawdown (fig. 23) overlap with but are not identical to the area of contribution (fig. 24). The size of the area of contribution under the conditions stated is about 0.6 mi^2 within the model area boundaries. Additional areas of till uplands, topographically up gradient from the contribution area within the model area also contribute water to the wells and are estimated to be about 1.1 mi^2. This total recharge area is considerably greater than the area included in the 400-foot protective radius required for public wells in the State of New Hampshire. For example, under New Hampshire law, the four wells modeled need a protection area of only 0.072 mi^2. As estimated by the superposition technique, the area of contribution simulated is 1.7 mi^2.

A sensitivity analysis of some of the model parameters indicates that the ratio of water coming from storage compared to the water coming from the river at the end of the 180 days remained essentially constant for the various values of hydrologic parameters analyzed:

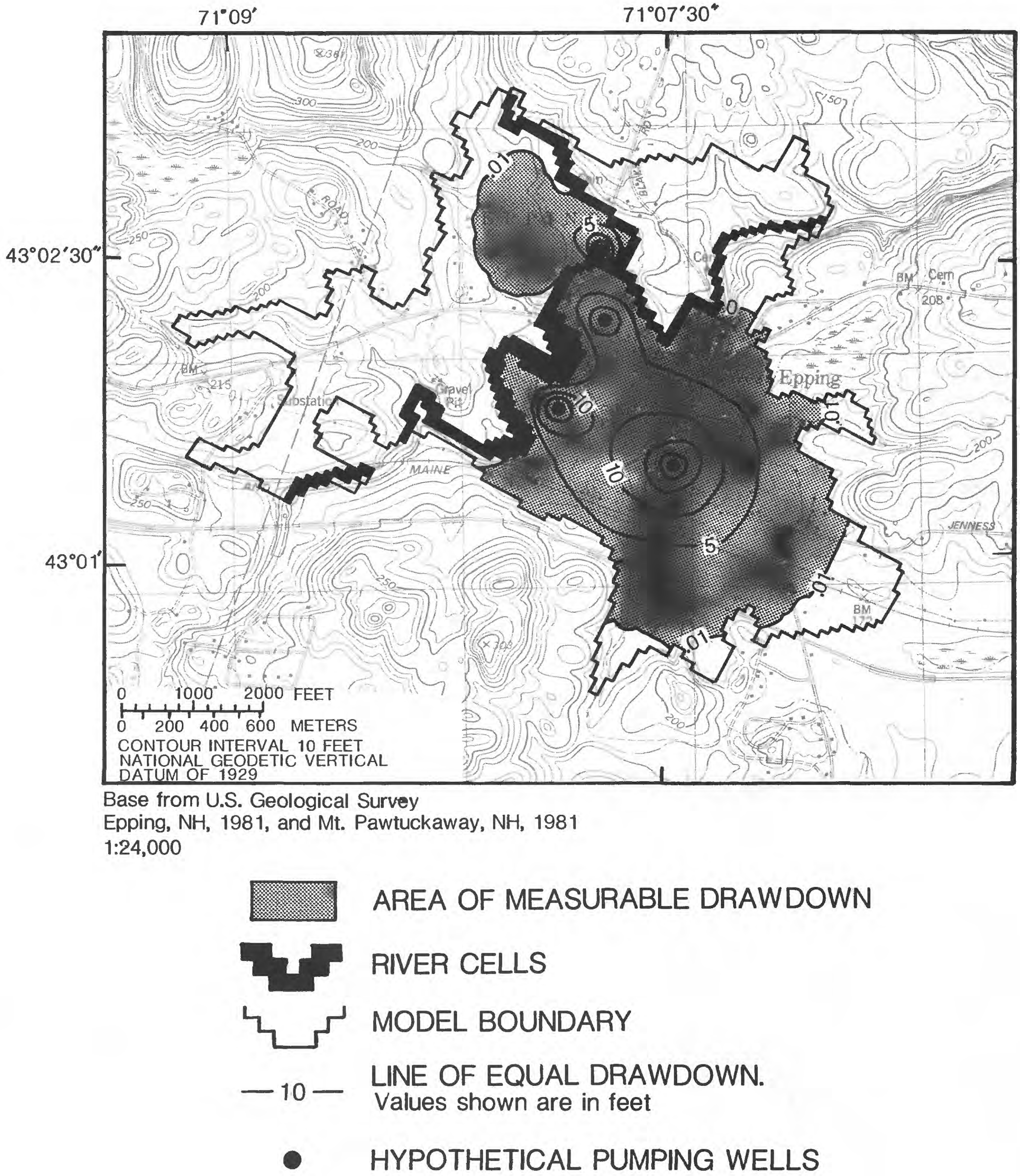
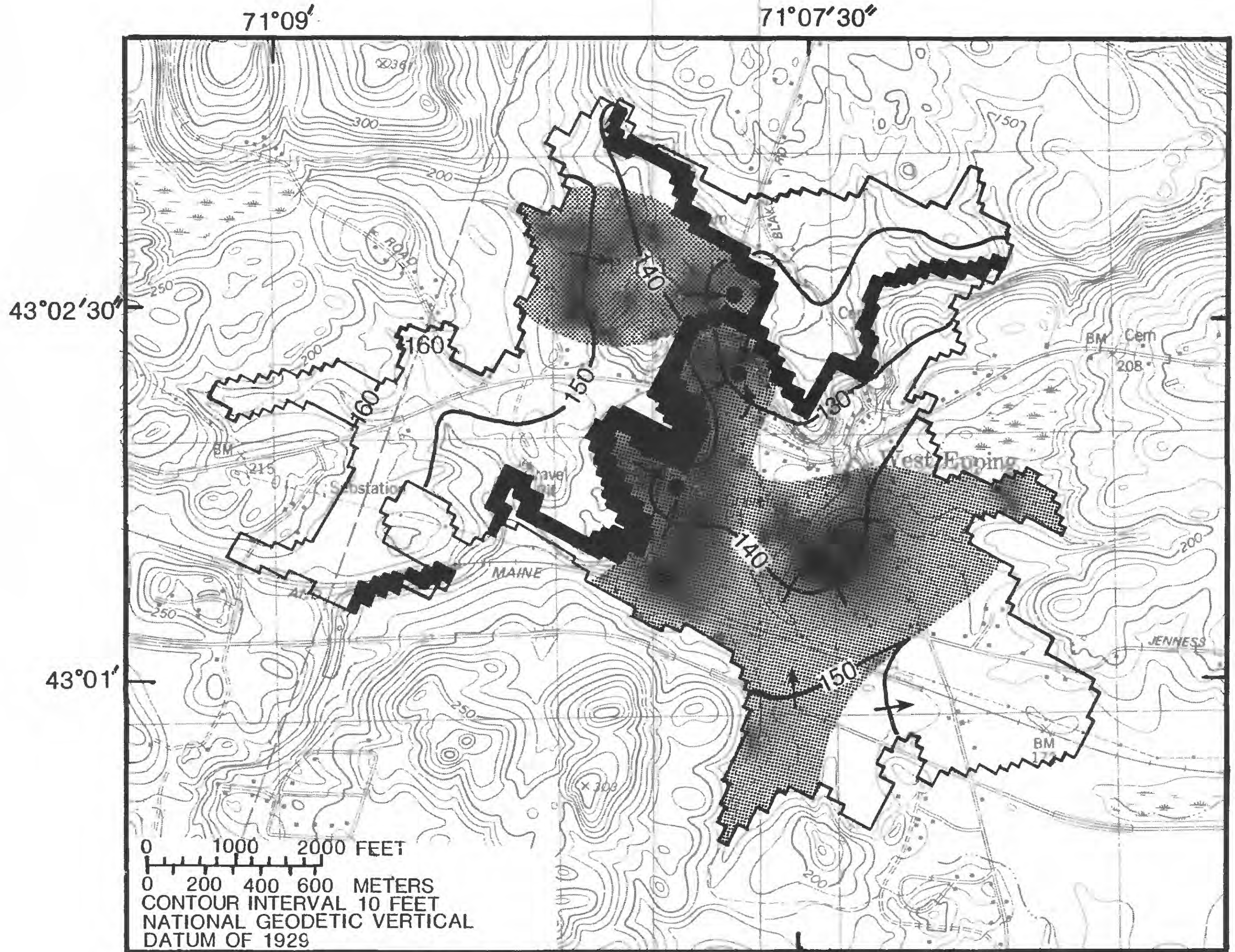


Figure 23.--Drawdown contours for four hypothetical wells in West Epping.



Base from U.S. Geological Survey
Epping, NH, 1981, and Mt. Pawtuckaway, NH, 1981
1:24,000

AREAS CONTRIBUTING WATER TO WELLS

RIVER CELLS

MODEL BOUNDARY

—150— LINE OF EQUAL WATER-TABLE ALTITUDE AFTER PUMPING.
Values shown are in feet above sea level
Arrow indicates direction of ground-water flow.

● HYPOTHETICAL PUMPING WELLS

Figure 24.--Final water-table configuration after 180 days of pumping, and the contributing areas to the four hypothetical wells in West Epping.

(1) the ratio changed insignificantly when depths of water in the river above the streambed were varied from 1 ft to 5 ft; (2) it changed insignificantly when streambed hydraulic conductance was varied from 1 to 4 ft/d; and (3) it decreased by less than one percent when the storage coefficient was changed from 0.2 to 0.1. Because streamflow requirements are the limiting factor, an estimated yield of 270,000 ft^3/d or 2.0 Mgal/d would be available from the West Epping aquifer 95 percent of the time, if the 99-percent-duration flow in the Lamprey River were maintained.

Newmarket Plains aquifer

An evaluation by the superposition technique also was done for the Newmarket Plains aquifer--an example of a grounding-line delta with no hydraulic connection between a river and the aquifer. The location of this aquifer is shown in figure 2. The model area is represented as a finite-difference grid of 75 rows and 71 columns with cell dimensions of 100 by 100 feet. The physical limits of this model are "no-flow" boundaries that represent the contacts between the aquifer and either till or silts and clays. These are shown in figure 25.

Discharges from the aquifer occur along parts of the aquifer boundary and are concentrated at Chapman Spring (fig. 25). Again, the term "no flow" means that no change in flow across the boundary is expected as a result of pumping. Drawdowns calculated along the boundary are small so the assumption that no change in flow occurs is justified. An exception is, perhaps, Chapman Spring where water discharging from the aquifer may be decreased as a result of pumping. If so, this condition is not simulated by the model. Discharge from Chapman Spring is, however, small enough that the ultimate conclusions reached are unchanged.

Model constraints are similar to those used for West Epping except no river is included and the pumping rates are those of the two existing municipal wells. The initial water-table map (fig. 25) does not show the impact of current pumpage. Figure 26 shows the location of the two municipal-supply wells and the drawdown simulated after 180 days of pumping. Pumpage from the well to the northwest was simulated as 80 gal/min (gallons per minute) and pumpage from the one to the southeast was simulated 200 gal/min. The former value is taken as the average of a typical daily pumpage from that well (Hill, 1979, pg. 76), whereas the latter is the rate at which the southeastern well was tested during an extended pump test. The simulated drawdown contours shown in figure 26 probably show excessive drawdown in the Chapman Spring area where actual pumpage would result in less drawdown than simulated and decreased spring discharge. Simulated drawdowns after 180 days of pumping are superimposed on the initial water table to estimate the water-table configuration under long-term pumping conditions (fig. 27).

As is the usual case, the areas where drawdown occurs are not identical with the areas of contribution to the wells. The size of the area of contribution is estimated to be about 0.38 mi^2 in the model area and is negligible for the till uplands. This is also considerably greater than the area determined by the 400-ft protective radius (0.036 mi^2 for two wells), as required by New Hampshire regulations.

All the water pumped by the wells comes from ground-water storage which is reduced by 7 percent. Because this aquifer is located on a hill and is relatively thin, a large number of wells would be needed to obtain a larger percentage of the ground water in storage. Because of this limitation, the estimated aquifer yield (0.40 Mgal/d) that assumed a small quantity (7 percent) of ground water can be recovered from storage probably is justified.

In aquifers not hydraulically connected to rivers, some consideration must be given to the annual hydrologic budget to determine if the assumption is justified that recharge at other times of the year is sufficient to supply water removed from storage during this 180-day period of low recharge intended to approximate the growing season. This assumption fails for the Newmarket Plains aquifer for withdrawals of 0.40 Mgal/d. Hill (1979) estimated that during a 3-month period (August 1-November 1, 1977), one third of the precipitation that fell on the Newmarket Plains aquifer actually recharged the aquifer. The National Oceanic and Atmospheric Administration has determined for a nearby station in Durham, N.H. a mean annual precipitation of 43 in/yr. One third of this mean annual precipitation rate (14.3 in/yr), distributed over the 0.38 mi^2 of aquifer surface area contributing water to the wells, results in an average recharge rate of 0.26 Mgal/d. Because the estimated average recharge rate to the contributing area is less than the anticipated pumping rate, the assumption that enough recharge occurs throughout the year to overcome losses incurred during the growing season is not true. Total well discharges greater than 0.26

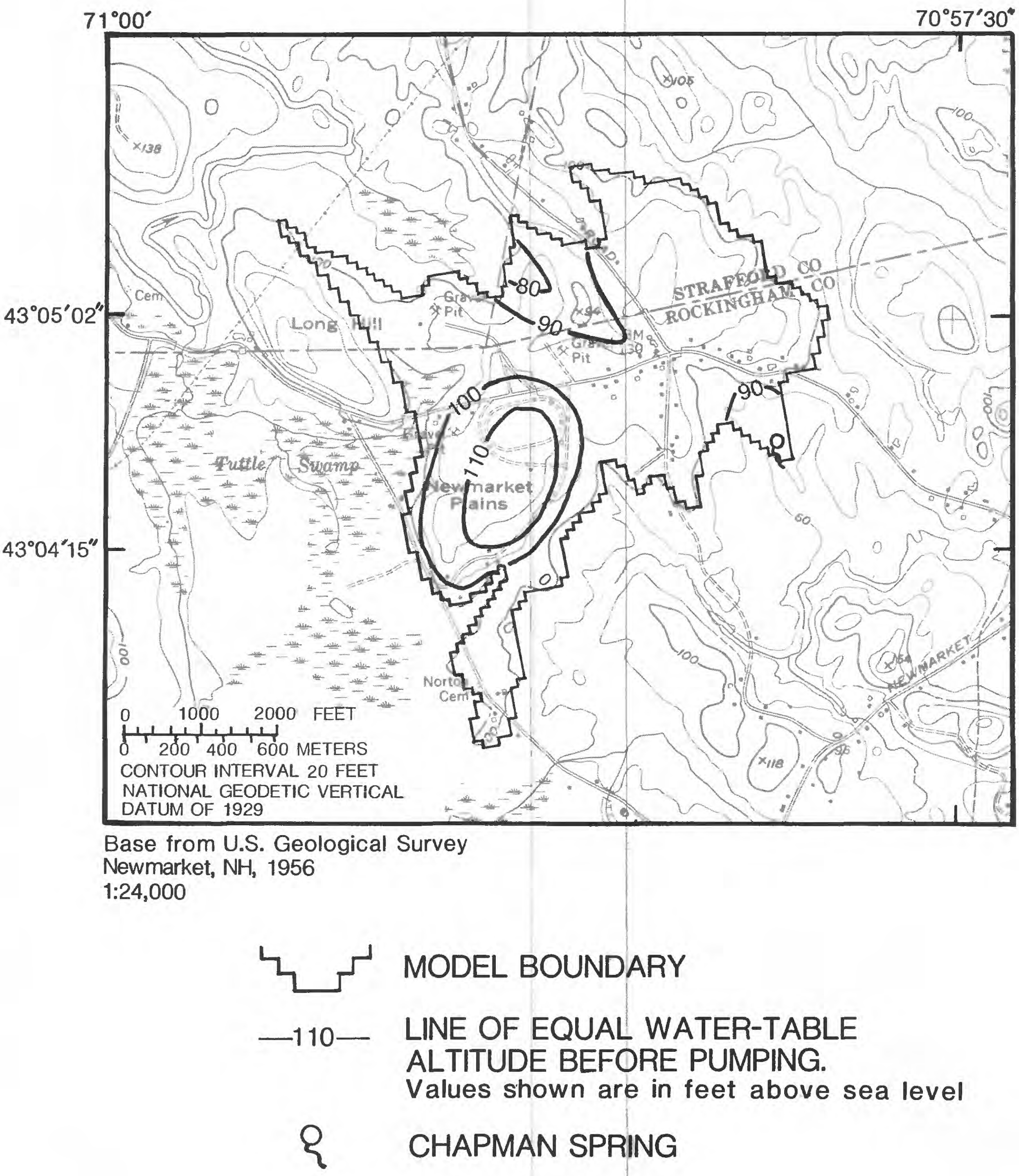


Figure 25.--Initial water-table configuration for simulation of the Newmarket Plains aquifer.

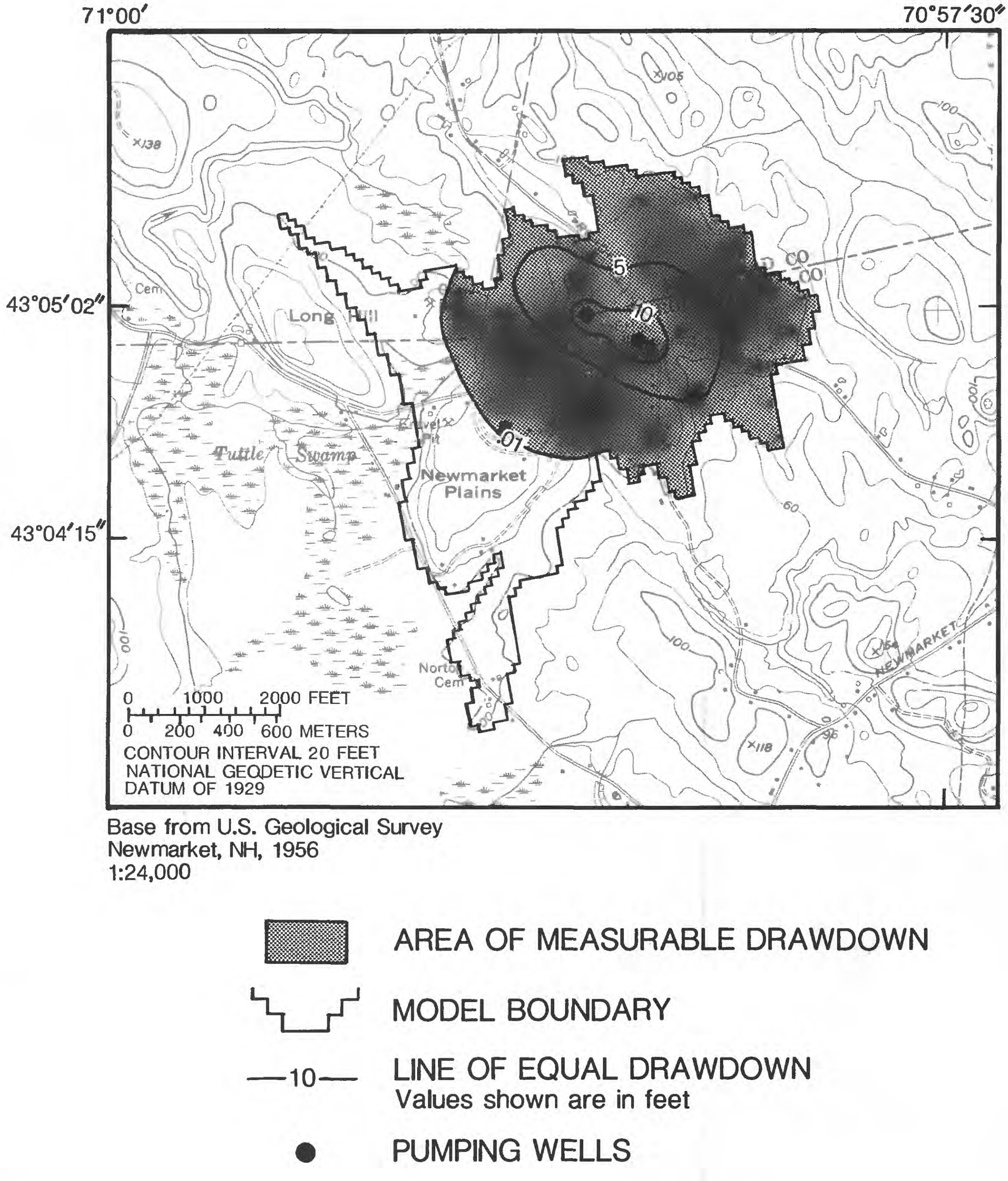
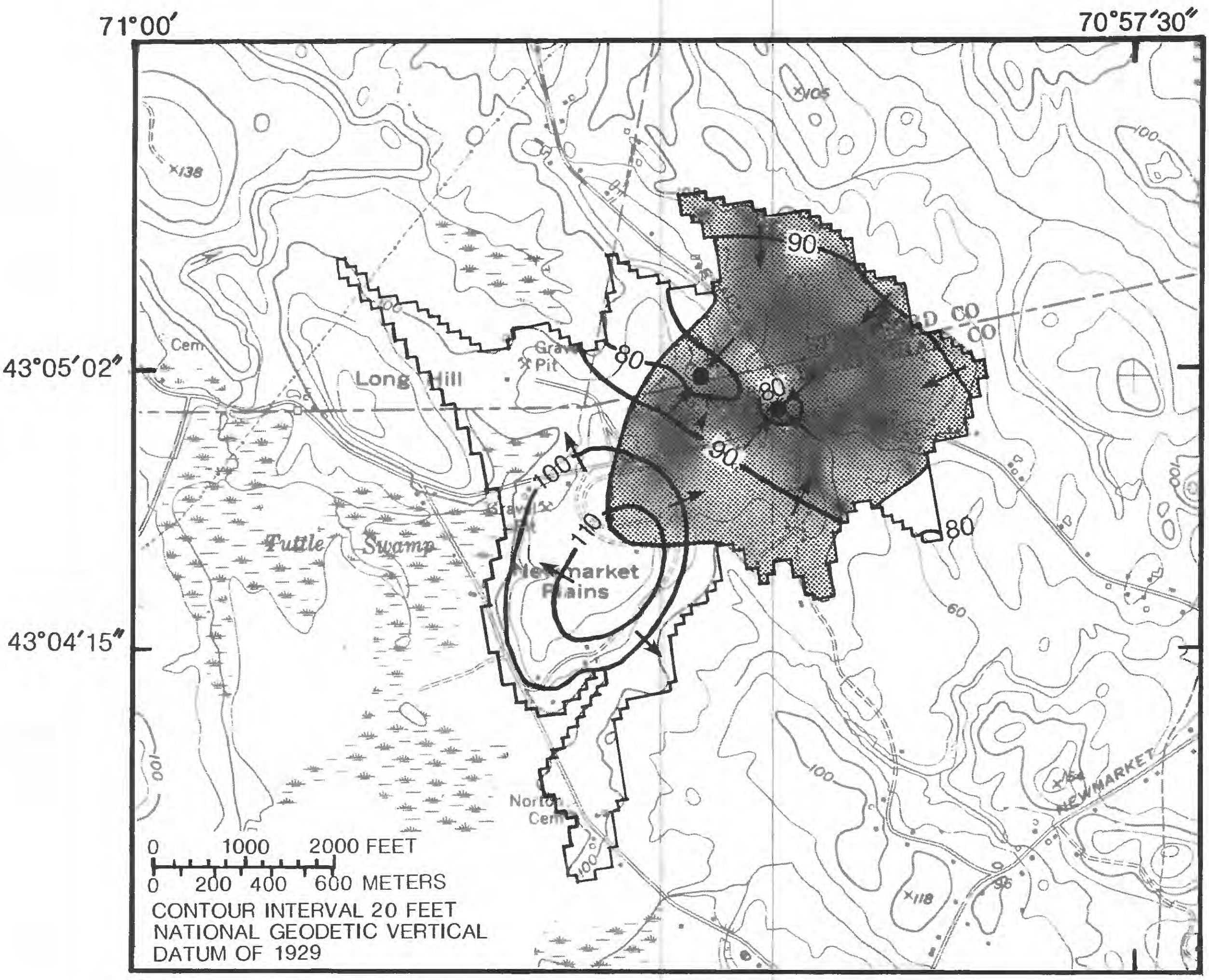


Figure 26.--Drawdown contours for the two existing municipal wells in Newmarket Plains.



Base from U.S. Geological Survey
Newmarket, NH, 1956
1:24,000

AREAS CONTRIBUTING WATER TO WELLS

MODEL BOUNDARY

—110— LINE OF EQUAL WATER-TABLE ALTITUDE AFTER PUMPING.
Values shown are in feet above sea level.
Arrow indicates direction of ground-water flow.

● PUMPING WELL

Figure 27.--Final water-table configuration after 180 days of pumping and the contributing areas to the two municipal wells in Newmarket Plains.

Mgal/d (or 180 gal/min) can not be maintained throughout the year without mining water from long-term storage.

WATER QUALITY

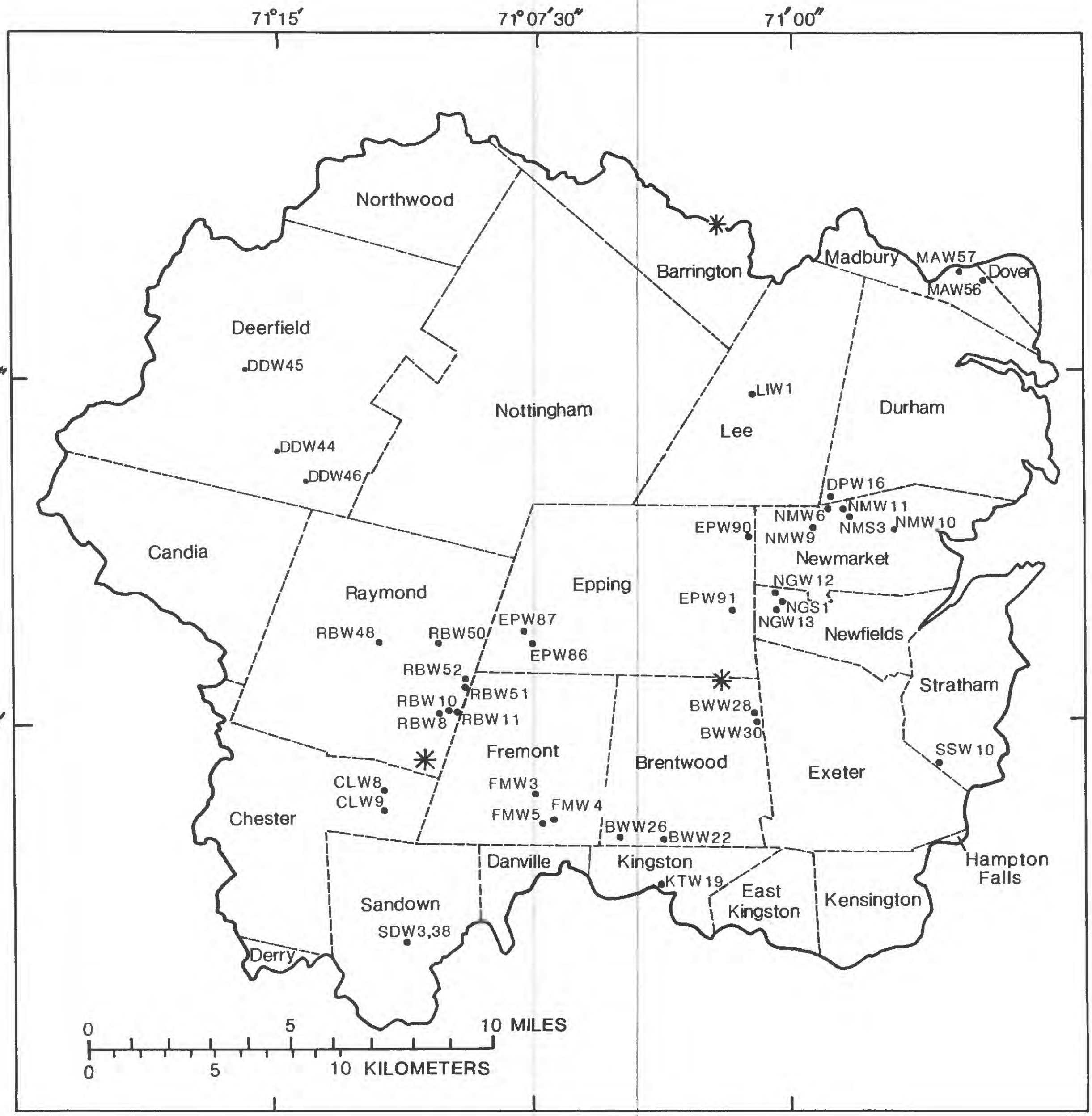
Samples of water from 38 test wells and 2 springs were analyzed for inorganic and organic chemicals to evaluate background water quality of the stratified-drift aquifers. During this phase of the study, areas with known ground-water contamination were avoided. Three sites, the Tibbets Road site in Barrington, (2) the Keefe Environmental Services in Epping, and (3) the Mottolo Pig Farm in Raymond, (fig. 28) are on the U.S. Environmental Protection Agency National Priority List (NPL) of hazardous-waste sites (Enivronmental Protection Agency (EPA), 1986b). A report for only one of these three sites, the Tibbetts Road site, has been published at the time of this writing (1987). At the Tibbetts Road site, leaking drums containing waste oils, kerosene, paints, thinners, transmission fluid, solvents, and other waste fluids reportedly have contaminated the ground water in till and bedrock. The drums have been removed, but three plumes of contaminated ground water are still evident in the till and bedrock aquifers (New Hampshire Water Supply and Pollution Control Commission, 1985). The three NPL sites and other sites located downgradient from landfills were avoided because the sampling program discussed in this report was designed to evaluate the general quality of water in the stratified-drift aquifers.

The sampling procedure varied with the source of the water sampled. No special preparations were made prior to sampling three wells and two springs. Wells NMW 6 (pl. 2) and SSW 10 (pl. 4) (fig. 28) were pumped continuously and springs NMS 3, NGS 1 and well NGW 12 (pl. 2) flowed naturally so evacuation of water prior to sampling was unnecessary. All other samples were obtained from the test wells after several volumes of water had been pumped from them (fig. 29). In most cases, 10 times the volume of water in each well casing was evacuated prior to sampling. In all cases pumping was continued until temperature and specific conductance readings stabilized and at least 3 times the volume of water in the well was evacuated before sampling. This procedure was followed to ensure that the water sampled represented water in the aquifer. In addition, water samples were not collected until at least 3 months had passed since the wells were constructed. This allowed sufficient time for the wash water, used in the well's construction, to move away from the well screen.

Results of the chemical analysis of the ground-water samples are summarized in table 3 and compared to the Environmental Protection Agency (EPA, 1979 and 1986a) standards for drinking water. Additional standards and criteria that apply to potable public-water supplies are published by the National Academy of Sciences and National Academy of Engineering (1972) and the U.S. Environmental Protection Agency (1975; 1976; 1977).

Results of the sample analyses indicate that water from the stratified-drift aquifers is generally of good quality and suitable for most uses with some exceptions. These include one sample with elevated chloride concentration and several samples with elevated sodium concentration (attributable to contamination by road deicing salt); several samples with elevated iron and manganese concentrations (presumably of natural origin); one sample with a 50 μg/L chromium concentration (perhaps of natural origin); one sample with a 4 μg/L mercury concentration, two samples with elevated arsenic concentrations of 14 and 11 μg/L, and one sample with evidence of volatile organic compounds. Individual constituents are discussed below.

Specific conductance, a measure of the total dissolved solids in water ranged from 26 to 1020 μS/cm (microsiemans per centimeter). Four of the 40 samples analyzed exceeded the recommended limit of 500 μS/cm established by the New Hampshire Water Supply and Pollution Control Commission (1984) for public drinking water. These values are probably high because many of the test wells are located along road right-of-ways where road salting, which contributes to high specific conductance levels in ground water, has occurred. Contamination from road salt is a common problem for stratified-drift aquifers in New Hampshire that are adjacent to roadways. The four highest values of specific conductance occurred at wells that are near State Highways 87, 107, 155 and 152--EPW 91 (pl. 4), FMW 3 (pl. 4), LIW 1 (pl. 2), and NMW 10 (pl. 2) (fig. 27). The median value of 186 μS/cm for all the samples compares with 132 μS/cm--a median value from large municipal supply wells in stratified drift throughout the state (Morrissey, D. J. and Regan, J. M., 1987), and the maximum of 1,020 μS/cm compares with 469 μS/cm from the same sample population. The data from the present study indicate that dissolved-solids concentration in ground water due to road-salting activities may be increasing.



EXPLANATION

—— BOUNDARY OF STUDY AREA

- - - - TOWN BOUNDARY

• RBW48 WATER – QUALITY SAMPLING LOCATION. A WELL OR SPRING WITH LOCAL IDENTIFIER

✳ HAZARDOUS-WASTE SITE---on the National Priorty List (EPA, 1986 b)

Figure 28.--Water-quality sampling locations and locations of hazardous-waste sites.

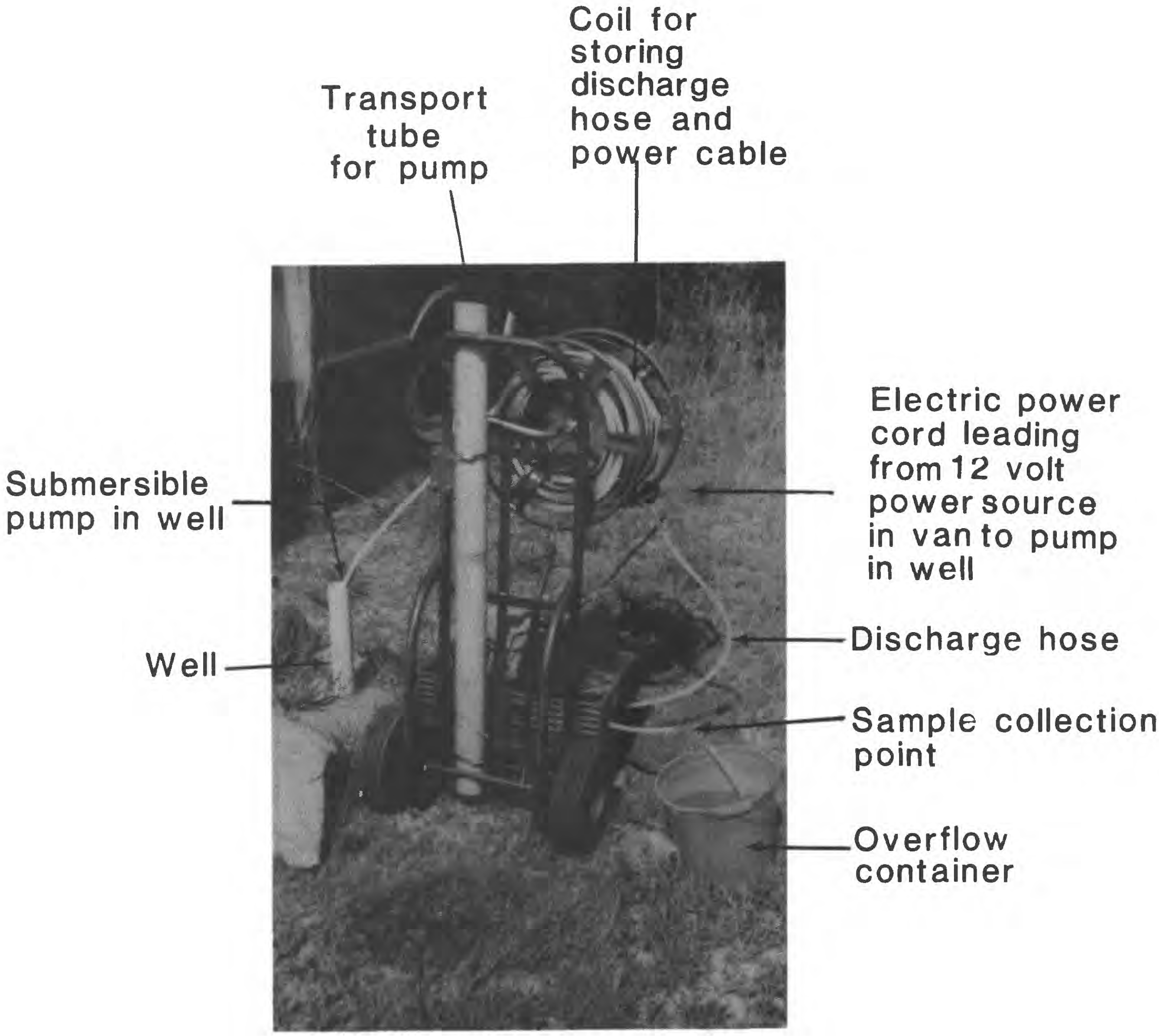


Figure 29.--Water-quality sampling of a test well.

Table 3.--*Summary of results of water-quality sample analyses*

[The symbol <, less than, proceeds many of the values whenever a concentration below detection limit was involved in its computation. To compute statistics these unknown low concentrations were assigned values equal to the detection limit; µS/cm at 25 °C, microsiemans per centimeter; mg/L, milligrams per liter; µg/L, micrograms per liter; --, no data.]

Constituents	[1]SMCL	[2]MCL	Number Samples	Mean	Median	Standard Deviation	Minimum	Maximum	First Quartile	Third Quartile
Specific conductance (µS/cm at 25 °C)			40	248	186	226	26.0	1020	85.2	374
Solids, sum of the dissolved constituents (mg/L)	500 *		38	12.1	91.5	106	24.0	500	50.0	172
Chloride, dissolved (mg/L as CL)	250 *		38	41.8	9.3	63.7	1.5	280	3.5	62.0
Sodium, dissolved (mg/L as Na)	20-250 *		39	24.8	13.0	33.9	1.6	180	4.2	35.0
pH (Standard units)			40	--	6.4	--	5.1	7.7	6.1	6.7
Alkalinity (mg/L as $CaCO_3$)			38	25.3	18.5	19.4	5.0	83.0	12.0	32.8
Hardness total (mg/L as $CaCO_3$)			39	41.2	25.0	49.0	5.0	280	13.0	48.0
Calcium, dissolved (mg/L as Ca)			39	12.5	8.1	15.0	1.4	87.0	3.6	15.0
Magnesium, dissolved (mg/L as Mg)			39	2.6	1.6	2.7	0.28	14.0	0.91	3.40
Nitrogen, Ammonia, dissolved (mg/L)			36	0.05	0.01	0.12	0.01	0.68	0.01	0.06
Potassium, dissolved (mg/L as K)			38	2.98	2.65	1.88	.50	10.0	1.75	3.60
Sulfate, dissolved (mg/L as SO4)	250 *		38	11.9	9.6	12.2	2.4	79.0	6.0	15.2
Fluoride, dissolved (mg/L as F)	4.0 *		38	<.1	<.1	--	<.1	.3	<.1	<.1
Carbon, organic, dissolved (mg/L as C)			36	1.2	1.0	.7	.3	2.9	.6	1.7
Silica, dissolved (mg/L as SiO2)			39	12.5	12.0	4.2	3.7	21.0	9.3	16.0
Arsenic, dissolved (µg/L as As)		50.0	39	<2	<1	--	<1	14	<1	<1
Barium, dissolved (µg/L as Ba)		1000	39	21	14	26	4	140	9	20
Beryllium, dissolved (µg/L as Be)			38	--	--	--	<.5	--	--	--
Boron, dissolved (µg/L as B)			38	<27	<20	--	<10	150	<10	30
Cadmium, dissolved (µg/L as Cd)		10.0	39	<1	<1	--	<1	4	<1	<1
Chromium, dissolved (µg/L as Cr)		50.0+	38	<11	<10	--	<10	50	<10	<10
Cobalt, dissolved (µg/L as Co)			38	<3	<1	--	<1	20	<1	3
Copper, dissolved (µg/L as Cu)	1000		38	<2	<1	--	<1	9	<1	2
Iron, dissolved (µg/L as Fe)	300		39	<258	13	--	<3	4300	6	35
Lead, dissolved (µg/L as Pb)		50.0	38	<2	<1	--	<1	5	<1	2
Manganese, dissolved (µg/L as Mn)	50.0		39	285	100	412	2	1900	17	390
Molybdenum, dissolved (µg/L as Mo)			38	<2	<1	--	<1	11	<1	<1
Mercury, dissolved (µg/L as Hg)		2.0	38	<.2	<.1	--	.1	4	<.1	<.1
Nickel, dissolved (µg/L as Ni)			38	<4	2	--	<1	16	<1	5
Silver, dissolved (µg/L as Ag)		50.0	38	<2	<1	--	<1	4	<1	<1
Strontium, dissolved (µg/L as Sr)			39	80	54	77	10	330	30	100
Zinc, dissolved (µg/L as Zn)	5000		39	<21	10	--	<3	230	5	19
Antimony, dissolved (µg/L as Sb)			38	<1	<1	--	<1	2	<1	1
Aluminum, dissolved (µg/L as Al)			38	<19	<10	--	<10	140	<10	12
Lithium, dissolved (µg/L as Li)			39	<5	<4	--	<4	19	<4	5
Selenium, dissolved (µg/L as Se)		10.0	38	--	--	--	--	<1	--	--

Table 3.--*Summary of results of water-quality sample analyses*---Continued

Constituents	[1]SMCL	[2]MCL	Number Samples	Mean	Median	Standard Deviation	Minimum	Maximum	First Quartile	Third Quartile
Dichlorobromomethane, total (µg/L)			40	--	--	--	--	<3.0	--	--
Carbontetrachloride, total (µg/L)			40	--	--	--	--	<3.0	--	--
1,2-Dichloroethane, total (µg/L)			40	--	--	--	--	<3.0	--	--
Bromoform, total (µg/L)			40	--	--	--	--	<3.0	--	--
Chlorodibromomethane, total (µg/L)			40	--	--	--	--	<3.0	--	--
Chloroform, total (µg/L)			40	--	--	--	--	<3.0	--	--
Toluene (µg/L)			40	--	--	--	--	<3.0	--	--
Benzene, total (µg/L)			40	--	--	--	--	<3.0	--	--
Chlorobenzene, total (µg/L)			40	--	--	--	--	<3.0	--	--
Chloroethane, total (µg/L)			40	--	--	--	--	<3.0	--	--
Ethylbenzene, total (µg/L)			40	--	--	--	--	<3.0	--	--
Methylene chloride, total (µg/L)			40	--	--	--	--	<3.0	--	--
Tetrachloroethylene, total (µg/L)			40	--	--	--	--	<3.0	--	--
Trichloroflouromethane, total (µg/L)			40	--	--	--	--	<3.0	--	--
1,1-Dichloroethane, total (µg/L)			40	--	<3.0	--	<3.0	11.0	<3.0	<3.0
1,1-Dichloroethylene, total (µg/L)			40	--	<3.0	--	<3.0	3.9	<3.0	<3.0
1,1,1-Trichloroethane, total (µg/L)			40	--	<3.0	--	<3.0	6.2	<3.0	<3.0
1,1,2-Trichloroethane, total (µg/L)			40	--	--	--	--	<3.0	--	--
1,1,2,2 Tetrachloroethane, total (µg/L)			40	--	--	--	--	<3.0	--	--
1,2-Dichloropropane, total (µg/L)			40	--	--	--	--	<3.0	--	--
Chloroethylene, total (µg/L)			40	--	--	--	--	<3.0	--	--
1,3-Dichloropropane, total (µg/L)			40	--	--	--	--	<3.0	--	--
2-Dichloroethylvinylether, total (µg/L)			40	--	--	--	--	<3.0	--	--
Dichlorodifluoromethane, total (µg/L)			40	--	--	--	--	<3.0	--	--
Vinylchloride, total (µg/L)			40	--	--	--	--	<3.0	--	--
Trichloroethylene, total (µg/L)			40	--	--	--	--	<3.0	--	--

[1]SMCL -- Secondary Maximum Concentration Levels are set by the Environmental Protection Agency (EPA), except where noted, to provide acceptable qualities of taste, odor, color and appearance in public water supplies. At higher concentrations some of these constituents may be associated with adverse health effects (EPA, 1979).

* -- Secondary level set by the New Hampshire Water Supply Bureau (written commun., 1987)

[2]MCL -- Maximum Concentration Levels are enforceable EPA primary drinking-water regulations (U.S. Environmental Protection Agency, 1986a)

\+ -- MCL for Chromium is 50 µg/L Cr^{+6} or 50 µg/L Cr^{+3}.

The sum of the dissolved constituents in the samples ranged from 24.0 to 500 mg/L. The highest value equals the recommended limit for drinking water established by the New Hampshire Water Supply Bureau (written commun., 1987). This value was determined for the sample from well EPW91 which also had the highest specific conductance, the highest sodium, and the highest chloride concentrations.

Sodium and chloride concentrations in the water sample from EPW 91 were 180 mg/L and 280 mg/L, respectively, and represent the highest determined. These convert to 7.8 and 7.9 meq/L (milliequivalents per liter), respectively, suggesting that NaCl (probably from road salt) is the source of both constituents. Sodium concentrations for all samples were below the standard established by the New Hampshire Water Supply and Pollution Control Division (written commun., 1987) for drinking water for healthy people (250 mg/L) and the median of 13 mg/L was below the standard of 20 mg/L for people with heart, hypertension, or kidney problems. One sample had a chloride concentration that exceeded the EPA (1979) secondary drinking-water recommended limit of 250 mg/L. This concentration basically is a taste threshold in as much as most people can drink up to 1,000 mg/L with little difficulty (Hall, 1975, p. 1). At present, the potential health problem is greatest for those people who require sodium-restricted diets and who have wells near, or downgradient from, heavily salted roads. One apparent trend is the rise in chloride concentrations over the years. Increases in chloride are documented by Hall (1975) over the entire State for samples collected during 1918-24 and 1968-70. In the Exeter, Lamprey, and Oyster River basins, concentrations seem to have risen from below 10 mg/L during 1918-24 to mostly above 10 mg/L during 1968-70. Also, 25 percent of the samples collected during 1984-85 had chloride concentrations that exceeded 62 mg/L, indicating that the rising trend is continuing.

The pH of 40 samples from the study area, measured in the field ranged from 5.1 to 7.7 standard pH units. In general, pH values determined for the ground water indicate slightly acid conditions. The most acidic waters sampled (pH = 5.1) were from wells FMW 4 and FMW 5 (pl. 4, fig. 28). Water samples with pH values that were slightly basic (greater than pH 7) were obtained from wells EPW 90 (pl. 2), NGW 12, and NGW 13 (pl. 4).

Alkalinity is an indicator of the water's ability to resist a change in pH due to the addition of acid. The background alkalinity of the ground water in the stratified-drift aquifers is relatively low, indicating little buffering capacity or ability to resist change. Alkalinity determined in the laboratory ranged from 5.0 to 83, expressed as mg/L of $CaCO_3$ (calcium carbonate). The sample with the highest alkalinity (83 mg/L) was collected from well NMW 10 (pl. 2, fig. 28). In carbonate-bedrock aquifers, ground water with alkalinity that exceeds 200 mg/L is not uncommon, and some concentrations exceed 1,000 mg/L (Hem, 1970). The stratified-drift aquifers in the study area, however, do not contain significant carbonate minerals, and, as a consequence, water associated with them have a low alkalinity and a low buffering capacity.

Hardness of the water, also expressed in mg/L as $CaCO_3$, ranged from 5.0 mg/L which is "soft" to 280 mg/L which is "very hard". More than three-quarters of the samples analyzed had a hardness of less than 60 mg/L, which, according to Hem (1970), indicates soft water. Five samples had a moderate hardness between (60 and 120 mg/L), whereas one sample from well MAW 57 (pl. 2), had a hardness of 120 mg/L, which is the dividing line between "moderately hard" and "hard" water. Water from well NMW 10 in Newmarket (pl. 2, fig. 28) was "very hard", with a hardness of 280 mg/L as CaCO . Well NMW 10 is screened in a sandy layer between layers of glacioestuarine silts and clays. Water from this well also had the highest concentrations of calcium and magnesium--the principal two components of hardness.

The water from well NMW 10 also had an abnormally high dissolved chromium concentration of 50.0 µg/L (micrograms per liter). This value exceeds the levels found in water samples from all other wells which were either at or below the detection limit of 10 µg/L. The concentration of 50 µg/L is the maximum drinking water regulation established by the EPA (1986a) for hexavalent and trivalent chromium ions. It is not known if the chromium species found in the water sample collected from NMW 10 is at one of these harmful valence levels.

Elevated concentrations of iron and manganese are the most common water-quality problems found during the course of the study. Iron concentrations above the EPA (1979) secondary drinking-water recommended limit of 300 µg/L were measured in samples from five wells--4,300 µg/L at RBW 50, 1,500 µg/L at RBW 52, 1,400 µg/L at RBW 51 (pl. 3), 1,300 µg/L at FMW 3, and 800 µg/L at KTW 19 (pl. 4, fig. 28). These values significantly exceed the EPA recommended limits and, although high iron is not known to be harmful to humans, it can stain clothes and plumbing fixtures and give water an objectionable taste and color. Elevated manganese concentrations commonly are found in water samples with elevated iron concentrations. Like iron, elevated concentrations of manganese in water can cause stains. These are typically a gray or black manganese dioxide residue. All but 12 of the 40 samples had concentrations of manganese that exceeded the EPA (1979) secondary drinking-water recommended limit of 50 µg/L. Manganese concentrations in half the samples exceeded 100 µg/L, three-quarters exceeded 390 µg/L, and the highest value, determined for water from well RBW 49, was 1,900 µg/L.

Low concentrations of mercury, less than 1 µg/L, were detected in eight of the samples. Water from one well, NMW 9 (pl. 2, fig. 28), had a mercury concentration of 4 µg/L, which exceeds the EPA (1986a) primary drinking-water regulation of 2 µg/L. The cause of mercury contamination at NMW 9 is unknown. The well is located at the entrance of the old Newmarket City landfill, but it is located upgradient from it. Ground water in the vicinity of NMW 9 flows away from the well toward the landfill, lessening the potential of contamination from that source.

Volatile organic compounds were detected in 1 of the 40 samples analyzed. Well BBW 30 (pl. 4, fig. 27), in Brentwood, contained 11 µg/L 1,1-dichloroethane, 3.9 µg/L 1,1-dichloroethylene, and 6.2 µg/L 1,1,1-trichloroethane. The specific cause of this contamination is unknown.

The EPA (1986a) primary drinking-water regulation for arsenic in drinking water is 50 µg/L. This standard was not exceeded by any of the samples. The highest concentrations measured are 11 µg/L at RBW 50 and 14 µg/L at NGW 13. About 10 to 15 percent of water from bedrock wells tested in New Hampshire have arsenic concentrations in excess of 50 µg/L (Morrissey, D. J. and Regan, J. M., 1987). This condition may result mainly from natural processes, such as the dissolution of minerals like arsenopyrite (U.S. Environmental Protection Agency, 1981). However, some investigators suggest that the major source of arsenic in ground water in New Hampshire is from human activities, especially the use of arsenic-rich detergents (Boudette and others, 1985).

Aside from the problems just discussed, the analyses show that the water in the stratified-drift aquifers is generally of good quality and suitable for most uses. Those constituents whose concentrations met the EPA primary drinking-water regulations and secondary drinking-water recommended limits (1979, 1986a) in all samples include sulfate, fluoride, barium, cadmium, copper, lead, silver, zinc, and selenium. In addition, none of the 40 samples analyzed had detectable concentrations of 23 of the 26 volatile organic compounds included in the analysis. The detection limit for these compounds was 3 µg/L.

Eight of the 40 water samples also were analyzed for the pesticide compounds listed below and none were detected at the very sensitive detection limit of 0.01 µg/L. The samples were collected from areas where pesticides were once used. Site selection was made following the suggestions of the New Hampshire Department of Agriculture, Pesticide Control Division who also suggested specific pesticides for analysis. Compounds tested included aldrin, chlordane, DDD, DDE, DDT, diazinon, dieldrin, endosulfan, endrin, ethion, PCB, polychlorinated naphthalenes, heptachlor epoxide, heptachlor, lindane, malathion, methyl parathion, methyl trithion, mirex, parathion, perthane, silvex, toxaphene, trithion, 2,4-D, 2,4-DP, and 2,4,5-T.

SUMMARY AND CONCLUSIONS

Rapid population growth and economic development have stressed the capacity of existing municipal-water systems in the Exeter, Lamprey, and Oyster River basins. As the need for water increases so too does the need for information to ensure optimal use of existing sources. This report provides geohydrologic information on stratified-drift aquifers in these basins. The purposes of this study are (1) to describe geohydrologic characteristics of the stratified-drift aquifers in the area, (2) to evaluate the hydrologic effect of ground-water development using digital modeling techniques, and (3) to describe background water quality within the stratified-drift aquifers.

Stratified-drift aquifers consist of stratified, sorted, principally coarse-grained sediments (sands and gravels) deposited by glacial meltwater at the time of deglaciation. Interconnected voids or pore spaces between sediment particles provide space through which stored ground water can flow. Characteristics of the sediments which affect ground-water storage and movement are related to the original glaciofluvial environment in which they were deposited.

Various types of stratified-drift deposits occur in the study area. Deglaciation of the western part of the study area is believed to have occurred by a systematic process of stagnation zone retreat, that resulted in valley-fill deposits, including eskers, kames, kame terraces, outwash, and outwash deltas. Deposits formed in contact with glacial ice tend to have larger pore spaces and a greater capacity to store and transmit water than other types of deposits.

Glacioestuarine deltaic deposits are found in the eastern part of the study area where marine inundation occurred. Deltas were formed at the inland marine limit and at glacial-ice/ocean interfaces where meltwater entered the ocean or estuary. Grounding-line aquifers are the most productive aquifers within the study area.

The geohydrology of the stratified-drift aquifers was investigated by focusing on basic aquifer properties, including aquifer boundaries, recharge, discharge, and direction of ground-water flow, aquifer thickness and storage, and aquifer transmissivity.

Aquifer boundaries were delineated from maps of surficial geology. A major source of information was data produced through the COGEOMAP program. Additional quadrangles were specifically mapped for this project.

Data were collected from wells, test holes, springs, and seismic-refraction profiles located principally in the stratified-drift aquifer areas. Well, test-hole, and spring data from 1,200 sites were checked for accuracy and added to the U.S. Geological Survey's computerized GWSI data base. The data was used to produce maps showing water-table configurations, saturated stratified-drift thickness, and transmissivity distributions.

Seismic-refraction profiles were completed at 26 locations within the study area. The maximum depth to bedrock determined with refraction data was 160 feet. The results aided production of the water-table and saturated-thickness maps.

Periodic water-level measurements have been made by the U.S.Geological Survey at 67 wells within the study area which show large fluctuations for till wells but only small fluctuations for wells in stratified drift. Using the above data, water-table contours were drawn to show the general directions of ground-water flow expected for the summer season under nonpumping natural conditions. Flow patterns are affected by sources of recharge and discharge and the ability of the aquifer to transmit water.

Thicknesses of saturated stratified drift were contoured for aquifer areas with the aid of the surficial mapping, seismic-refraction profiling, test drilling, and inventoried data stored in GWSI. A computer-assisted procedure was developed and used to calculate saturated thicknesses from data stored in the GWSI data base. Saturated thickness is related to the geohydrologic setting in which the aquifers were formed. Layers of saturated silts and clays that lie above, below, or interfingering with the aquifer are included in the saturated thicknesses depicted.

Hydraulic conductivity of the aquifer material was estimated from grain-size distributions of samples collected during test drilling. Aquifer transmissivity was calculated from the estimates of hydraulic conductivity and from aquifer-thickness data. Geologic and drillers' logs were examined during this process, and saturated silts and clays were excluded from the transmissivity estimates because their contribution is negligible. Transmissivity ranges from nearly 0 to greater than 3,000 ft^2/d.

Within the study area, 18 aquifers locally have transmissivities that exceed 1,000 ft^2/day. Of these, 6 presently supply municipal wells and 12 are not being used. Towns with aquifers with transmissivities that exceed 1,000 ft^2/d that are used for municipal water supplies include Dover, Durham, Epping, Lee, Madbury, Newmarket, and Raymond. Towns with aquifers that are not being fully used for municipal water supplies are Brentwood, Deerfield, Durham, Epping, Exeter, Lee, Newfields, Nottingham, Raymond, and Sandown.

The yield and contributing recharge area of existing or potential wells in two aquifers were estimated with computer models of groundwater flow. The principle of superposition was used to superimpose drawdowns, simulated with a digital model, on the measured, predevelopment water-table surface. This procedure simulated the extent of the area contributing water to the pumping wells and showed where this differed from the area affected by drawdown.

The two aquifers selected for analysis were a deltaic deposit at West Epping formed at the inland limit of marine inundation and a grounding-line delta at Newmarket Plains. The West Epping aquifer is in hydraulic connection with the Lamprey River and part of the simulated well yield of 2.0 Mgal/d was derived from the river by induced infiltration.

A technique using streamflow and basin characteristics was used to estimate the maximum quantity of water that could be derived from the river.

The Newmarket Plains aquifer is similar in size to the West Epping aquifer but is not in hydraulic connection with a surface-water body. As a consequence, the long-term yield of the Newmarket Plains aquifer is significantly smaller.

Water-quality samples were collected at 38 test wells and 2 springs in the study area. Known areas of contamination were avoided, including three sites that are on the National Priority List of hazardous-waste sites established by the U.S. Environmental Protection Agency (1986b). The water quality of the stratified-drift aquifers generally is suitable for most uses with the following exceptions: One sample had a 280-mg/L chloride concentration and 12 samples had sodium concentrations that exceeded 20 mg/L (mainly from road salt); 5 samples had iron concentrations that exceeded 1,000 µg/L and 27 samples had manganese concentrations that exceeded 50 µg/L (of natural origin). Other evidence of possible degraded ground-water conditions include one sample with a chromium concentration of 50 µg/L, one sample with a mercury concentration of 4 µg/L, two samples with elevated arsenic concentrations of 14 and 11 µg/L, and one sample with detectable concentrations of volatile organic compounds. The origins of these substances are not known. The EPA drinking-water regulations and recommended limits (1979, 1986a) for sulfate, fluoride, barium, cadmium, copper, lead, silver, zinc, and selenium were not exceeded in any sample. In addition, 23 volatile organic compounds tested were not detected in all 40 samples. Eight samples near sites where pesticides had been used were selected and analyzed; none were detected.

GLOSSARY

Ablation Till: Loosely consolidated rock debris, formerly carried by glacial ice, that accumulated in places as the surface ice was removed by ablation.

Aquifer: A geologic formation, group of formations, or part of a formation that contains sufficient saturated permeable materials to yield significant quantities of water to wells and springs. Where water only partly fills an aquifer, the upper surface of the saturated zone is free to rise and decline (Heath, 1983).

Aquifer boundary: A feature that limits the extent of an aquifer.

Bedrock: Solid rock, locally called "ledge," that forms the earth's crust. It may be exposed at the surface but more commonly is buried beneath a few inches to more than 100 feet of unconsolidated deposits.

Coefficient of determination (R^2): A measure of the proportion of variation in the dependent variable that can be explained by the regression model:

$$R^2 = 1 - \frac{\text{Error Sum of Squares}}{\text{Total Sum of Squares}}$$

Cone of depression: A depression produced in a water table or other potentiometric surface by the withdrawal of water from an aquifer; in cross section, shaped like an inverted cone with its apex at the pumped well.

Confined Aquifer: An aquifer saturated with water and bounded above and below by material having a distinctly lower hydraulic conductivity than the aquifer itself.

Constant-head permeameter: A laboratory apparatus for measuring hydraulic conductivity where a sediment sample is enclosed between two porous plates in a cylindrical tube with a constant hydraulic head difference set up across the sample as water is passed through the cylinder.

Contact: A plane or irregular surface between two different types or ages of rocks or unconsolidated sediments.

Cubic feet per second (ft^3/s): A unit expressing rate of discharge. One cubic foot per second is equal to the discharge of a stream 1 foot wide and 1 foot deep flowing at an average velocity of 1 foot per second.

Cubic feet per second per square mile [$(ft^3/s)/mi^2$]: A unit expressing average number of cubic feet of water flowing per second from each square mile of area drained.

Darcy's Law: An equation relating the factors controlling ground-water movement. Darcy's law is

$$Q = KA\frac{dh}{dl}$$

where Q is the quantity of water per unit of time; K is the hydraulic conductivity and depends on the size and arrangement of the water-transmitting openings (pores and fractures) and on the dynamic characteristics of the fluid (water) such as kinematic viscosity, density, and the strength of the gravitational field; A is the cross-sectional area, at a right angle to the flow direction, through which the flow occurs; and dh/dl is the hydraulic gradient.

Deposit: Earth material that has accumulated by some natural process.

Dissolved solids: The residue from a clear sample of water after evaporation and drying for 1 hour at 180° C; consists primarily of dissolved mineral constituents, but may also contain organic matter and water of crystallization.

Drainage area: The area or tract of land, measured in a horizontal plane, that gathers water and contributes it ultimately to some point on a stream channel, lake, reservoir, or other water body.

Drawdown: The lowering of the water table or potentiometric surface caused by the withdrawal of water from an aquifer by pumping; equal to the difference between the static water level and the pumping water level.

Drumlin: A low, smoothly rounded, elongated oval shaped hill of glacial till, built under the margin of glacial ice and shaped by its flow; its longer axis is parallel to the direction of movement of the ice.

Effective size: The grain size at which 10 percent of the sample consists of smaller grains and 90 percent consists of larger grains.

Esker: A long ridge of sand and gravel that was deposited by water flowing in tunnels within or beneath glacial ice.

First quartile: For a set of measurements arranged in order of magnitude, that value where 25 percent of the measurements are lower in magnitude and 75 percent are higher.

Flow duration, of a stream: The percentage of time during which specified daily discharges are equaled or exceeded within a given time period.

Fracture: A break, crack, or opening in bedrock along which water may move.

Gneiss: A coarse-grained metamorphic rock with alternating bands of granular and micaceous minerals.

Granite: A coarse-grained, light colored, igneous rock.

Granodiorite: A coarse-grained igneous rock that contains quartz, plagioclase, potassium feldspar, biotite and hornblende.

Gravel: Unconsolidated rock debris composed principally of particles larger than 2 mm in diameter.

Ground water: Water beneath the water table in soils or geologic formations that are fully saturated.

Ground-water discharge: The discharge of water from the saturated zone by (1) natural processes such as ground-water seepage into stream channels and ground-water evapotranspiration and (2) discharge through wells and other manmade structures.

Ground-water divide: A hypothetical line on a water table on each side of which the water table slopes downward in a direction away from the line. In the vertical dimension, a plane across which there is no ground-water flow.

Ground-water evapotranspiration (GWET): Ground water discharged into the atmosphere in the gaseous state either by direct evaporation from the water table or by the transpiration of plants.

Ground-water recharge: Water that is added to the saturated zone of an aquifer.

Ground-Water Site Inventory (GWSI): A computerized file maintained by the U.S. Geological Survey that contains information about wells and springs collected throughout the United States.

Head, static: The height of the surface of a water column above a standard datum that can be supported by the static pressure of a given point.

Hydraulic conductivity (K): A measure of the ability of a porous medium to transmit a fluid that can be expressed in unit length per unit time. A material has a hydraulic conductivity of 1 foot per day if it will transmit in 1 day, 1 cubic foot of water at the prevailing kinematic viscosity through a 1 foot square cross section of aquifer, measured at right angles to the direction of flow, under a hydraulic gradient, of 1 foot change in head over 1 foot length of flow path.

Hydraulic gradient: The change in static head per unit of distance in a given direction. If not specified, the direction is generally understood to be that of the maximum rate of decrease in head.

Hydrograph: A graph showing stage (height), flow velocity, or other property of water with respect to time.

Ice-contact deposits: Stratified drift deposited in contact with melting glacial ice. Landforms include eskers, kames, kame terraces, and grounding-line deltas.

Igneous: Descriptive term for rocks or minerals solidified from molten or partially molten material,--that is, from a magma, such as basalt or granite.

Image well: An imaginary well so placed with respect to a real well and hydrologic boundary that by discharging or recharging it produces a ground-water divide or condition of no drawdown along the boundary position.

Induced infiltration: The process by which water infiltrates an aquifer from an adjacent surface-water body in response to pumping.

Kame: A low mound, knob, hummock or short irregular ridge composed of stratified sand and gravel deposited by glacial meltwater; the precise mode of formation is uncertain.

Kame terrace: A terrace-like ridge consisting of stratified sand and gravel formed as a glaciofluvial deposit between a melting glacier or stagnant ice lobe and a higher valley wall, and left standing after the disappearance of the ice.

Lodgement till: A firm, compact clay-rich till deposited beneath a moving glacier, containing abraided stones oriented, in general, with their long axes parallel to the direction of ice movement.

Marine limit: The former limit of the sea. The highest shoreline during a period of late-glacial submergence.

Mean (arithmetic)**:** The sum of the individual values of a set, divided by their total number; also referred to as the "average."

Median: The middle value of a set of measurements, that are ordered from lowest to highest, 50 percent of the measurements are lower than the median and 50 percent are higher.

Metamorphic: Descriptive term for rocks such as gneiss and schist which have formed, in the solid state, from other rocks.

Micrograms per liter (μg/L): A unit expressing the concentration of chemical constituents in solution as the mass (micrograms) of a constituent per unit volume (liter) of water. One thousand micrograms per liter is equivalent to one milligram per liter.

Milligrams per liter (mg/L): A unit for expressing the concentration of chemical constituents in solution as the mass (milligrams) of a constituent per unit volume (liter) of water.

Outwash: Stratified deposits chiefly of sand and gravel removed or "washed out" from a glacier by meltwater streams and deposited beyond the margin of a glacier. Usually occurring in flat or gently sloping outwash plains.

Outwash deltas: Deltas formed beyond the margin of the glacier where glacial meltwater entered a water body.

pH: The negative logarithm of the hydrogen-ion concentration. A pH of 7.0 indicates neutrality; values below 7.0 denote acidity, those above 7.0 denote alkalinity.

Phi grade scale: A logarithmic transformation of the Wentworth grade scale based on the negative logarithm to the base 2 of the particle diameter, in millimeters.

Phyllite: A fine-grained, metamorphic rock, similar to schist often having a silky luster.

Porosity: The property of a rock or unconsolidated deposit that is a measure of the size and number of internal voids or open spaces; it may be expressed quantitatively as the ratio of the volume of its open spaces to its total volume.

Precipitation: The discharge of water from the atmosphere, either in a liquid or solid state.

Primary porosity: Porosity that is intrinsic to the sediment or rock matrix. See secondary porosity.

Runoff: That part of the precipitation that appears in streams. It is the same as streamflow unaffected by artificial diversions, storage, or other human activites in or on the stream channels.

Saturated thickness (of stratified drift): Thickness of stratified drift extending down from the water table to the till or bedrock surface.

Saturated zone: The subsurface zone in which all open (interconnected) spaces are filled with water. Water below the water table, the upper limit of the saturated zone, is under pressure greater than atmospheric.

Schist: A metamorphic rock with subparallel orientation of the visible micaceous minerals, which dominate its composition.

Secondary porosity: Porosity which may be due to such phenomena as secondary solution or structurally controlled regional fracturing.

Sediment: Fragmental material that originates from weathering of rocks. It can be transported by, suspended in, or deposited by water.

Specific capacity, of a well: The rate of discharge of water divided by the corresponding drawdown of the water level in the well. Stated in this report in gallons per minute per foot (gal/min)/ft).

Specific yield: The ratio of the volume of water that a rock or soil will yield, by gravity drainage, after being saturated to the total volume of the rock or soil.

Standard deviation: A measure of the amount of variability within a sample; it is the square root of the average of the squares of the deviations about the arithmetic mean of a set of data.

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. In an unconfined aquifer, the storage coefficient is essentially equal to the specific yield.

Stratified drift: Sorted and layered unconsolidated material deposited in meltwater streams flowing from glaciers or settled from suspension in quiet-water bodies fed by meltwater streams.

Surficial geology: The study of or distribution of unconsolidated deposits at or near the land surface.

Superposition: A principle that states--for linear systems, the solution to a problem involving multiple inputs (or stresses) is equal to the sum of the solutions to a set of simpler individual problems that form the composite problem.

Third quartile: For a set of measurements arranged in order of magnitude, that value where 75 percent of the measurements are lower in magnitude and 25 percent are higher.

Till: A predominantly nonsorted, nonstratified sediment deposited directly by a glacier and composed of boulders, gravel, sand, silt and clay mixed in various proportions.

Transmissivity: The rate at which water is transmitted through a unit width of aquifer under a unit hydraulic gradient. Equal to the average hydraulic conductivity times the saturated thickness.

Unconfined aquifer (water-table aquifer): An aquifer only partly filled with water. In such aquifers the water is unconfined in that the water table or upper surface of the saturated zone is at atmospheric pressure and is free to rise and fall.

Unconsolidated deposit: A sediment in which the particles are not firmly cemented together, such as sand in contrast to sandstone.

Unsaturated zone: The zone between the water table and the land surface in which the open spaces are not completely filled with water.

Variable-head permeameter: A laboratory apparatus for measuring hydraulic conductivity. In use water is passed through sediment sample in a cylindrical tube enclosed between two porous plates. Time is measured as the hydraulic head is allowed to decline over a known distance.

Water table: The upper surface of the saturated zone. Water at the water table is at atmospheric pressure.

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