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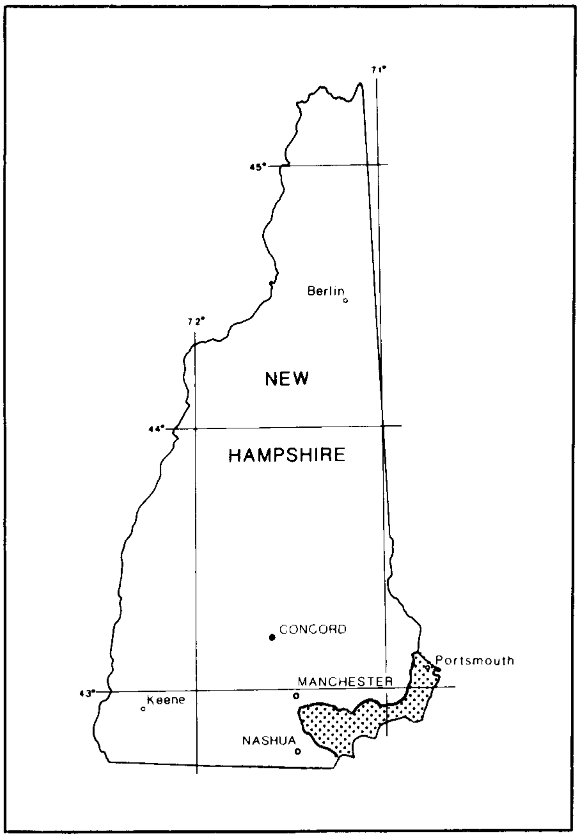
Geohydrology and Water Quality of Stratified-Drift Aquifers in the Lower Merrimack and Coastal River Basins, Southeastern New Hampshire

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 91-4025



Prepared in cooperation with the

NEW HAMPSHIRE DEPARTMENT OF ENVIRONMENTAL SERVICES
WATER RESOURCES DIVISION

GEOHYDROLOGY AND WATER QUALITY OF STRATIFIED-DRIFT AQUIFERS IN THE LOWER MERRIMACK AND COASTAL RIVER BASINS, SOUTHEASTERN NEW HAMPSHIRE

By Peter J. Stekl and Sarah M. Flanagan

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Bow, New Hampshire
1992

U.S. DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
square mile (mi^2)	2.590	square kilometer
	Volume	
gallon (gal)	3.785	liter
million gallons (Mgal)	3,785	cubic meter
cubic foot (ft^3)	0.02832	cubic meter
	Flow	
foot per second (ft/s)	0.3048	meter per second
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per square mile [$(ft^3/s)/mi^2$]	0.01093	cubic meter per second per square kilometer
gallon per minute (gal/min)	0.06309	liter per second
gallon per day (gal/d)	3.7854	liter per day
million gallons per day (Mgal/d)	0.04381	cubic meter per second
million gallons per day per square mile [$(Mgal/d)/mi^2$]	1,460	cubic meter per second per square kilometer
	Hydraulic Conductivity	
foot per day (ft/d)	0.3048	meter per day
	Transmissivity	
square foot per day (ft^2/d)	0.09290	square meter per day

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

Geohydrology and Water Quality of Stratified-Drift Aquifers in the Lower Merrimack and Coastal River Basins, Southeastern New Hampshire

By Peter J. Stekl and Sarah F. Flanagan

ABSTRACT

Communities in the lower Merrimack River basin and coastal river basins of southeastern New Hampshire are experiencing increased demands for water because of a rapid increase in population. The population in 1987 was 228,495 and is expected to increase by 30 percent during the next decade. As of 1987, five towns used the stratified-drift aquifers for municipal supply and withdrew an estimated 6 million gallons per day. Four towns used the bedrock aquifer for municipal supply and withdrew an average of 1.6 million gallons per day.

Stratified-drift deposits cover 78 of the 327 square miles of the study area. These deposits are generally less than 10 square miles in areal extent, and their saturated thickness ranges from less than 20 feet to as much as 100 feet. Transmissivity exceeds 4,000 square feet per day in several locations. Stratified-drift aquifers in the eastern part are predominantly small ice-contact deposits surrounded by marine sediments or till of low hydraulic conductivity. Stratified-drift aquifers in the western part consist of ice-contact and proglacial deposits that are large in areal extent and are commonly in contact with surface-water bodies.

Five stratified-drift aquifers, in the towns of Derry, Windham, Kingston, North Hampton, and Greenland, have the greatest potential to supply additional amounts of water. Potential yields and contributing areas of hypothetical supply wells were estimated for an aquifer in Windham near Cobbetts Pond and for an aquifer in Kingston along the Powwow River by use of a method analogous to superposition in conjunction with a numerical ground-water-flow model. The potential yield is estimated to be 0.6 million gallons per day for the Windham-Cobbetts Pond aquifer and 4.0 million gallons per day for the Kingston-Powwow River aquifer. Contributing recharge area for supply wells is estimated to be 1.6 square miles in the Windham-Cobbetts Pond aquifer and 4.9 square miles in the Kingston-Powwow River aquifer.

Analyses of water samples from 30 wells indicate that the water quality in the basins studied is generally suitable for drinking and other domestic purposes. Concentrations of iron and manganese exceeded the U.S. Environmental Protection Agency's (USEPA) and the New Hampshire Water Supply Engineering Bureau's secondary maximum contaminant levels for drinking water in 20 samples. With one exception, concentrations of volatile organic compounds at all wells sampled met New Hampshire Water Supply and Engineering Bureau's drinking-water standards. At one well, trichloroethylene was detected at a concentration of 5.7 micrograms per liter.

Ground-water contamination has been detected at several hazardous-waste sites in the study area. Currently, 5 sites are on the USEPA's National Priority List of superfund sites, 10 sites are Resource Conservation and Recovery Act of 1976 sites, and 1 site is a Department of Defense hazardous-waste site.

INTRODUCTION

Southeastern New Hampshire has undergone a rapid increase in population in the past few decades. Population in the region increased by more than 39 percent from 1970 through 1987, when it reached 228,495. The population is projected to increase at an average annual rate of 3.32 percent by the end of the century (New Hampshire Office of State Planning, written commun., 1989). Economic development has increased in southeastern New Hampshire because of its proximity to metropolitan Boston. This growth, accompanied by industrial expansion, increased energy needs, and changes in land use, has steadily increased the demands for potable water and has stressed existing municipal water supplies. Currently, this area depends on ground water as its primary source of water. The increased stress on this resource from a growing population has created occasional shortages in water quantity and deterioration of water quality.

Extensive ground-water contamination has occurred at five hazardous-waste sites, and the migration of contaminants has prevented development of productive aquifers in some areas. Water quality in the shallow stratified-drift aquifers is of a concern because depth to water is typically 20 ft or less, and the highly permeable surficial materials above the water table offer little protection from seepage of contaminants into ground water. Development of new public water supplies is needed to satisfy current and future demands. Additional ground-water data are needed to facilitate development of water supplies and protection of water quality.

To meet this need for ground-water data, the U.S. Geological Survey (USGS), in cooperation with the New Hampshire Department of Environmental Services, Water Resources Division, began a 10-year program in 1983 to provide detailed maps of stratified-drift aquifers statewide. Maps that show aquifer boundaries, water-table altitudes, general directions of ground-water flow, saturated thickness, and aquifer transmissivity are being compiled on a scale of 1 in. equals 2,000 ft. The study also provides statewide data on background water quality in stratified-drift aquifers. Detailed geohydrologic information is provided in the reports for use by regional and local planners in making maximum use of existing ground-water resources and in locating and developing new resources. This report describes stratified-drift aquifers for the Beaver Brook, Spicket River, Powwow River, and Little River subbasins of the lower Merrimack River basin and the coastal rivers basin, which include Berry Brook, Winnicut River, Taylor River, and Hampton Falls River that flow directly into Great Bay or the Atlantic ocean (fig. 1).

Purpose and Scope

The purpose of this report is to (1) describe the hydrologic and geologic characteristics of the stratified-drift aquifers--areal extent, saturated thickness, and transmissivity; ground-water levels; general directions of ground-water flow and yield of stratified drift and contributing areas for selected aquifers after prolonged pumping; (2) describe general geohydrology of till and bedrock and water use and water-yielding characteristics of the bedrock aquifer; and (3) document ground-water quality in the stratified-drift aquifers.

This investigation focused on but was not limited to collection, compilation, and evaluation of data from stratified-drift aquifers. Some water yield data was also collected and evaluated for the bedrock aquifer. Two stratified-drift aquifers, in Windham near Cobbetts Pond and in Kingston along the Powwow River, have the greatest potential to supply additional ground water. A superposition modeling technique was used to estimate yields of these two aquifers and to delineate the size of the contributing areas after 180 days of pumping.

Description of the Study Area

The study area, in southeastern New Hampshire (fig. 2), is east of the Merrimack River and extends from the towns of Londonderry to New Castle. Beaver Brook, Little River, Spicket River, and Powwow River are the largest drainage subbasins (fig. 1). For the purpose of discussion in this report, the area has been divided into three subareas (western, central, and eastern), and two map plates (at the back of the report) are used to present geohydrologic information on each subarea (fig. 2). The study area of 327 mi^2, is underlain by stratified-drift aquifers (78 mi^2), marine deposits (69 mi^2), and till deposits (180 mi^2). Many towns with a municipal water supply rely completely or partly on ground water for that supply.

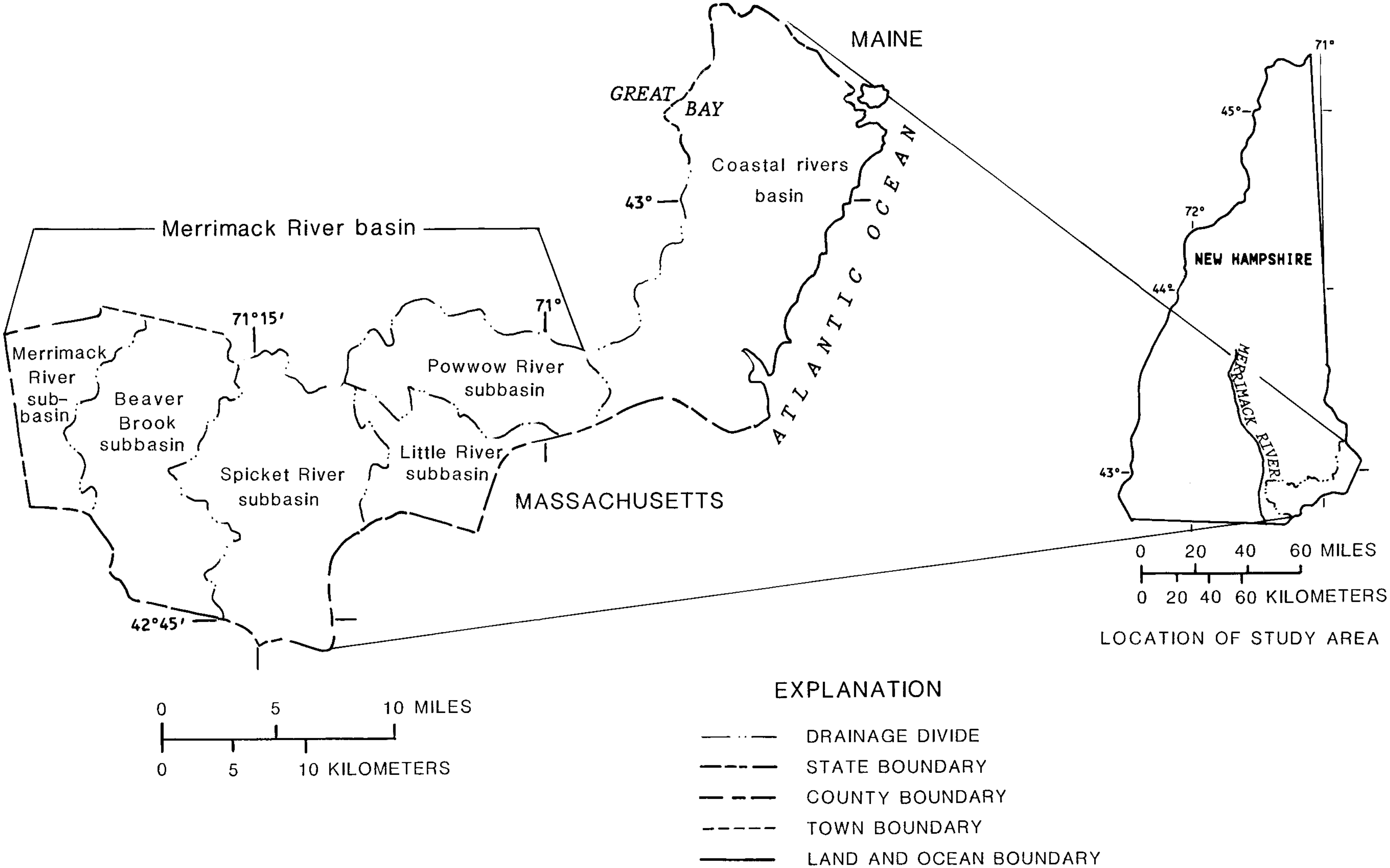


Figure 1.--Location of the lower Merrimack and coastal rivers basins, southeastern New Hampshire.

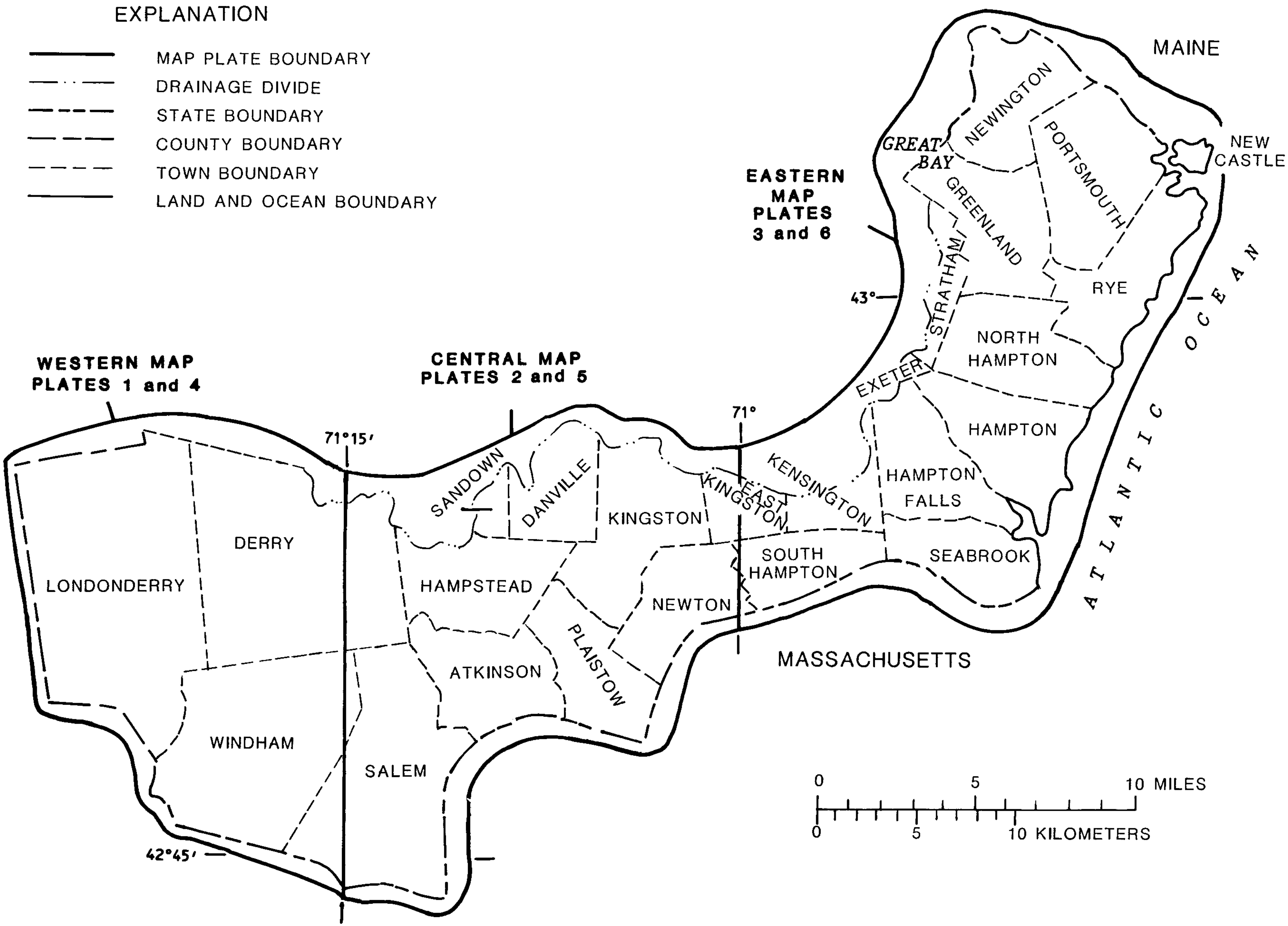


Figure 2.--Western, central, and eastern map plates of the lower Merrimack and coastal rivers basins.

Previous Investigations

Regional investigations include two basic-data reports for wells and springs in southeastern New Hampshire (Bradley and Peterson, 1962; Weigle and Kranes, 1966), an interpretive report on ground-water resources (Bradley, 1964), and an evaluation of water resources and the extent of ground-water contamination at a stratified-drift aquifer underlying Pease Air Force Base (Bradley, 1982).

Other studies on water resources and hazardous-waste sites from several towns have been done by private consultants and a State agency. Camp Dresser & McKee, Inc. (1966, 1973) assessed water resources in the town of Derry. NUS Corporation (1985, 1986) investigated ground-water contamination at a commercial repair garage in Londonderry and ground-water contamination at the Auburn Road Landfill in Londonderry. New Hampshire Water Supply and Pollution Control Division (NHWSPC) (1985a, 1985b) investigated ground-water contamination at the Coakley Landfill in North Hampton and ground-water contamination at the Duston Road area in Salem. Goldberg-Zoino and Associates (1986) investigated ground-water contamination at the Ottati and Goss site in Kingston. Roy F. Weston, Inc. (1986) investigated ground-water contamination at Pease Air Force Base in Portsmouth. Leggette, Brashears, & Graham, Inc. (1987) evaluated recharge areas to water-supply wells owned by the Hampton Water Works Company that service the towns of Hampton and North Hampton.

Previous maps of stratified-drift aquifers in southeastern New Hampshire by the USGS include reconnaissance maps at a scale of 1:125,000 for the lower Merrimack River basin (Cotton, 1977a) and the Piscataqua and other coastal river basins (Cotton, 1977b). Surficial-geology maps for parts of the study area are available through the Cooperative Geologic Mapping Program (COGEOMAP)--a cooperative program between various states and the Geologic Division of the USGS. For New Hampshire, the New Hampshire Department of Environmental Services, Office of the State Geologist, is the cooperator in this program.

Approach and Methods

The areal extent of stratified-drift aquifers was delineated from published and unpublished surficial-geology maps provided by the COGEOMAP program and from lithologic data collected from auger holes. Available subsurface data on stratigraphy, saturated thickness, ground-water levels, and aquifer-test results were compiled. Data were obtained from published and unpublished sources of the U.S. Geological Survey, New Hampshire Department of Environmental Services, New Hampshire Department of Transportation, well-drilling contractors, towns, and local residents. Flanagan and Stekl (1990) have summarized data collected for this study.

Data points were plotted on base maps, and about 1,400 site entries were added to the Geological Survey's computerized Ground-Water Site Inventory (GWSI) data base. The GWSI data base allows retrievals for specific data requirements. For example, retrievals can be restricted to data for wells finished in a particular type of aquifer or wells from a specific geographical area. Each well is cross referenced to a well-identification number, latitude and longitude, original driller, and owner.

Seismic-refraction profiling, a surface geophysical method for subsurface exploration, was done at 49 sites (pls. 1-4) for a total distance of 10.0 mi to map depths to water table and bedrock and to estimate saturated thickness of aquifers. A 12-channel, signal-enhancement seismograph was used to record arrival times of refracted waves generated from the ignition of a two-component explosive (Haeni, 1986a). Altitudes of geophones and shot points on each seismic line were determined by leveling to a common datum. Seismic data were interpreted with a computer program (Scott and others, 1972) that incorporates time delay and ray-tracing methods. Data from nearby test holes were used to verify the results of the computer-generated profiles.

Continuous seismic-reflection profiling--a geophysical method for investigating stratigraphy below surface-water bodies--was done at Cobbetts and Island Ponds (pls. 1 and 2). The profiles aid in mapping fine and coarse-grained layers in the aquifer, the continuity of the aquifer, and depth to bedrock (Haeni, 1986b). Seismic-reflection profiles are generated by towing a displacement-type sound source and a hydrophone streamer across the water surface at a constant speed and monitoring the reflected signal (fig. 3). Sound energy generated from the sound source travels through the water column as outgoing seismic waves and into the subbottom materials. This energy or seismic wave is sensitive to changes in the acoustic impedance of the underlying stratigraphic units and is reflected back to the surface (Haeni, 1986b). Acoustic impedance

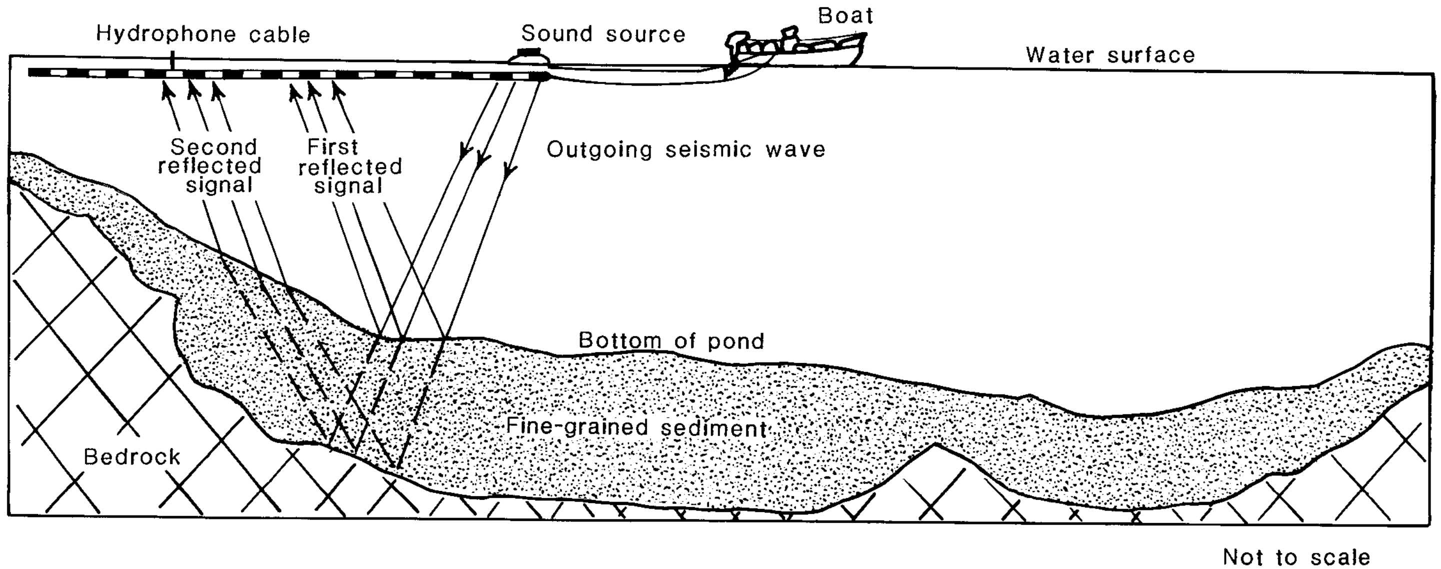


Figure 3.--High-resolution, continuous seismic-reflection-profiling system.

of stratigraphic layers is a product of a material's density and the velocity at which sound travels through that material. The reflected signals return to the hydrophones at the water surface and are then filtered, amplified, and displayed graphically on the chart recorder to allow interpretation of aquifer stratigraphy and bedrock depths. Lithologic data from nearby wells and test holes were used as control points to check the interpretation of the reflection profiles.

Test drilling was done at 66 locations (pls. 1-3) to determine sediment grain size, stratigraphy, depth to water table, depth to bedrock, and ground-water quality. A 6-inch-diameter, hollow-stem auger was used for test drilling. Split-spoon samples of subsurface materials collected at specific depths were used to evaluate the grain-size characteristics and identify the stratigraphic sequence of materials comprising the aquifers. Thirty-eight test holes cased with a 2-inch-diameter polyvinyl-chloride (PVC) pipe and slotted screens were used to make ground-water-level measurements and collect ground-water-quality samples.

Surface-water-discharge measurements were made at 16 sites during low flow when the surface water is primarily ground-water discharge. These low-flow measurements indicate quantities of ground water potentially available from aquifers.

Hydraulic conductivities of aquifer materials were estimated from grain-size-distribution data from 61 samples of stratified drift. Transmissivity was estimated from well logs by assigning hydraulic conductivity to specific well-log intervals, multiplying by the saturated thickness of the interval, and summing the results. Additional transmissivity values were obtained from an analysis of specific-capacity and aquifer-test data.

Long-term aquifer yields and contributing areas to hypothetical supply wells were estimated by application of a method that is analogous to superposition and incorporates a ground-water-flow model developed by McDonald and Harbaugh (1988). This method was applied to two aquifers judged to have the best potential for providing additional ground-water supplies.

Samples of ground water from 26 test wells and 4 municipal wells were collected in March and August 1987 for analysis of common inorganic, organic, and volatile organic constituents. Methods for collecting and analyzing the samples are described by Fishman and Freidman (1989). The water-quality results from the well samples were used to characterize background water quality in the stratified-drift aquifers.

Numbering System for Wells, Test Holes, and Springs

Numbers assigned by the USGS to wells, test holes, and springs consist of a two-character town designation (table 1), a supplemental letter designation ("A" for test holes done for geohydrologic purposes with no casing set, "B" for test holes done primarily for constructional purposes, "S" for springs, and "W" for all wells with a casing set), and a sequential number within each town. For example, the first well in the town of Atkinson is ARW-1.

Acknowledgments

The authors wish to express appreciation to State and municipal officials, well drillers, consulting engineers, and residents of the area who provided useful information and granted access to their properties. The authors gratefully acknowledge the interest and support extended by the staff of the Rockingham Planning Commission.

GEOLOGIC SETTING

Bedrock

Metamorphic rocks of sedimentary and volcanic origin underlie the lower Merrimack River basin at depths of 0 to 120 ft. The regional structural pattern has a northeast-southwest trend and is defined by three major tectonic features: the Massabesic anticlinorium along the western boundary; the Merrimack trough, which occupies most of the basin; and the Rye anticlinorium, which extends along the coastal boundary and includes towns from Portsmouth to Hampton (Lyons and others, 1982).

The Rye Gneiss of Precambrian age contains the oldest rocks in southeastern New Hampshire and most commonly consists of coarse-grained gneiss, quartzites, and schists. The metamorphic rocks of these formations are intruded by small lenticular bodies of granite, pegmatite, and diabase aligned parallel to the regional structural trend (Billings, 1956). The Merrimack Group of pre-Silurian age underlies most of the study area and is divided into the

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

Town	Code	Town	Code
	New Hampshire		
Atkinson	AR	Newington	NI
Danville	DC	Newton	NQ
Derry	DF	North Hampton	NS
East Kingston	EA	Plaistow	PW
Exeter	EX	Portsmouth	PX
Greenland	GT	Rye	RY
Hampton	HE	Salem	SA
Hampton Falls	HF	Sandown	SD
Hampstead	HD	Seabrook	SG
Kensington	KF	South Hampton	SL
Kingston	KT	Stratham	SS
Londonderry	LR	Windham	WP
New Castle	NE		
	Massachusetts		
Merrimac	MR	Salisbury	SB

Kittery, Eliot, and Berwick Formations[1] (Lyons and others, 1986). The Merrimack Group consists of schists, calc-silicate rocks, and quartzites, and the grade of metamorphism increases irregularly from east to west toward the Massabesic anticlinorium, which extends from about the western town border of Londonderry to the Seacoast (Lyons and others, 1982).

All formations are folded and faulted. Large faults are oriented parallel to the regional northeast-southwest strike of the bedrock. The Portsmouth fault is one of the large faults and forms the Rye-Gneiss Kittery-Formation contact for about 9 mi (Novotny, 1969). Smaller faults strike northwesterly, cut across the regional structural grain, and do not dislocate rocks more than a few tens of feet.

Surficial Deposits

The surficial deposits are characteristic of the two physiographic provinces in the study area: the coastal lowlands, which include the area east of the Spicket River drainage basin, and the southeastern New Hampshire uplands, which include the Spicket basin and areas farther west. Topography east of the Spicket River drainage basin is generally less than 200 ft above sea level; the area is largely a broad flat coastal plain underlain by unconsolidated glacial and marine deposits. Except in some high hills, surficial deposits in this area were affected by marine inundation and beach processes that reworked older glacial deposits. Unique to this region are zones of coarse-grained glacial drift that underlie fine-

1 The stratigraphic nomenclature of bedrock units used in this report is that of the New Hampshire Geological Survey (Lyons and others, 1986) and does not necessarily follow usage of the U.S. Geological Survey.

grained marine deposits in some localities. Where this stratigraphic relation is present and the underlying coarse-grained deposits are thick, confined aquifers have the potential to supply large quantities of ground water. In contrast, the uplands to the west have high ridges, steep slopes, and distinct valley walls incised in bedrock. Marine deposits are absent, and the shape of the bedrock surface is the primary control on the distribution of glacial sediments.

Till, stratified drift, and marine deposits primarily comprise the surficial deposits in the study area. These deposits, which control the storage and movement of ground water in the subbasins of the study, are discussed in the context of their geologic origin (fig. 4).

Unconsolidated deposits of Pleistocene and Holocene age cover the bedrock throughout most of southeastern New Hampshire. During late Wisconsin time in the Pleistocene Epoch (approximately 13,000 to 20,000 years ago) the entire region was covered by a vast continental glacier (Boudette, 1990). As the glacier advanced and its front melted, a fairly continuous blanket of unsorted material, called till, was spread over the bedrock.

Proglacial stratified-drift deposits were formed when meltwater flowing in channels or tunnels, next to or under the ice, transported sediment derived from till or from melting ice to sites of deposition near or beyond the ice margin. Stratified drift deposited against or on top of melting ice formed ice-contact deposits. As the ice sheet melted, sea level rose in relation to the land surface and flooded part of the present coastal area. Sand, silt, and clay were deposited in large estuaries or bays similar to present-day Great Bay and the Piscataqua River. Since deglaciation, the land uplifted and sea level retreated to its current position. The sand, silt, and clay sediments are marine deposits as indicated by marine fossils found in sediment exposures. The fine-grained marine deposits partly cover ice-contact deposits, till, or bedrock.

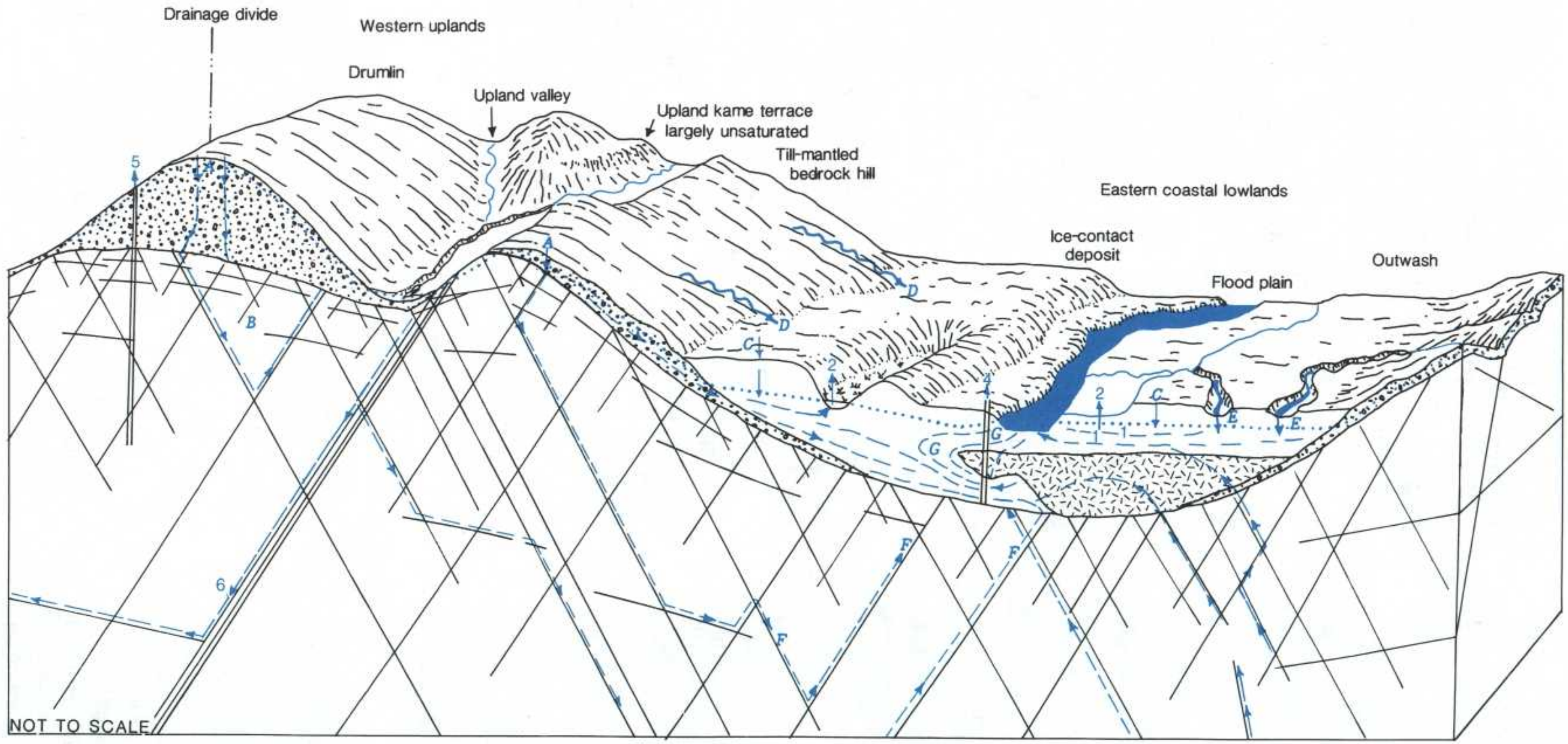
Ice was probably near the coast when the sea flooded part of coastal New Hampshire. The ice continued to melt and supplied outwash, which graded to the level of shore deposits in the flooded areas.

Till is the predominant surficial material and covers 55 percent of the study area. Till--an unsorted, unstratified mixture of rock fragments--consists of particles ranging in size from clay to boulders and is present either as basal till (debris deposited beneath the ice and compressed by its weight) or as ablation till (debris entrained within the ice and, as the ice melted, deposited by processes that involve repeated mudflows and sorting by meltwater). Most basal till has an oriented fabric and is fine-grained, compact, and fissile. The thickness of basal till ranges from 0 to 15 ft, but is much thicker in streamlined elongate ridges, termed drumlins. Examples of drumlins are found in Kensington and South Hampton. The thickness of till in one drumlin in Kensington exceeds 220 ft. Ablation till has more sand and is less compact than basal till, lacks fissility or consistent fabric, and contains lenses of silt, sand, or gravel. This till is found everywhere in the upland areas and coastal lowland ridges and probably averages about 40 ft in thickness.

Glaciofluvial and glaciolacustrine stratified drift cover 24 percent of the study area. Glaciofluvial stratified drift consists of sorted, stratified sand and gravel deposited by glacial meltwater streams. Glaciolacustrine drift is also found and consists of well-sorted, stratified, and commonly laminated fine sand, silt, and clay deposits formed in the standing water of lakes and ponds. An example of these glaciolacustrine deposits are the laminated couplets of silt and clay, as much as 60 ft thick, beneath the bottom of Island Pond in the town of Derry.

Glaciofluvial and glaciolacustrine stratified drift can be grouped into two broad genetic types--ice-contact and proglacial stratified drift--which are distinguished by the abundance of stagnant or detached ice in the original depositional environment. Ice-contact stratified drift consists of sediment deposited on or against decaying ice. Proglacial stratified drift is deposited by or in meltwater beyond the margin of a glacier. Generally, sorting and texture among sands and gravels is more uniform in a proglacial environment than in an ice-contact environment. Sand and gravel deposited in an ice-contact position commonly contains interbedded thick lenses of silt and fine sand, which were deposited in quiet parts of the temporary lakes near stagnant ice. The thickness of ice-contact deposits in the study area ranges from 0 to 80 ft.

Many prominent topographic features among the lowlands of the basin are composed of ice-contact and proglacial stratified drift that can be further classified on the basis of the landform in which they occur. Landforms composed of ice-contact glaciofluvial stratified drift include ice-channel fillings, kame plains, kame terraces, and kame deltas. Characteristic features are ice-contact slopes, collapsed surfaces, and kettles that formed in the deposits as the supporting ice melted away.



EXPLANATION

RECHARGE TO BEDROCK

A Infiltration of precipitation through till in uplands

B Inflow to the basin from circulation through bedrock

RECHARGE TO STRATIFIED DRIFT

C Precipitation on valley floor, which infiltrates to water table unless diverted as evapotranspiration or storm runoff from pavement or saturated soil

D Runoff from adjacent hillsides at shallow depth through sandy till, through soil horizons and (or) as surface rivulets

E Natural seepage losses from small tributaries not incised to the water table

F Lateral and upward flow from bedrock

G Induced infiltration from rivers near large-capacity wells where the water table is lowered by pumping

DISCHARGE FROM STRATIFIED DRIFT

1 Seepage to river

2 Ground-water evapotranspiration where the water table is shallow

3 Underflow downvalley through stratified drift (not shown)

4 Pumpage from well screened in stratified drift

DISCHARGE FROM BEDROCK

5 Pumpage from well that intersects fractures

6 Outflow from the basin from circulation through bedrock

GEOLOGIC UNIT

Till

Stratified drift

Marine deposits

River and streams

Fractured bedrock

Water table

Direction of ground-water flow

Fault

Figure 4.--Idealized geohydrologic block diagram showing distribution of geologic units and ground-water flow (Modified from Randall and others, 1988a, fig. 1).

Ice-channel fillings are linear ridges of sand and gravel deposited in meltwater streams confined by stagnant ice. Eskers are generally a curvilinear type of ice-channel filling deposited in confined tunnels in or under the ice. The largest ice-channel filling, in the town of Plaistow, is a linear southeast-trending ridge about 5.5 mi long with occasional breaks caused by sand and gravel mining and postglacial erosion. The shape and orientation of the ridge indicates deposition between stagnating tongues of ice or in a large fracture in the ice (crevasse). Kame terraces--flat-topped masses of sand and gravel deposited by meltwater between a receding or stagnant ice tongue and the valley wall--are present in the western section. The entire thickness of many kame terraces is above the grade of modern streams; therefore, the bulk of the sand and gravel is unsaturated. Kame deltas typically have a flat-topped triangular shape and were built onto or against glacial ice. These deltas are the most widespread landforms of stratified drift in the eastern section. Most of the deltas in the area graded to estuaries or open marine waters. Foreset beds of the deltas are commonly well-sorted sands that are transitional downslope to silts and clays of marine origin. Locally, these deposits have been modified by beach processes.

Landforms composed of proglacial stratified drift in the area include valley trains and outwash plains. A valley train consists of stratified drift that fills a valley from wall to wall and was formed by the deposition of sediment-laden meltwater draining from a glacier upvalley (Flint, 1971). The most extensive valley train is in the Beaver Brook valley. Although large in area, this valley train is less than 40 ft thick, and numerous interbedded layers of silt interrupt the vertical continuity of sand and gravel.

Outwash plains are similar to valley trains but are not confined by valley walls. They are the largest landforms of stratified drift in the study area and are generally thicker and more extensive inland than on the coast. Outwash deposits are finer textured and better sorted, as a result of their distance of transport, than ice-contact deposits. Outwash deposits consist primarily of loose medium- or fine-grained sand but include some fine and coarse materials. The deposits become fine grained downward, often grading into marine and estuarine deposits. An extensive outwash plain locally reworked by beach processes is found in Kingston and Newton where thick deposits of sand and gravel exceed 120 ft in places.

Marine deposits cover 21 percent of the surface and are found only in the eastern section. (This percentage refers to those parts where marine deposits are actually at the surface or overlain by outwash or beach deposits too thin to map or analyze.) They consist of fine-grained sand, silt, and clay deposited in shallow estuaries and tidal areas during the later stages of deglaciation when sea level rose and much of the valleys and lowlands was inundated. Thin outwash and beach deposits typically overlie the fine-grained marine deposits in the eastern part. In some areas, marine deposits, up to 90 ft thick, overlie permeable ice-contact deposits and act as confining layers.

GEOHYDROLOGIC SETTING

Occurrence of Ground Water

Water occurs beneath the land surface in two different zones. In the upper or unsaturated zone, which usually extends from a few inches to several tens of feet below the land surface, the openings are filled with air and water. In the lower or saturated zone, the interconnected openings contain only water. The surface that divides these two zones is the water table. The water table rises when recharge exceeds the sum of withdrawal, discharge to streams, and evapotranspiration from the saturated zone, and declines when the converse is true. In general, the water table is a subdued replica of the land surface; however, it commonly is deepest beneath hills and is at or near the surface in the lowlands.

Lithology also controls the configuration and fluctuation of the water table. For example, in upland or lowland till, the water table is at or within a few feet of the land surface every spring but declines considerably during dry summers. In coarse-grained stratified drift, the water table slopes gently toward streams regardless of the season or topographic irregularities and tends to be slightly above the grade of the nearest perennial stream. At many eskers, kame terraces, and kame deltas that form ridges, depths to water can be several tens of feet. In areas where outwash overlies lacustrine or marine deposits, the topography is low and flat, the water table is typically several feet above the top of the fine-grained sediments if they are above stream grade.

Ground water is present in unconfined and confined aquifers in the study area. Where water partially fills the aquifer and the upper surface of the saturated zone is at atmospheric pressure, ground water is unconfined. The most extensive aquifers in the study area are unconfined. Ground water is commonly confined under hydrostatic pressure in the eastern part where stratified-drift and bedrock aquifers are locally buried beneath relatively impermeable silt and clay. Examples of high-yield wells that produce water from confined aquifers are the Sherburne well in Portsmouth (PXW-4) and gravel-pack wells 3 (SGW-44) and 4 (SGW-65) in Seabrook (table 2).

Water levels in wells finished in the unconfined aquifers will rise to the water table and fluctuate slowly as the volume of stored water changes. In contrast, ground water in confined aquifers is under hydrostatic pressure and water levels in wells will rise above the top of the aquifer (fig. 5).

General Description and Water-Yielding Characteristics of the Lithologic Units

The lower Merrimack and Coastal River basins are underlain by three general types of geologic units that can yield useable quantities of water to properly constructed wells and, therefore, can be considered aquifers: stratified drift, till, and crystalline bedrock. These geologic units, however, differ greatly in their ability to store and transmit water.

Stratified Drift

Stratified-drift deposits constitute the most extensive and productive aquifer in the region. Currently, 79 percent of ground water withdrawn from high-capacity wells in the basin is pumped from wells screened in the stratified-drift aquifer. Towns served by high-yield, gravel-packed wells finished in the stratified-drift aquifer include Hampton, North Hampton, Portsmouth, Rye, and Seabrook (table 2). The maximum well yield from 19 gravel-packed wells averages 377 gal/min and ranges from 125 to 900 gal/min. The yield from gravel-packed wells represents maximum yield for the well technology used at each site; therefore, the yields of these wells (table 2) are useful approximations of the withdrawal rates that can be expected from the aquifers.

The most productive high-yield stratified-drift deposits are ice-contact and proglacial (valley train and outwash) deposits. Ice-contact deposits exhibit abrupt changes in stratification and grain size that cause large variations in the water-bearing characteristics of the deposits. Ice-contact sediments are deposited in sequences that are graded to a particular base level--generally thickest near the ice-contact slope, and thinnest and interrupted by bedrock outcrops near the till contact. The proximal end of a sequence is characterized by poorly sorted and poorly stratified deposits containing lenses of till (flow till) that form the ice-contact faces of kame terraces, kame deltas, and heads of outwash. These features commonly supply small amounts of water to wells because of the poorly sorted materials and the absence of thick saturated intervals.

An example of the head of outwash is found between 140 and 150 ft elevation, in the town of Newton less than 1,000 ft southeast of the intersection between Amesbury and Bear Hill Roads (pl. 2). Much of this ridge of stratified drift is unsaturated and consists of very poorly sorted pebble-cobble-gravel material that has a low water-bearing capacity. The distal end of the sequences is characterized by well-stratified, moderately well-sorted deposits that comprise most of the ice contact and (or) proglacial landform. These deposits of well-sorted sand and gravel allow rapid flow of ground water and are capable of large well yields where the saturated interval is sufficiently thick. Examples of these deposits are the kame plain near Route 1 north of the town of Hampton (pl. 3) and the kame delta that underlies Pease Air Force Base in the town of Newington (pl. 3). Both aquifers serve as primary sources of the public water supply.

In some areas, fine-grained marine deposits overlie ice-contact deposits or overlap the perimeters of such deposits. For example, the Sherburne well in Portsmouth is drilled to a depth of 50 ft into a confined aquifer. The top 20 ft consists of silt and clay of marine origin that form a confining layer and the bottom 30 ft consists of highly permeable sand and gravel that forms the productive zone in a confined aquifer. Because of the confinement by marine deposits, recharge to the ice-contact deposits from precipitation and runoff is greatly reduced.

Maximum thickness of ice-contact deposits inferred from seismic data is 100 ft and from well logs is 78 ft; well yields range from 3 to 900 gal/min.

Proglacial deposits comprising valley trains and outwash plains are generally finer grained, more homogeneous, and better sorted than ice-contact deposits, and consist primarily of sand with small amounts of gravel and silt. Many of the valley trains, in the western part of the study area, have well-sorted sand interbedded with layers of silt and clay that formed from temporary glacial ponds that occupied the valleys. Gravel-packed wells developed

Table 2.--Maximum well yields for major water-supply wells

[ft, feet; gal/min, gallons per minute; --, no data available; User: SNHWC, Southern New Hampshire Water Company; DPW, Department of Public Works; HWWC, Hampton Water Works Company; AFB, Air Force Base. Type of well: DVN, driven; GPW, gravel-packed well; BrW, open-hole bedrock well.]

Well identifier	Latitude	Longitude	User or owner	Other identifier	Type of well	Depth of well (ft)	Maximum well yield (gal/min)
				DERRY			
DFW-79	42 52′19″	71 18′35″	SNHWC	Maple Hills	BrW	200-825	270 (3 wells)
				GREENLAND			
GTW- 1	43 01′50″	70 49′46″	Portsmouth DPW	Greenland well #5	GPW	60	450
				HAMPTON			
HEW- 3	42 57′27″	70 49′35″	HWWC	White's Field	GPW	50	400
HEW- 6	42 57′12″	70 49′38″	HWWC	Scammon	GPW	50	490
HEW- 7	42 56′30″	70 48′56″	HWWC	Ryder	GPW	45	350
HEW-24	42 57′21″	70 49′30″	HWWC	Sicard	GPW	63	625
				LONDONDERRY			
LRW-144	42 53′03″	71 21′38″	SNHWC	Birchville	BrW	250-788	33.5 (5 wells)
LRW-145	42 53′54″	71 25′54″	SNHWC	Brook Park	BrW	150-620	29.6 (4 wells)
				NEWINGTON			
NiW- 8	43 05′08″	70 50′45″	Pease AFB	MMS No. 2	BrW	170	29
NiW- 9	43 05′13″	70 50′41″	Pease AFB	MMS No. 1	BrW	130	28
NiW- 50	43 04′43″	70 51′29″	Pease AFB	Loomis well	BrW	300	15
NiW- 51	43 06′42″	70 49′01″	C.H.Sprague & Sons Co.	--	BrW	--	20.8 (2 wells)
				NORTH HAMPTON			
NSW- 8	42 57′31″	70 49′24″	HWWC	Marston Springs	GPW	44	150
NSW- 27	43 00′05″	70 51′48″	HWWC	BRW #13	BrW	318	350
NSW- 31	43 00′09″	70 51′55″	HWWC	Coakley	GPW	55	200
NSW- 70	43 00′01″	70 51′43″	HWWC	Crenshaw	GPW	46	350
				PORTSMOUTH			
PXW- 2	43 04′34″	70 49′13″	Pease AFB	Haven	GPW	66	900
PXW- 4	43 03′34″	70 47′22″	Portsmouth DPW	Sherburne	GPW	45	450
PXW- 5	43 03′26″	70 47′53″	Portsmouth DPW	Portsmouth well #1	GPW	63	350
PXW- 47	43 03′56″	70 48′19″	Pease AFB	Harrison	GPW	46.3	150
PXW- 49	43 03′34″	70 48′24″	Pease AFB	Smith	GPW	67	430

Table 2.--Maximum well yields for major water-supply wells--Continued

Well no.	Latitude	Longitude	User or owner	Other identifier	Type of well	Depth of well (ft)	Maximum well yield (gal/min)
				RYE			
RYW- 12	42 59'27"	70 46'23"	HWWC	Jeness Beach	GPW	21	125
RYW- 38	42 59'53"	70 47'17"	Rye Water Dist.	Garland	GPW	49	400
RYW- 45	42 59'41"	70 47'18"	Rye Water Dist.	BRW #5A	BrW	500	260
				SALEM			
SAW-207	42 45'34"	71 14'43"	BCI Inc., Salem DPW	Turner	BrW	460	416
SAW-208	42 46'23"	71 15'29"	BCI Inc., Salem DPW	Donigan	BrW	250	240
				SEABROOK			
SGW- 1	42 53'37"	70 54'47"	Seabrook DPW	GPW #1	GPW	54	350
SGW- 2	42 53'37"	70 54'51"	Seabrook DPW	GPW #2	GPW	49	250
SGW- 44	42 53'15"	70 54'07"	Seabrook DPW	GPW #3	GPW	98	350
SGW- 65	42 53'12"	70 53'59"	Seabrook DPW	GPW #4	GPW	83	400
SGW- 89	42 54'17"	70 54'59"	Seabrook DPW	Brw #1	BrW	500	200
SGW- 90	42 54'20"	70 54'53"	Seabrook DPW	BrW #2	BrW	500	350
SGW- 91	42 54'21"	70 54'59"	Seabrook DPW	BrW #3	BrW	500	500
SGW- 92	42 53'59"	70 54'54"	Seabrook DPW	BrW #4	BrW	400	305
				WINDHAM			
WPW-273	42 48'00"	71 16'01"	SNHWC	W.& E.	BrW	345-941	90 (2 wells)
WPW-274	42 46'20"	71 18'39"	SNHWC	Golden Brook	DVN	46	100 (2 wells)

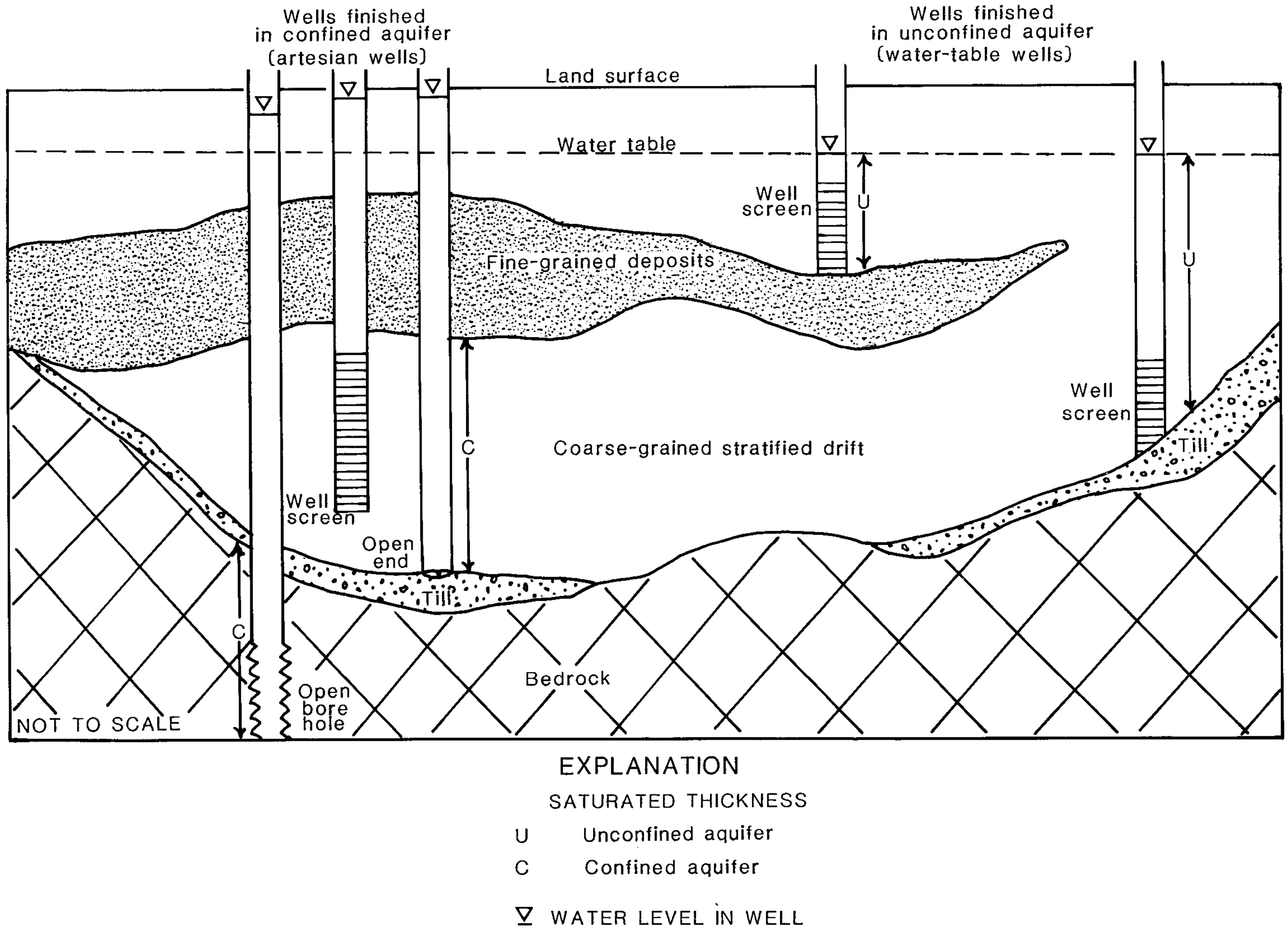


Figure 5.--Idealized geohydrologic section showing unconfined and confined aquifers.

in these deposits yield as much as 300 gal/min; however, where coarse sand and gravel overlie thicker deposits of fine-grained sand, silt, and clay, less than 300 gal/min is expected. Toward the coast, proglacial deposits thin, probably because the marine waters they were deposited in became progressively shallower as relative sea level declined and marine sediments accumulated. Thinning of deposits also occurred with the retreat of the ice sheet northward.

Outwash in the basin contains generally well-sorted, coarse-grained deposits with large pore spaces. In many places, a veneer of outwash deposits overlies thick marine deposits; these outwash deposits form a thin aquifer with small storage capacity. Where outwash deposits have a large saturated thickness, properly constructed, gravel-packed wells have large yields. Maximum thickness of these deposits is in the outwash plain at Kingston. Maximum depth to bedrock, determined by seismic-refraction, is about 120 ft and, from well logs, is 90 ft. Currently, high-capacity production wells have not been drilled in this deposit.

Till

Till consists of a mixture of grain sizes ranging from clay to boulders. Because it is dense and contains a large proportion of fine-grained particles, till is considered a poor aquifer and normally will not yield enough water to meet municipal, industrial, or commercial needs. Historically, large-diameter wells dug in till have provided water for domestic and agricultural use, but these wells are shallow (less than 30 ft deep) and generally yield only a few gallons per minute. Many wells fail to meet current demands during dry summers when the water table lowers and water storage decreases. Layers or lenses of stratified sand and gravel are present at places in ablation till and, where these layers are saturated, more reliable long-term well yields can be expected. In contrast, basal till is more compact and denser than ablation till and produces a smaller water yield. Because the yield from the till aquifer is seasonally inadequate to meet modern domestic demands, the trend is toward the drilling of bedrock wells.

Bedrock

All rocks in the study area have been subjected to uplift, weathering, and erosion, which have resulted in the widening of fractures and the formation of new openings, such as stress-relief fractures. These breaks in the otherwise solid rock are the conduits for ground-water flow and control both the movement and storage capacity of water in bedrock. Storage capacity is generally small because the fractures are narrow and widely spaced. The orientation, width, and number of water-bearing fractures also differs from place to place, making systematic exploration for large production wells difficult. If two wells are adjacent to each other, different fractures may be intersected. As a result, one well may yield an ample supply of water at depth, whereas the other, even though drilled to a lesser depth than the first, may yield a comparatively small supply. For the most part, however, crystalline bedrock is a reliable source of water for both domestic and municipal supplies.

Information from 94 bedrock wells drilled in the towns of Greenland, Newington, and Portsmouth (Stewart, 1968) indicate that the average well drilled is a domestic well 118 ft deep, up to 6 in. in diameter, and yielding 13 gal/min. On the basis of these and similar data collected from drillings in New England, the following assumptions were made: crystalline rocks generally yield only small amounts of water to wells and water is obtained from vertical fractures that typically pinch out at a depth of 300 ft because of lithostatic pressure (Hodges, 1969).

Data collected for this study from recent drillings of bedrock municipal wells, however, indicate that the crystalline bedrock aquifer beneath the region can sustain high yields to properly located wells. The maximum yield from eight bedrock municipal water-supply wells ranges from 200 to 500 gal/min and averages 328 gal/min (table 2). All but one of these high-capacity bedrock wells exceeds 300 ft in depth, and all exceed 8 in. in diameter. In each of these wells, maximum yields were obtained by drilling to greater depths than previously thought necessary. The rate of ground-water withdrawal from bedrock municipal wells is estimated to be 1.6 Mgal/d--a rate equal to 21 percent of the ground water pumped from all public-water-supply wells in the study area. The largest quantities of recoverable water are found where the bedrock is extensively fractured or brecciated as a result of the intersection of several fractures and (or) faults (Daniel, 1987).

The brecciated zones associated with the northeast- and northwest-trending faults are potential areas for providing above-average well yields. Although the locations of several large northeast-trending faults have been shown on bedrock geology maps (Billings, 1956; Novotny, 1969; Lyons and others, 1986), additional information on the structural fabric of the bedrock is necessary to prospect for large yields from bedrock aquifers.

GEOHYDROLOGY OF STRATIFIED-DRIFT AQUIFERS

Stratified drift is subdivided on plates 4-6 into four categories on the basis of grain size. These categories are (1) coarse-grained material (sand and gravel) with a median particle diameter predominantly larger than 0.0049 in.; (2) fine-grained material (very fine sand, silt, and clay) with a median particle diameter predominantly smaller than 0.0049 in.; (3) coarse-grained deposits that overlie fine-grained deposits; and (4) fine-grained deposits (including marine) that overlie coarse-grained deposits.

The coarse-grained deposits in the central Powwow River valley, Derry-Island Pond area, the Golden Brook valley, and the isolated kame plains and deltas in Portsmouth-Newington, North Hampton-Hampton, and Kensington (pls. 4-6) constitute some of the most important aquifers in the basin. Of these areas, the aquifers at Powwow River, Golden Brook valley, and the Derry-Island Pond area are the only ones not currently developed at or near their maximum potential yield to wells.

Coarse-grained deposits are part of a valley-train sequence in the Golden Brook valley of Windham. The stratigraphy of these proglacial deposits is characterized by coarse sand and gravel overlying very fine to medium sand (fig. 6). The maximum thickness of these deposits (60 ft) is determined from seismic-refraction surveys in the area. Present flow regulation at Golden Brook causes the stream to go dry during parts of the year, and, therefore, the brook cannot be considered a reliable source of water to recharge the deposits.

Geohydrologic section B-B′ (fig. 7), which extends northwest-southeast across the axis of the Powwow River, shows a striking contrast between the level outwash and the irregular bedrock surface. Seismic-refraction data indicate maximum depths to bedrock of 125 ft. The outwash-plain deposits are generally well-sorted and permeable; therefore, water is believed to flow easily between this aquifer and the Powwow River and nearby Great Pond. The aquifer and surface-water bodies are interdependent and together comprise a water system that is capable of a high yield to wells completed in the aquifer.

Geohydrologic section C-C′ (fig. 8) shows fine- to coarse-grained sand and gravel underlying a kame delta in North Hampton that is interbedded with discontinuous layers of marine sediments. The sand and gravel deposits have excellent water-bearing characteristics and, where saturated thicknesses are large, would yield large supplies of water to wells. Kame-delta deposits penetrated by well NSW-69 consist of exceptionally clean, well-washed coarse-grained sand and pebble gravel that has a 70-ft saturated thickness. Low rates of recharge to the aquifer are considered the primary limit on the productivity of this and many other coastal aquifers. This deposit, like similar kame plains and deltas in the eastern part of the study area, is small in areal extent; thus recharge from precipitation is limited.

Present at the aquifer margins and within the aquifer section are marine deposits of silt and clay that are relatively impermeable and do not yield usable quantities of water to wells. Where the marine sediments border the aquifer perimeter and extend the full saturated thickness, as in the northwestern end of the section, lateral recharge to the aquifer as ground-water discharge from neighboring uplands is restricted. The deposit is not bordered by land significantly higher in elevation and, therefore, recharge from upland runoff is negligible. In addition, the hydraulic connection between Cornelius Brook and the aquifer is poor because of the presence of marine impermeable sediments in the streambed. Aquifers hydraulically isolated from streams can serve as storage reservoirs that can be tapped during late summer periods of drought without causing a serious depletion of streamflow that normally would result if withdrawals are made from aquifers that border a river and are sustained by induced infiltration of river water.

In some localities, sand and gravel is buried beneath the marine sediment. Geohydrologic section D-D′ (fig. 9) shows that Seabrook municipal wells SGW-44 and SGW-65 are completed in coarse-grained sand and gravel, which underlies 20 to 40 ft of fine-grained sand and clay. The contact between the base of the marine deposits and the underlying sand and gravel is gradational at these wells. Contacts are typically gradational where clay overlies ice-marginal deposits, deposited as submarine fans and deltas (Thompson and others, in press) in a high-energy environment that prevailed when meltwater currents flowed from the nearby ice margin. To the northwest, the vertical and horizontal contact between the marine sediments and the sand and gravel is more abrupt and probably is erosional. A 20-ft-thick layer of ice-contact sand and gravel forms an aquifer confined above and below by sediments.

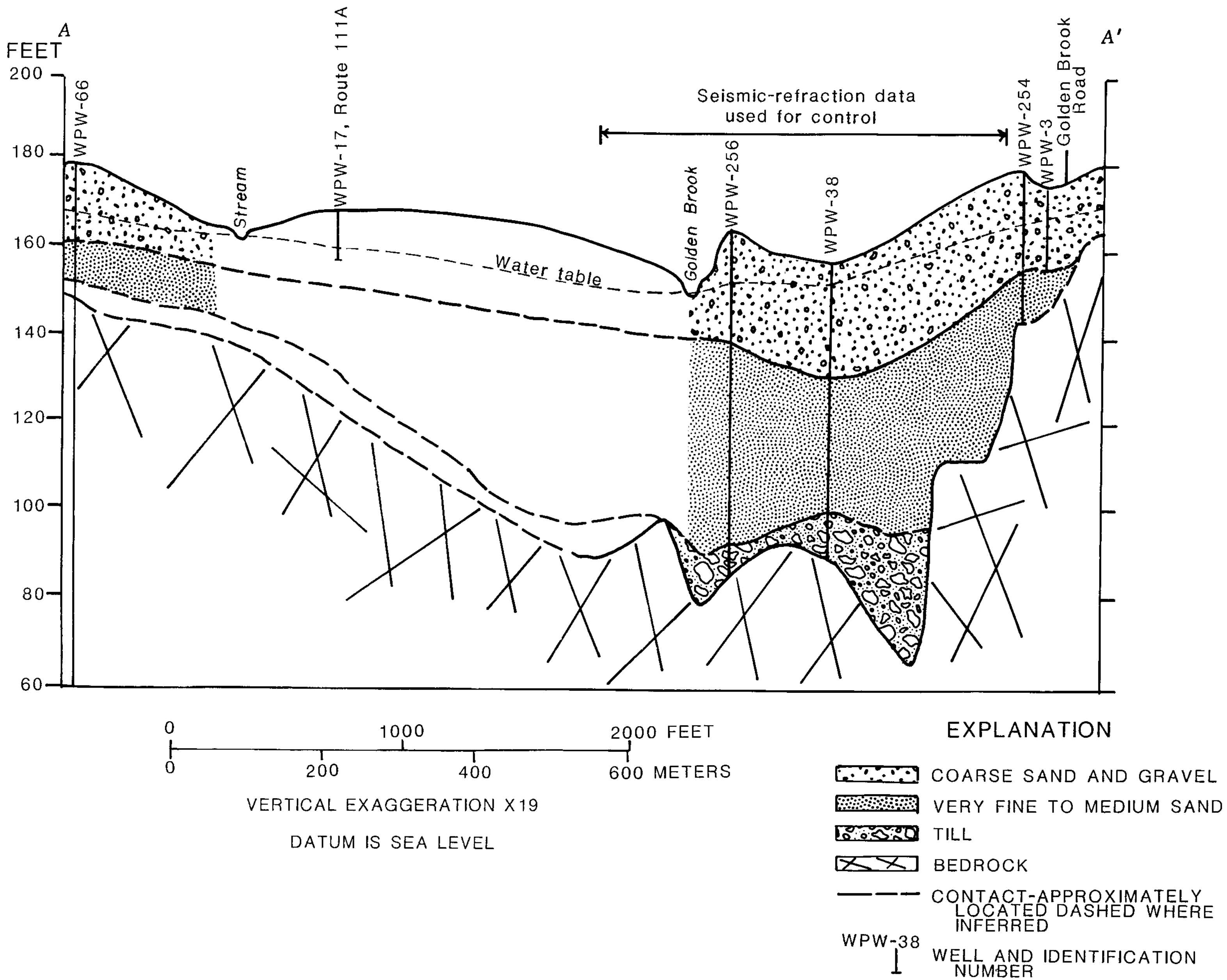


Figure 6.--Geohydrologic section A-A′ showing the valley train in southern Windham. Line of section is shown on plate 1.

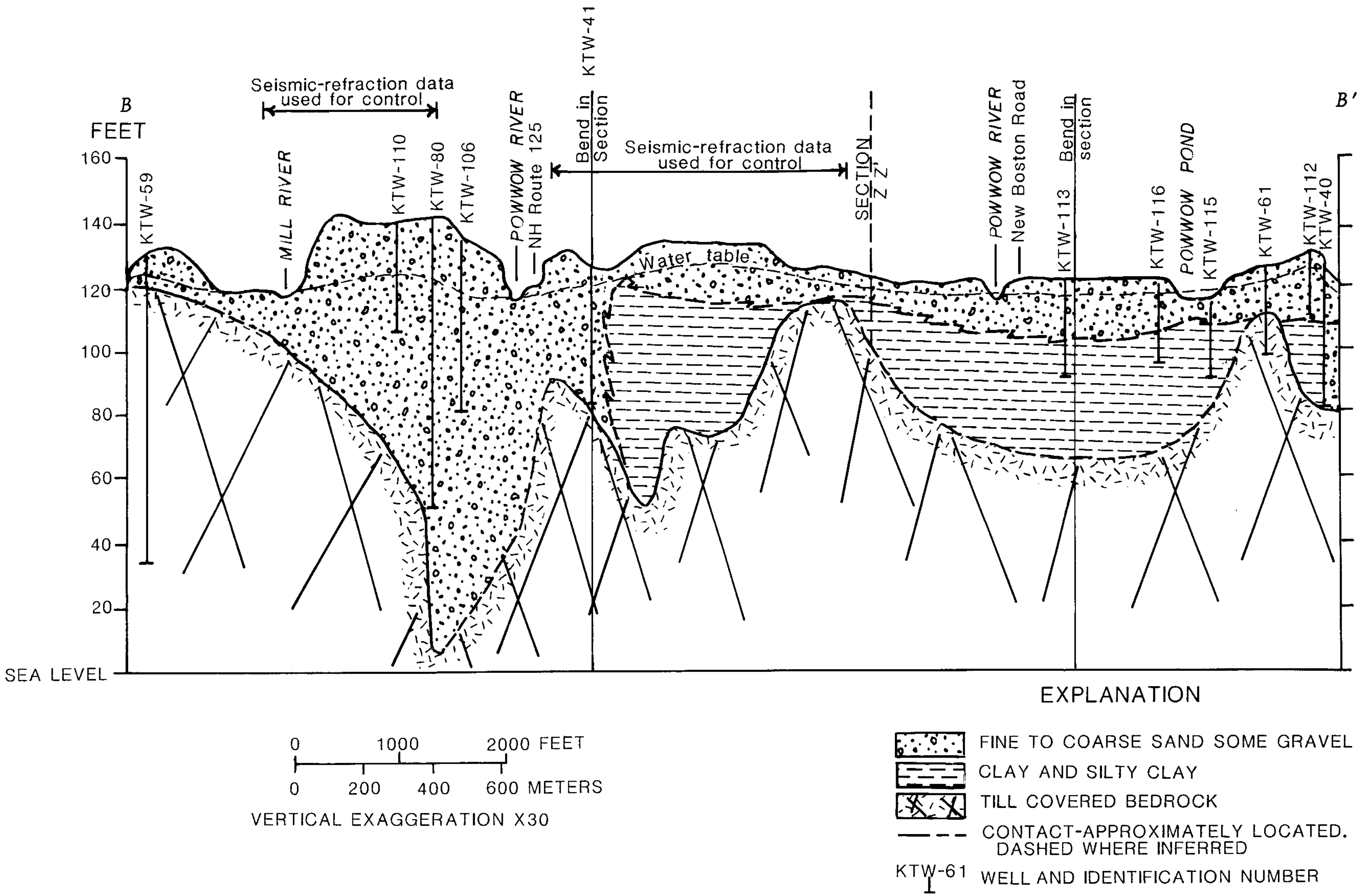


Figure 7.--Geohydrologic section B-B′ showing the outwash plain in Kingston. Line of section is shown on plate 2.

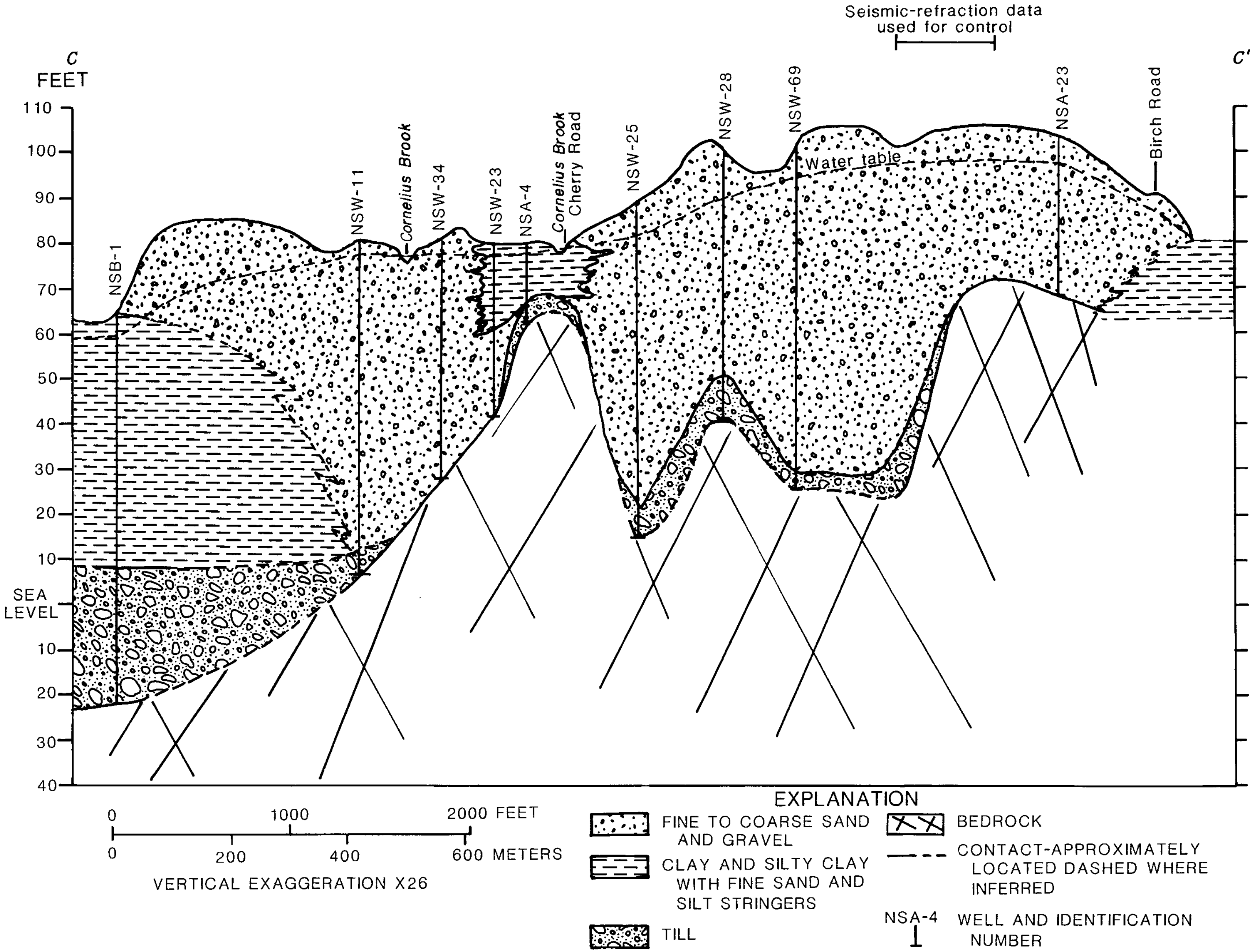


Figure 8.--Geohydrologic section C-C′ showing the kame delta in North Hampton. Line of section is shown on plate 3.

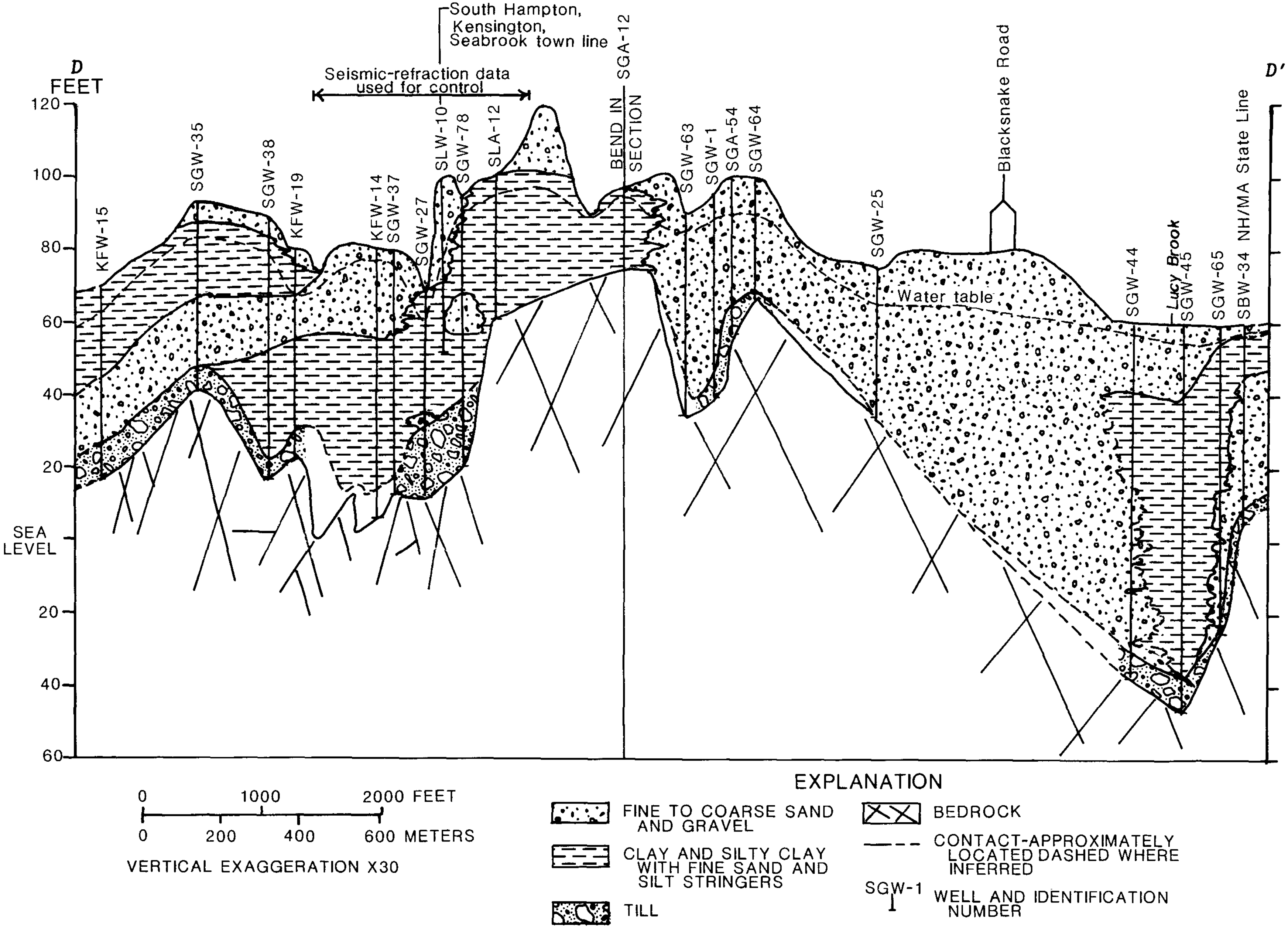


Figure 9.--Geohydrologic section D-D' showing the kame delta in Kensington and Seabrook. Line of section is shown on plate 3.

Description of Aquifer Boundaries

Areal extents of stratified-drift aquifers are shown on plates 1-3. Also shown on the plates are the locations of marine silt and clay and till-mantled bedrock. The thickness of the solid-line contact on the 1:24,000-scale U.S. Geological Survey map implies ±80-foot horizontal accuracy. Aquifers located within moderate to steeply sloping uplands and valley walls in the western part of the study area are generally mapped to this level of accuracy. Delineation of the aquifer is difficult and contact locations are uncertain in the eastern part of the study area, where a complex geologic history of marine inundation, postglacial erosion, and uplift has produced low scarps and broad swampy lowlands with few ice-contact slopes or meltwater drainageways. As a result, several of the aquifer contacts in the coastal lowlands are inferred and appear as dashed lines, or the contacts are concealed by swamps and marshes and appear as dotted lines.

The boundaries of an aquifer are of particular importance in describing the response of the ground-water-flow system to withdrawal stress. The ground-water-flow system has two types of flow boundaries--impermeable (no flow) boundaries and recharge and discharge (flow) boundaries (Heath, 1983). Low scarps composed of marine sediments limit the extent of stratified-drift aquifers in the eastern part of the study area. Because these geologic units are virtually impermeable compared to stratified-drift aquifer material, flow across the interface is limited. Wells that tap stratified drift in the proximity of such boundaries yield less water than they would if the aquifer had infinite extent. As shown in figure 10, pumping near an impermeable boundary lowers the water level between the well and the boundary more than pumping does at the opposite side of the well where the aquifer is extensive. Drawdown, therefore, increases with decreasing distance to an impermeable (no flow) boundary at a given pumping rate.

Major perennial streams or large ponds hydraulically connected to stratified-drift aquifers are considered recharge boundaries because they can serve as a source of recharge to the aquifer. When a well near a surface-water body is pumped, the water is initially withdrawn from aquifer storage. As the cone of depression continues to spread, water from an increasingly large area flows toward the well. When the water table in the vicinity of the nearby stream or pond is sufficiently lowered, ground water that would have naturally discharged to the surface water is diverted and captured by the well. Eventually, ground-water levels can be lower than the surface of the surface-water body, at which time surface water can recharge the aquifer by induced infiltration (fig. 11).

An understanding of these basic principles of boundary hydraulics is important for determining the optimum sites for ground-water development. Recharge to pumped wells is greatest and the effects on water levels from pumping are the least when wells are parallel and adjacent to recharge boundaries and at maximum distance from impermeable boundaries.

Recharge, Discharge, and Direction of Ground-Water Flow

Recharge to the stratified-drift aquifers is by infiltration from precipitation, seepage losses from tributary streams, and lateral flow from adjacent till and bedrock. Discharge from the aquifers is by flow to the rivers and ponds in the basin, by evapotranspiration in areas where ground water is near the land surface, and by ground-water withdrawals. The water table marks the top of the saturated zone in the unconsolidated deposits and fluctuates continuously in response to changes in recharge and discharge.

The 10-year hydrograph for well LIW-1, which is completed in stratified drift in the town of Lee, shows the cyclic seasonal variation of water level that is common in stratified-drift aquifers (fig. 12). Ground-water recharge from precipitation exceeds evapotranspiration in late fall and early winter (November-December) and even more in the spring (March-June) when snow melt is an additional component of recharge. Lowest ground-water levels are in late summer or early fall. The depth to water table at this well (30 ft) is generally attained only in the elevated kame plains and deltas of the eastern study area; this depth contrasts with the shallow depths (a few feet) in sand and gravel deposits of lower altitude. The seasonal fluctuation in ground-water levels is typically 3 to 5 ft for wells completed in stratified drift.

Flow

Circulation of ground water is usually confined within topographic basins. The five subbasins that comprise distinct ground-water-flow systems of the report area are shown in figure 1, and include the

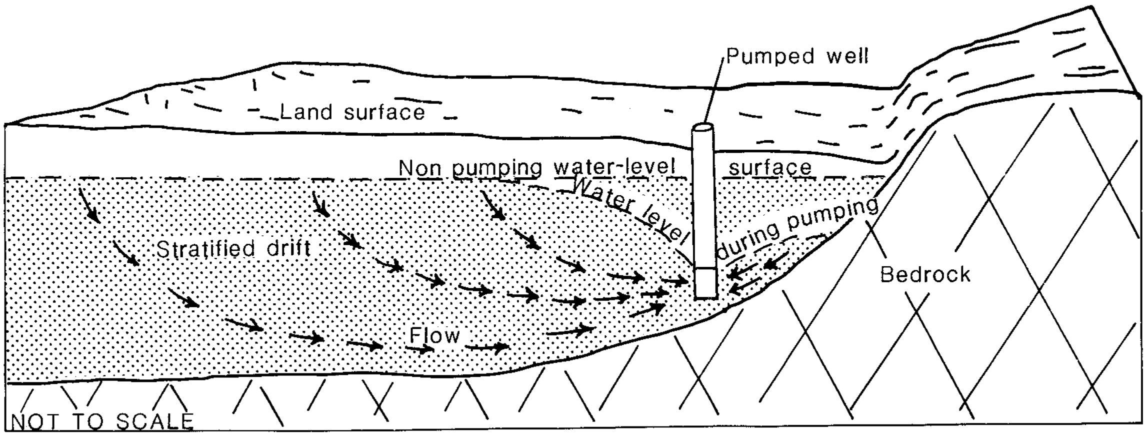


Figure 10.--Ground-water flow and water-level drawdowns at a pumped well near an impermeable boundary.

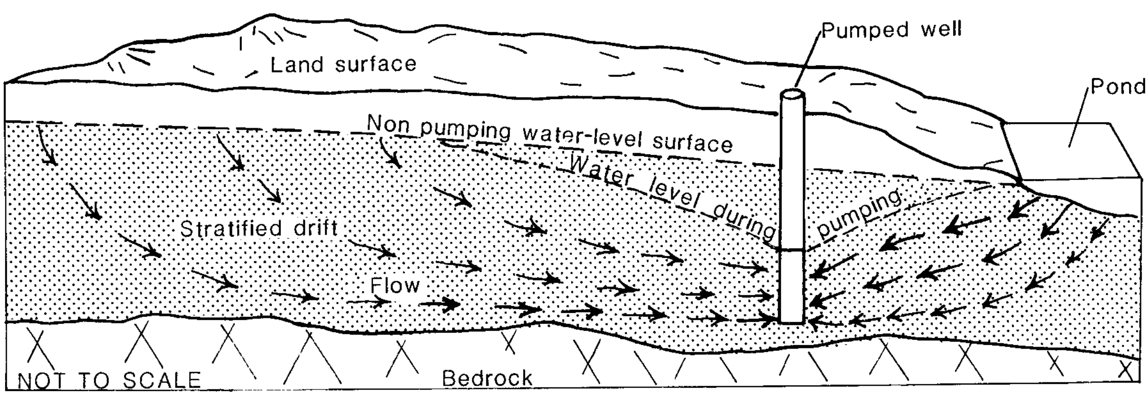


Figure 11.--Ground-water flow and water-level drawdowns at a pumped well near a recharge boundary.

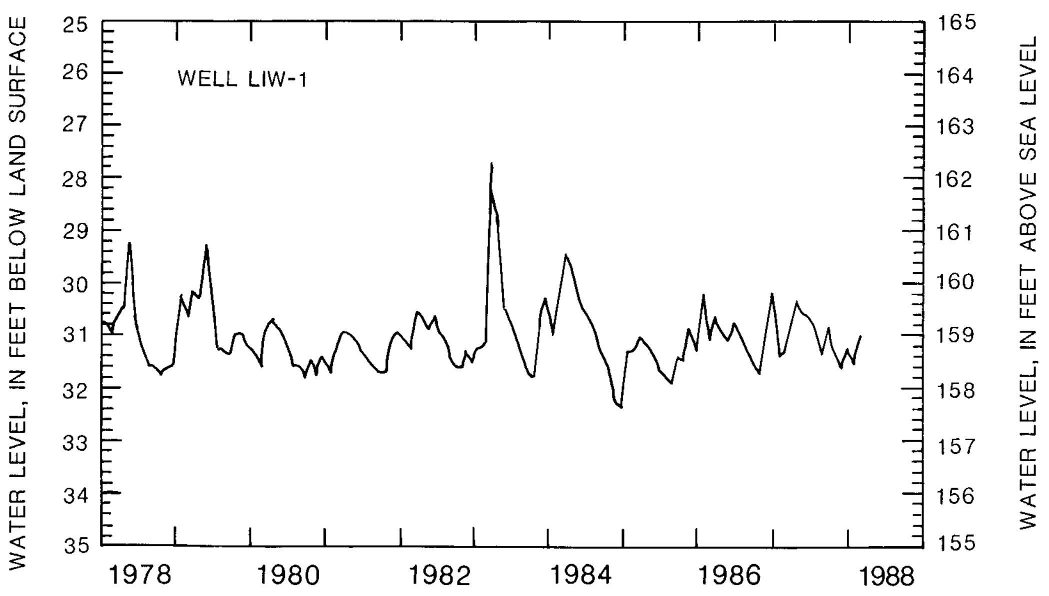


Figure 12.--Water-level fluctuations typical of fluctuations in wells completed in stratified-drift aquifers in elevated kame plains.

Beaver Brook, Spicket River, Little River, Powwow River, and Coastal River basins. The generalized ground-water circulation within a subbasin of the study area is shown in figure 4. The saturated stratified drift within each major flow system can be thought of as a large underground reservoir bounded on top by the water table and on the bottom by fractured crystalline bedrock.

Regional ground-water divides commonly coincide with topographic divides on ridges of till or bedrock. In some areas, major flow systems extend across major drainage divides that separate the lower Merrimack basin from adjacent basins. Areas where this is most likely to occur include the northeast-southwest-trending faults and stress fractures that parallel the regional structural grain and extend beyond the basin boundaries into the Cocheco and Exeter River basins to the north (Lyons and others, 1986).

Ground water in the basin that does not evaporate or transpire or that is withdrawn by wells eventually discharges to lakes, streams, or the Atlantic Ocean. The transit time of ground water in the saturated zone differs spatially, depending on the locations of recharge and discharge zones and the hydrologic characteristics of the aquifer. Generally, the closer to the basin-drainage boundary the water enters the saturated zone, the deeper and greater the distance traveled before it discharges.

Recharge

Recharge is the process by which water is added to the zone of saturation in an aquifer. The amount of water available for development from a stratified-drift aquifer can be limited by the amount of recharge; therefore, when aquifer potential yield is estimated, the amount of water that recharges the system needs to be evaluated. Water pumped from aquifer storage can be replenished by natural and induced recharge, and the contributions from both sources need to be estimated. Neither natural nor induced recharge has been measured directly in the study area. The estimates in this report are based on regional information on ground-water discharge and streamflow.

The sources of recharge to stratified-drift aquifers are infiltration of precipitation that falls directly on the aquifer, surface and subsurface runoff from upland hillslopes adjacent to an aquifer, and leakage from streams that cross the aquifer (fig. 4). Leakage from streams to the ground-water reservoir occurs where the hydraulic head in the aquifer is less than the stream stage.

Under steady-state conditions, the amount of water available for natural recharge from precipitation on stratified drift is roughly equivalent to the average stream runoff (Lyford and Cohen, 1988). Maps showing contours of average annual runoff for the glaciated northeast (Knox and Nordenson, 1955) were adjusted to a more recent period of precipitation (1951-80) to estimate the average annual runoff in southeastern New Hampshire. From this analysis, the approximate recharge to stratified drift from precipitation is 19 in., or 0.9 (Mgal/d)/mi^2.

Natural recharge from tributaries and unchanneled runoff from upland sources can be estimated from streamflow records. The 1966-77 average annual streamflow runoff from till and bedrock uplands was considered a reasonable estimate for the maximum recharge available from all upland sources.

Recharge from unchanneled runoff from upland hillsides has not been extensively documented; however, several investigators (Crain, 1974; MacNish and Randall, 1982; Randall, 1986) assumed that the total runoff from upland hillsides, including surface and subsurface flow, will infiltrate a stratified-drift aquifer at the base of a hillside.

Recharge from tributary seepage losses was not measured directly; however, results from several investigations indicate that rates may vary considerably depending on the location within the basin and streambed characteristics (Morrissey and others, 1988). Measurements of tributary losses in south-central New York (Randall, 1978) indicate that losses were small near the margins of the main valley (average loss of 0.13 ft^3/s per 1,000 ft of channel) and increased to 1.0 ft^3/s or more per 1,000 ft of channel farther downstream. Rates of seepage loss from streams can differ spatially and temporally, and upland streams can gain rather than lose water, making predictions of upland recharge rates difficult. Estimates of the maximum upland tributary losses to aquifers in the study area were assumed to equal the average annual (1966-77) stream runoff for streams draining till and bedrock uplands.

Few data are available on the amount of runoff from till-covered uplands because of the absence of long-term streamflow records. Recharge from upland runoff was calculated from streamflow data collected at a long-term station in the nearby Mohawk River basin in the town of Strafford. Average annual runoff from till and bedrock in this basin is 1.4 (ft^3/s)/mi^2 or 0.9 (Mgal/d)/mi^2. Recharge to the stratified-drift aquifer from upland runoff and tributary losses was calculated by applying the rate of runoff per unit area of upland to the upland areas bordering the aquifer.

Induced recharge to an aquifer can also occur from the pumping of wells near a surface-water body. As previously mentioned, sustained withdrawal of wells that tap stratified drift can lower the water table below an adjacent stream or lake, thereby inducing recharge from the surface-water body to the aquifer. The quantity of water potentially available to the aquifer through induced recharge during dry periods is limited by the streamflow. Excessive pumping near streams can result in undesirable reductions in streamflow and perhaps even the drying up of sections during periods of low flow.

The 7-day, 10-year estimate of low flow ($Q_{7,10}$) can be used as a measure of the amount of induced recharge available during dry periods. Streamflow statistics from several streams in New Hampshire indicate that the ($Q_{7,10}$) is about the 99-percent flow duration, which represents the amount of streamflow equaled or exceeded 99 percent of the time. If all the streamflow at 99-percent duration became induced recharge, the stream would be dry 1 percent of the time on the average. The ($Q_{7,10}$) was selected because (1) flows of this magnitude are a reasonable estimate of the minimum natural ground-water discharge to streams during a 180-day period of no recharge and (2) limiting the induced recharge to this amount reduces the effect of pumping on streamflow, particularly during dry years.

Discharge

Natural ground-water discharge from the aquifers consists of seepage to streams and ponds and ground-water evapotranspiration.

Ground-water discharge to streams sustains their flow in dry weather. After long periods of little or no precipitation, the rate of discharge per square mile from coarse-grained stratified drift is many times greater than that from till (Thomas, 1966). Low flow--and, therefore, ground-water discharge--can be estimated for any site on a stream in New England by determining the upstream drainage area underlain by coarse-grained stratified drift and till-mantled bedrock (Cervione and others, 1982) and by considering certain other watershed properties (Wandle, 1988).

Streamflow was measured at several sites on unregulated streams in 1986 and 1987 during periods when flow was relatively low and consisted entirely of ground-water discharge. Low-flow measurements are summarized in table 3; locations of measurement sites are shown on plates 1-3.

Low-flow measurements at five separate sites on Beaver Brook indicate that for the 2 years of measurements, streamflows increased progressively downstream in direct proportion to the upstream drainage area. No unusual gains or losses were found between measured segments for a 4.2-mi reach of the river. Comparison of low-flow yields (discharge per square mile of drainage area) indicates that similar proportional relations apply to the other streams measured during the study. Anomalous sources or sinks of ground water were not found between measured segments, and most streamflows increased proportionally to upstream drainage area.

Ground-water evapotranspiration is another significant source of discharge from the aquifers and is greatest during the growing season (April-October) when plants use a large amount of water, temperatures are above freezing, and the days are long. Ground-water evapotranspiration has been estimated to range from 1 to 9 inches per year in the northeastern United States (Lyford and others, 1984). Large amounts of moisture are lost to the atmosphere by evapotranspiration from wetlands and marshes where the water table is within 5 ft of the land surface. Streamflow can be reduced where such areas are extensive.

Water Table and Direction of Ground-Water Flow

Generalized water-table altitudes for aquifers are shown on plates 1-3. These maps are based on available water-level data measurements of depth to water at various times during 1986-88 at all observation wells, and surface-water altitudes on topographic maps. Water-table contours represent "average" water levels for a 3-year period (1986-88) and reflect the adjustments made to water-table altitudes during high- and low-water seasons. Because the seasonal fluctuation in water-table altitude is typically 3 to 5 ft in the stratified-drift aquifers (fig. 12), an approximate average water-table altitude was estimated by taking the average of high and low water-table altitudes measured during 1986-88. In addition, topographic maps were used for vertical control, such that the uncertainty of water levels shown on the plates is approximately one-half of the contour interval (10-20 ft) shown on the map.

Arrows drawn at right angles to the water-table contour lines are shown on plates 1-3 to indicate the

Table 3.--Low-flow measurements at miscellaneous sites

[01073830, station identification number, a unique 8 digit station number assigned by the U.S. Geological Survey to stream-gaging stations or single-flow measurement sites with numbers ascending in the downstream direction; mi, mile; mi^2, square miles; ft^3/s, cubic feet per second; $(ft^3/s)/mi^2$, cubic feet per second per square mile; --, no data]

Location (plate and site number)	Station identification number	Stream	Tributary to	Location	Drainage area (mi^2)	Measurements: Date	Measurements: Discharge (ft^3/s)	Basin yield ($(ft^3/s)/mi^2$)
				PICATAQUA RIVER BASIN				
Plate 3 1	01073830	Bailey Brook	Atlantic Ocean	Lat 42°59′25″, long 70°47′48″, Rockingham County, downstream side of bridge at culvert on West Road, 0.15 mi south of intersection with Garland Road, 0.36 mi north of intersection with South Road, 1.82 mi southwest of Rye, N.H. (plate 3).	0.5	10-21-86 8-26-87	0.15 No flow	0.30 --
2	01073835	Bailey Brook	Atlantic Ocean	Lat 42°59′20″, long 70°46′37″, Rockingham County, downstream side of bridge at culvert on Love Lane, 0.22 mi south-west of intersection with Central Road, 0.60 mi northwest of intersection with South Road, 1.7 mi south of Rye, N.H. (plate 3).	1.73	10-21-86 8-26-87	.35 No flow	.20 --
				MERRIMACK RIVER BASIN				
Plate 1 3	010965844	Beaver Brook	Merrimack River	Lat 42°50′21″, long 71°21′00″, Rockingham County, downstream side of Kendall Pond outlet exactly on the Windham-Londonderry town line, 0.01 mi south of the intersec-tion of South Road and Kendall Pond Road, 3.45 mi northwest of Windham, N.H. (plate 1).	30.8	10-21-86 8-25-87	6.71 .97	.22 .031
4	010965846	Beaver Brook	Merrimack River	Lat 42°49′40″, long 71°20′51″, Rockingham County, 50 ft behind house numbered 16 Pleasant Drive, 0.06 mi east of intersection of Pleasant Drive and Tranquil Road, measurment site is also on Windham-Londonderry town line, 2.9 mi northwest of Windham, N.H. (plate 1).	37.7	10-21-86 8-25-87	8.88 1.33	.24 .035

Table 3.--Low-flow measurements at miscellaneous sites--Continued

Location (plate and site number)	Station identification number	Stream	Tributary to	Location	Drainage area (mi^2)	Measurements Date	Measurements Discharge (ft^3/s)	Basin yield ($(ft^3/s)/mi^2$)
				MERRIMACK RIVER BASIN--Continued				
Plate 1 5	010965848	Beaver Brook tributary	Beaver Brook	Lat 42°49'02", long 71°20'41", Rockingham County, 50 ft upstream from mouth of tributary to Beaver Brook, 0.07 mi north of Sirod Road, 0.15 mi west of intersection between tributary and Kendall Pond Road, 2.45 mi northwest of Windham, N.H. (plate 1).	--	10-21-86 8-25-87	.99 .06	-- --
6	01096585	Beaver Brook	Merrimack River	Lat 42°48'23", long 71°21'12", Rockingham County, 20 ft upstream from bridge at the intersection of State Route 128 and Anderson Road, 0.28 mi north of the intersection between State Routes 128 and 111, 2.73 mi west of Windham, N.H. (plate 1).	41.8	10-21-86 8-25-87	11.3 1.26	0.27 .030
7	010965851	Beaver Brook	Merrimack River	Lat 42°47'25", long 71°21'53", Rockingham County, upstream from side of bridge on Bridle Bridge Road, at the Windham-Hudson town line, 0.45 mi west of State Route 128, 3.6 mi southwest of Windham, N.H. (plate 1).	43.6	10-21-86 8-25-87	11.5 1.42	.26 .032
8	[1]010965852	Beaver Brook	Merrimack River	Lat 42°46'59", long 71°21'14", on the Rockingham-Hillsborough county line, 100 ft fownstream from bridge on State Route 128 (Mammoth Rd.)., 0.23 mi south of the intersection with Glance Road, 1.4 mi south of West Windham, N.H. (plate 1).	47.8	10-21-86 8-26-87	13.0 1.42	.27 .030
9	010965905	Golden Brook	Beaver Brook	Lat 42°47'32", long 71°18'16", Rockingham County, upstream from side of bridge on Golden Brook Road, 0.5 mi northwest of intersection with State Route 111A, 1.6 mi south of Windham, N.H. (plate 1).	--	8-26-87	.09	[2].023
Plate 2 10	011005034	Taylor Brook	Spicket River	Lat 42°52'20", long 71°13'47", Rockingham County, 50 ft upstream from bridge on Island Pond Road, 0.3 mi northwest of intersection with North Shore Road, 5.42 mi east of Derry, N.H. (plate 2).	4.8	10-20-86 8-26-87	1.07 .45	.22 .09

Table 3.--Low-flow measurements at miscellaneous sites--Continued

Location (plate and site number)	Station identification number	Stream	Tributary to	Location	Drainage area (mi^2)	Measurements Date	Measurements Discharge (ft^3/s)	Basin yield ((ft^3/s)/mi^2)
				MERRIMACK RIVER BASIN--Continued				
Plate 2 11	011005038	Taylor Brook	Spicket River	Lat 42°52'10", long 71°13'27", Rockingham County, upstream from side of culvert on North Shore Road, 0.12 mi east of intersection with Island Pond Road, 5.75 mi east of Derry, N.H. (plate 2).	5.0	10-20-86 8-26-87	.71 .48	.14 .09
12	01100530	Hittytity Brook	Widow Harris Brook	Lat 42°48'18", long 71°13'07", Rockingham County, downstream 100 ft from culvert on Bluff Road, 0.07 mi west of intersection with Zion's Hill Road, 0.46 mi east of intersection with Scotland Avenue, 1.42 mi northwest of Salem, N.H. (plate 2).	9.4	10-20-86 8-27-87	0.94 No flow	0.10 --
13	01100535	Widow Harris Brook	Spicket River	Lat 42°47'58", long 71°11'58", Rockingham County, at culvert on Bridge Street, 0.23 mi southeast of intersection with Bluff Street, 0.74 mi north of Salem, N.H. (plate 2).	10.8	10-20-86	4.17	.39
Plate 2 14	01100674	Little River Tributary	Little River	Lat°42 51'12", long 71°04'55", Rockingham County, at culvert on Boston and Maine railroad track, 0.38 mi southwest of intersection with Whittier Street Extension, 2.7 mi southwest of Newton, N.H. (plate 2).	7.95	8-25-87	.42	.18
15	01100675	Kelly Brook	Little River	Lat 42°51'15", long 71°06'03", Rockingham County, at culvert on State Route 125, 0.18 mi southwest of intersection with Old County Road and State Route 125, 1.26 mi northwest of Plaistow, N.H. (plate 2).	1.9	10-20-86	.81	.43
16	01100676	Little River	Merrimack River	Lat 42°50'37", long 71°06'07", Rockingham County, downstream side of bridge on North Main Street, 0.32 mi southeast of intersection with State Route 125, 0.6 mi northwest of Plaistow, N.H. (plate 2).	8.8	10-20-86 8-25-87	3.35 .54	.38 .06

[1]U.S. Geological Survey streamflow-gaging station.

[2]Low flow is affected by regulation such that the discharge per square mile may not be representative.

direction of the horizontal component of ground-water flow. Flow may have a vertical as well as horizontal component in some localities, such as along the basin-drainage divides in and adjacent to the marine-silt and -clay confining layers that are in the vicinity of pumped wells and beneath ponds and streams of the basin. Because of the scale of these maps and the presence of local lenses of fine-grained material, flow directions at specific sites could differ from the regional flow directions shown on the plates.

Aquifer Characteristics

The capacity of a stratified-drift aquifer to store, transmit, and yield water can be partly described by its hydraulic characteristics--saturated thickness, transmissivity, and storage coefficient--and by its boundary conditions. The estimated yield to pumped wells and the resulting drawdowns throughout an aquifer also can be determined if these aquifer properties are known.

Saturated Thickness

Saturated thickness of an unconfined stratified-drift aquifer is the vertical distance between the water table and the bottom of the aquifer. In confined aquifers, saturated thickness is the distance from the top or overlying confining layer of the aquifer to the bottom of the aquifer. The stratigraphy of an unconfined aquifer above a confined aquifer and water levels in these aquifers is shown in figure 5. In the western part of the study area, where extensive fine-grained deposits are absent, the bottom of the stratified-drift aquifer is the till or bedrock surface. Some flow is expected to occur between stratified drift and bedrock wherever open fractures in bedrock are in contact with the stratified drift and there is a hydraulic head difference between these units. Where these conditions exist, the drift and bedrock form a single water-bearing unit. Given the number of high capacity bedrock municipal-supply wells in the study area (8 wells with an average yield of 328 gal/min) recharge from bedrock to stratified-drift aquifers may be significant in some areas. East of the towns of Kingston, Plaistow, and Newton, the bottom of the aquifer typically is the top of the fine-grained marine deposits.

Saturated thickness was mapped separately for unconfined and confined aquifers (pls. 4-6). Saturated thickness of unconfined aquifers was determined by plotting the difference between the water table and the depth to marine sediments, till, or bedrock from interpretation of seismic-refraction profiles (figs. A1-A17, Appendix), seismic-reflection profiles (figs. 13 and 14), logs of wells and test holes, and bedrock outcrops. It should be emphasized that the contours on the saturated-thickness maps apply only to saturated stratified-drift deposits.

The maps of saturated thickness can be used in conjunction with other hydrologic data to indicate favorable areas for the placement of high-yielding production wells. Where all other hydrologic characteristics are equal, a thick aquifer will produce more than a thin aquifer. Stratified drift having saturated thicknesses less than 20 ft cannot usually provide large water supplies, even where the deposits are coarse grained. Such thinly saturated, low-yield areas are found along valley margins and in upland areas where most of the section of stratified drift is dry; examples include kame-terrace deposits high on valley walls in the western part of the study area and elevated kame plains and kame deltas above the marine lowlands in the coastal areas. The saturated thickness is less than 20 ft in any areas of stratified drift where no saturated-thickness lines are shown on plates 4-6. In some of these areas, such as between the Powwow River south of Great Pond and the till contact east of Powwow Pond, the saturated thickness may exceed 20 ft because of discontinuity in the fine-grained marine sediments.

Saturated thickness ranges from 20 to 100 ft in outwash in a long north-south-trending valley that extends from Greenwood Pond to Country Pond in Kingston (pl. 5). This outwash represents the most extensive, thickly saturated aquifer in the study area. Other aquifers that consist of thickly saturated (60 ft or more) coarse-grained material include: the delta along the western shore of Island Pond in Derry; the ice-contact deposits in Newton, south of Amesbury Road; the kame delta that underlies Pease Air Force Base in Portsmouth, specifically the center of the kame delta near the Haven supply well (PXW-2); the kame delta that crosses Route 95 in Greenland; and the kame delta, which includes Knowles Pond, in North Hampton. These aquifers contain the largest stored volume of water within stratified-drift aquifers in the lower Merrimack and coastal river basins.

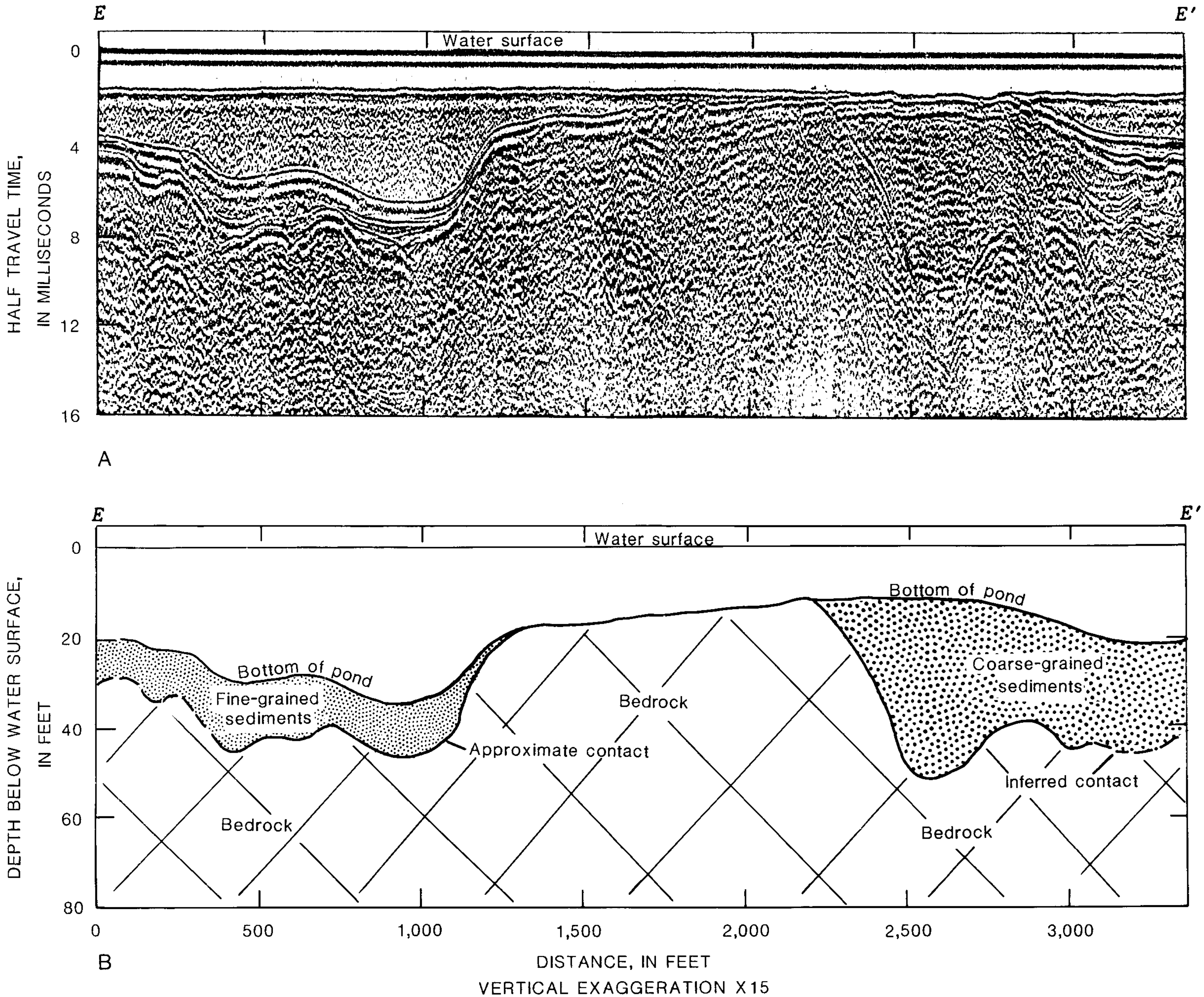


Figure 13.--Seismic-reflection profile (A) and cross section (B) of Cobbetts Pond, Windham, interpreted from seismic-reflection data. Line of section shown on plate 1.

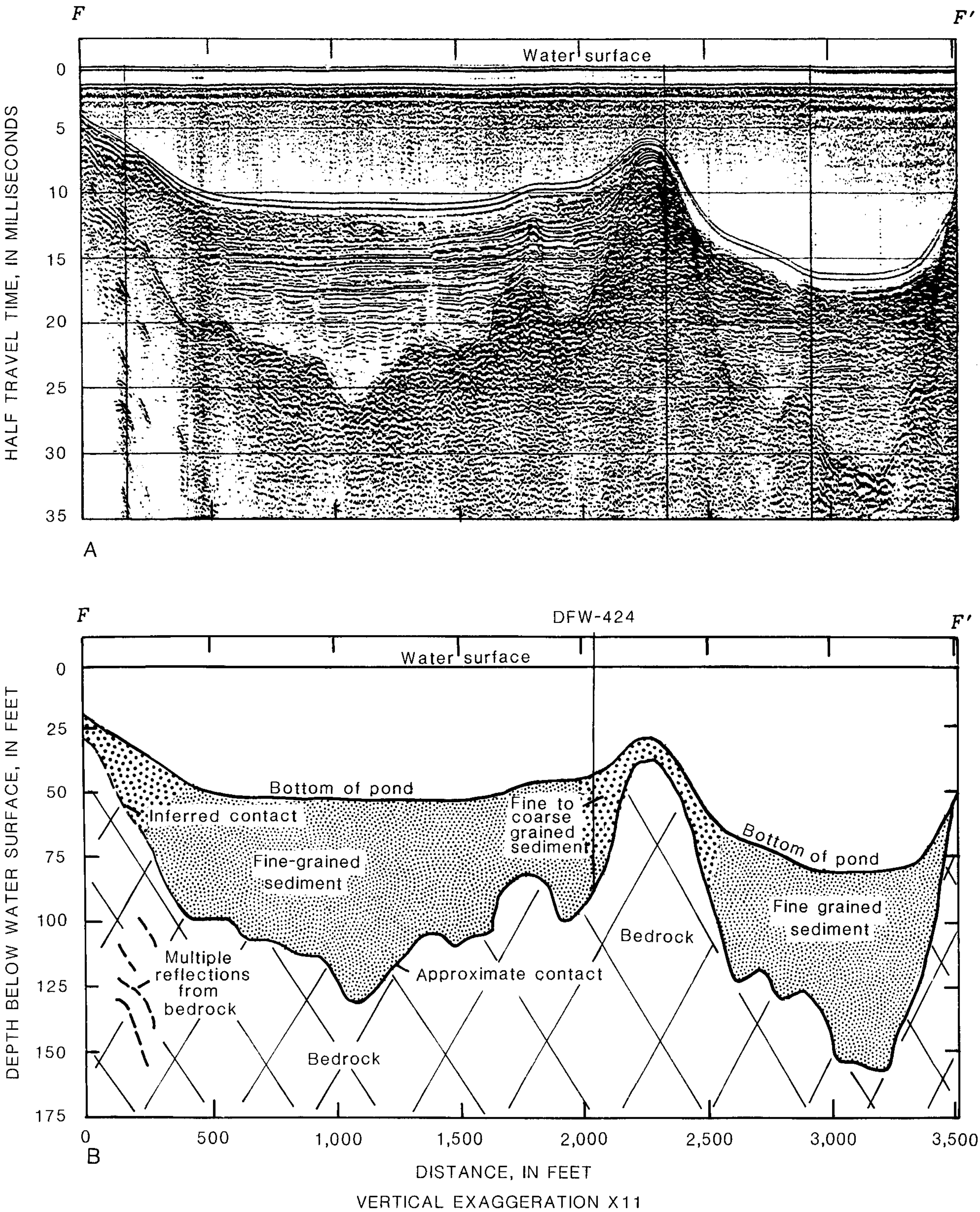


Figure 14.--Seismic-reflection profile (A) and cross section (B) of Island Pond, Derry, interpreted from seismic-reflection data. Line of section shown on plate 2.

Saturated thickness was also mapped for confined aquifers wherever well data were sufficient to locate saturated coarse-grained deposits beneath confining layers. Significant confined aquifers having saturated thickness of 20 ft or more include: a buried ice-contact deposit tapped by the Sherburne municipal well field in south Portsmouth; the aquifer tapped by wells PXW-27, PXW-28, PXW-29, and PXW-39; and the buried ice-contact material at the border of Seabrook, N.H. and Salisbury, Mass., which is tapped by three municipal wells (SGW-44, SGW-45, and SBW-34).

Storage Coefficient

The storage coefficient of an aquifer is defined as the volume of water an aquifer releases from 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 is equal to specific yield--the volume of water that can be obtained by complete 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 and average 0.26 (Weigel and Kranes, 1966). A value of 0.2 is commonly used to estimate specific yield in unconfined aquifers in New England.

The storage coefficient for the confined aquifers was not measured in this investigation. Typical values for confined aquifers are in the range of 0.00005 to 0.005 (Todd, 1980). This range indicates that much less water is released from storage per unit decline in head from confined aquifers than from unconfined aquifers until pumping lowers the head in confined aquifers to the point that they are no longer confined.

Transmissivity and Hydraulic Conductivity

Transmissivity, a measure of the ability of an aquifer to transmit a fluid, is calculated by multiplying the horizontal hydraulic conductivity (the volume of water at the existing kinomatic viscosity that moves in unit time through a unit area of aquifer under a unit hydraulic gradient) by the saturated thickness (Heath, 1983). The transmissivity distribution in an aquifer reflects the combined effects of variations in both of these factors. An aquifer composed of well-sorted, coarse-grained material will have a much higher transmissivity than one with the same saturated thickness but composed of fine-grained material. For example, although the aquifer in Londonderry immediately south of the Manchester/Grenier airport and the aquifer at Pease Air Force Base in Portsmouth have similar saturated thicknesses, the transmissivities of the Portsmouth aquifer are more than double those of the Londonderry aquifer because of differences in texture (grain-size distribution).

Hydraulic conductivities were estimated from stratigraphic logs of wells and test holes for sites for which reliable logs were available. These estimates are based on an empirical relation developed by Olney (1983) that was derived from regression of hydraulic conductivity data. The relation expresses hydraulic conductivity (K, in ft/d) as a function of effective grain size determined from grain-size analyses (D_{10} in phi units)--

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

Effective size is defined as the grain-size diameter at which 10 percent of the sample consists of small grains and 90 percent consists of large grains. A relation between hydraulic conductivity and median grain size (table 4) was developed by applying equation 1 to the results of grain-size analyses of 175 samples obtained from drilling in southeastern New Hampshire. Hydraulic conductivity values were assigned to each interval of a stratigraphic log by applying equation 1 if grain-size analyses were available, or by carefully comparing material descriptions in the logs to table 4 if grain-size distribution curves were unavailable. Estimates for horizontal hydraulic conductivity were made for 48 test holes by applying equation 1 and for 556 wells on the basis of lithologic descriptions and the data in table 4. The latter method is more subjective and less accurate then the method based on grain-size analysis; however, there is agreement between estimates derived from descriptive logs and those derived from quantitative techniques such as specific-capacity and aquifer tests.

Transmissivity at each well and test hole was determined by multiplying the horizontal hydraulic conductivity by the saturated thickness of the corresponding interval of the stratigraphic log and summing the products. Specific-capacity tests and (or) aquifer tests at nine wells also were used to estimate transmissivity by methods described by Ferris and others (1962) and Theis (1963). Although specific-capacity and aquifer tests provide the most accurate estimates of transmissivity, reliable records of such

Table 4.--*Hydraulic conductivity estimated for lithologies in stratified drift in southeastern New Hampshire*

[mm, millimeters; ft/d, feet per day]

Sample description	Median grain size (mm)	Hydraulic conductivity[1] (ft/d)
Sand		
Very fine	0.06 – 0.125	3
Fine	.125 – .25	10
Medium	.25 – .50	30
Coarse	.50 – 1.00	130
Very Coarse	1.00 – 2.00	190
Gravel		
Fine	2.00 – 4.00	250
Coarse	4.00 – 16.00	300 or greater

[1] Estimates based on empirical relations assuming isotropic conditions in the sample [From Olney, 1983].

tests are available for only a few municipal wells or test wells.

Transmissivity zones on plates 4-6 are based on interpolation and extrapolation of transmissivity from individual wells and auger holes, with consideration of saturated thickness and horizontal hydraulic conductivity of the surficial geologic units. Transmissivity can be extremely variable over short distances because of the heterogeneity of stratified-drift deposits. Because the distribution and quality of the transmissivity data differ from place to place and subjective judgement was involved in drawing the zones of equal transmissivity, the zones shown on plates 4-6 should be considered general estimates of transmissivity.

Evaluation of Water Availability and Simulation of Ground-Water Flow

Ground-water availability in the shallow stratified-drift aquifers is generally enhanced where surface-water bodies are in direct hydraulic connection with the aquifer. Recharge induced from a surface-water body augments well yields, especially where large freshwater ponds or lakes are close to pumping centers in coarse stratified drift. In the lower Merrimack River and coastal river basins, however, most public-water-supply wells are in stratified-drift aquifers that are several tens of thousands of feet distant from freshwater bodies; therefore, induced recharge from non-saline surface-water sources is expected to have little to no effect on well yields for most gravel-pack production wells in the study. The pond-aquifer system is an underutilized public-water-supply source that has potential for further exploration and development. Although it is an untapped water-supply resource, if pumpage of the pond (and stream) aquifer system is much greater than natural recharge, streams could show reduced flow or dry up and pond levels could be lowered to a point that water resources are adversely affected.

Two pond-aquifer systems, the one at Cobbetts Pond in Windham and another at Powwow River valley in Kingston (pls. 1 and 2), were selected for detailed hydrologic evaluation because of their potential importance as public water supplies. Water from the ponds is an important source of recharge because of the large storage volume of the ponds and hydraulic connection to the aquifers. Results from drilling and seismic reflection indicate that the ponds generally have a well-sorted, medium-grained sand bottom in the nearshore areas and a dense organic mud in the deep parts of the ponds. Maximum exchange between surface water and ground water is expected where the sandy bottom sediments predominate. The objectives of the evaluation were to (1) estimate the potential yield of the stratified-drift aquifer, (2) delineate the contributing areas for pumped wells withdrawing water from the pond-aquifer system, and (3) discuss selected aquifer areas in terms of favorability for future withdrawal centers.

Description and Conceptualization of Model

The aquifer evaluation involved application of a method that is analagous to the principle of superposition and incorporates the USGS modular three-dimensional finite-difference ground-water-flow model (McDonald and Harbaugh, 1988). The procedure for evaluation involved construction of a water-table map representing a natural (unstressed) aquifer and a numerical model of the aquifer. The model was then used to calculate drawdown that would result from hypothetical pumping stress. Finally, the composite water-table that would result from the pumping of production wells was generated by superimposing the drawdowns calculated with the model on the map of the unstressed water table. The aquifers near Cobbetts Pond and the Powwow River were simulated as two-dimensional ground-water systems, and ground-water withdrawals were simulated for 180 days without recharge. A stress period of 180 days approximately represents the maximum duration of annual periods when evapotranspiration is high and recharge is small. It is assumed that recharge to the aquifers for the remainder of the year would supply sufficient water to sustain pumping during periods of negligible recharge.

Potential yield was determined from the model by analyzing the effect of pumping stress on water levels in the aquifer. The area contributing water to the pumped wells was determined from the final water-table configuration.

The principle of superposition states that, for systems governed by linear equations, the solutions to individual parts of a problem can be added to solve composite problems (Reilly and others, 1987). Superposition reduces many ground-water problems to simpler terms. The most important constraint is that the governing differential equation and boundary conditions must be linear.

The pond aquifers in Windham and Kingston are unconfined (saturated thickness changes in response to pumping); therefore, the governing differential equation is nonlinear and superposition is not strictly applicable. Models can be formulated, however, so that changes in saturated thickness caused by pumping and the corollary changes in transmissivity are taken into account in the simulation. This enables the problem to be formulated by accounting only for changes in stress on the system and calculating drawdowns, which is analagous to superposition. Such models calculate drawdown on the basis of stated initial thicknesses of the aquifer. The water table is specified to start at zero drawdown, and the bottom of the aquifer is set equal to the negative of the saturated thickness. The drawdown solution is dependent on the initial thickness and the amount of change in thickness due to the applied stress. An example of the application of this method of prediction of aquifer response to pumping stress is described by Moore (1990) for similar stratified-drift aquifers in southeastern New Hampshire.

The general procedure for estimating the potential yield of the aquifers was to introduce production wells into the two-dimensional numerical model and vary their discharges. The locations of hypothetical production wells in the model were selected on the basis of hydrologic and practical considerations. The maximum well yields were at aquifer locations of maximum transmissivity and near ponds where induced infiltration could occur. In addition, well sites surrounded by an adequate ground-water-protection area were selected. It was assumed that open space, such as farms, parks, and wetlands, would be the most desirable types of land use to have in proximity to the wells. Selecting sites in open areas was done to satisfy the requirement that wells be surrounded by a minimum 400-foot protection radius, as specified in the New Hampshire Water Supply and Pollution Control Commission rules WS 309.04 and 309.5 of the Drinking-Water Regulations (1984). This protection radius was not always possible for the final well site; however, the chosen area was generally free from conflicting land uses. The maximum possible amounts of ground water that could be withdrawn were determined by adjusting the number of hypothetical pumped wells, the well locations, and well-discharge rates until maximum drawdown within the model approached, but did not exceed, 50 percent of the initial saturated thickness of the aquifer. A limitation of the numerical model is the inability to simulate the decline in pond-stage that would result from pumping. The model assumes the ponds are at constant stage and are unresponsive to changes in pumping stress.

The numerical models developed for the Windham-Cobbetts Pond and Kingston-Powwow River aquifers represent approximations of complex natural systems. Aquifer yields estimated by use of the models are based on several assumptions; therefore, yields should be considered not as exact quantities but rather as reasonable estimates of the maximum amount of water available from wells having specific locations and construction characteristics and tapping a stratified-drift aquifer with specific hydraulic characteristics and boundaries. Certain basic assumptions and limitations of the model simulations are as follows:

1. The aquifer characteristics of transmissivity, saturated thickness, and the water-table configuration shown on plates 1-6 are the source of input values used in the model simulations and are assumed to be representative of the natural system.

2. Prevailing ground-water flow in the stratified drift is predominantly horizontal, there is no change in flow to or from the underlying bedrock as a result of pumping, and the aquifer is isotropic. Vertical-flow components, which could be present near streams or ponds or near partially penetrating production wells, could cause local deviations from simulated water levels.

3. The variable characteristics of the aquifer can be represented by a finite number of blocks or cells, within which each of the aquifer characteristics is assumed to be uniform. Each block represents a discrete area of the aquifer with a single value for saturated thickness, horizontal hydraulic conductivity, and specific yield. This generalization introduces some error because the variability of aquifer characteristics in a given area can be greater than what is represented by the corresponding parameters for a discretized cell of the model.

4. The use of a numerical model to solve the ground-water-flow equation provides only an approximation of the true solution. The numerical model arrives at a solution indirectly through successive iterations of solving the ground-water-flow equation until the maximum head difference between successive iterations is less then a set tolerance level. Errors introduced are minimal as compared with errors involved in estimating aquifer characteristics.

5. All hypothesized production wells are considered to be screened through the full saturated thickness of the aquifer and to be 100-percent efficient. To compensate for the fact that few wells actually meet these ideal well-construction criteria, the maximum allowable drawdown at wells was 50 percent of the initial saturated thickness.

   Because drawdowns in the model represent the average drawdown over the area of a model cell, an adjustment is necessary to estimate drawdown at a pumped well. The total drawdown at well locations was estimated by adding the average drawdown computed by the model for the cell to the additional drawdown in the well calculated from solving the following equation (Trescott and others, 1976):

$$S_A = \frac{2.3Q}{2\pi T} \log \frac{a}{4.81(r_w)}, \qquad (2)$$

   where S_A is an adjustment to drawdown calculated in the cell containing the pumped well;
   Q is discharge at the well, in cubic feet per day;
   T is transmissivity, in ft^2/d;
   a is length of a model cell, in ft; and
   r_w is radius of pumped well, in ft.

   The equation for estimating the total drawdown at a well location is

$$S_T = S_m + S_A, \qquad (3)$$

   where S_T is the theoretical total drawdown, in feet in the production well; and
   S_m is drawdown, in feet, computed by the finite-difference flow model in the model cell containing the pumped production well.

   The theoretical total drawdown represented by this sum, which is always more than the average drawdown computed by the model, more accurately reflects the actual drawdown at the production well than the drawdown for the model cell.

6. The simulation of ponds as head-dependent flux boundaries allows a reasonable estimate for the potential yield of a pond-aquifer system. In the model simulation, the ponds are treated as constant-head boundaries such that surface-water elevations are arbitrarily held at a constant level. In actuality, ground-water withdrawals in an adjacent aquifer may lower pond levels. If the

amount of discharge at the production wells were greater than the amount of water that naturally flows out of the system, pond levels as well as ground-water levels would be lowered throughout the modeled area. Because the model could not simulate this occurrence, an independent calculation of the amount of water that naturally flows out of the system was needed to check the reasonableness of the model solution.

Description of Analytical Method

An analytical method was applied to check the reasonableness of the total amount of water withdrawn from pumped wells compared with the availability of water in the aquifer. Estimates of the amount of water available to an aquifer in hydraulic connection with a surface-water body require information on the quantity of water obtained from the surface reservoir. The low flow of streams, specifically the 7-day, 10-year low flow ($Q_{7,10}$), can be used as an index for evaluating basin-wide potential yield in stream-aquifer systems. The $Q_{7,10}$ is a statistically derived value; the minimum mean discharge for 7 consecutive days in a given year will be equal to or less than the $Q_{7,10}$ average for once in 10 years. This index was chosen as a reasonable approximation of aquifer potential yield after considering the following:

1. Any withdrawal from wells will be balanced by an equal reduction in discharge to streams or ground-water evapotranspiration. As long as the amount of water withdrawn from wells is small in relation to the natural ground-water discharge to streams, the average decline in the water table from pumping should not differ from what would occur naturally during a non-pumping period.
2. The $Q_{7,10}$ is a reasonable estimate of the minimum natural ground-water discharge to streams during a 180-day period without recharge.
3. Verification that the simulated model discharge does not exceed the $Q_{7,10}$ is important because the model is based on the assumption of constant stage in several ponds. If the average decline in the water table during a stress period was no greater than would occur naturally, pond level would not decline significantly during the stress period. Typically, pond levels in these aquifers remain relatively constant throughout the summer; therefore, the model would be a close approximation to reality. If a significant decline in water table were allowed, the model-simulated recharge from ponds would be too large and the results would be invalid.

The aquifer at Cobbetts Pond is drained by a small intermittent stream regulated by sluice gates at the western shore of Cobbetts Pond. Because of this regulation, an accurate measure of the range in natural streamflow is not possible; however, the $Q_{7,10}$ can be estimated by applying an analytical method that was developed for ungaged basins (Cervione and others, 1982). The method, based on the assumption that low flows are sustained by the discharge of water from adjacent aquifers, has been successfully applied to estimate potential yield for stratified-drift aquifers in Connecticut and Massachusetts. The analytical method, developed by Thomas (1966) and later modified by Cervione and others (1982), makes use of a regression equation to relate the $Q_{7,10}$ at any site on a stream to the proportion of upstream drainage area underlain by stratified drift and the proportion underlain by till-mantled bedrock. This regression equation is

$$Q_{7,10} = 0.67A_{sd} + 0.01A_{till}\,, \tag{4}$$

where $Q_{7,10}$ is the 7-day, 10-year low flow, in ft^3/s;

A_{sd} is the drainage area underlain by coarse-grained stratified drift, in mi^2; and

A_{till} is the drainage area underlain by till-mantled bedrock, in mi^2.

Application of the method is as follows:

1. The basin drainage divide upstream from a site on the master stream of the basin is drawn on the map by use of the topographic contours.
2. The area enclosed by the drainage divide is measured in square miles.
3. The area of stratified drift contained within the drainage divide is measured in square miles. (The area of till-mantled bedrock is equal to the total drainage area less the area of stratified drift).
4. $Q_{7,10}$ is estimated by use of equation 4.

Windham-Cobbetts Pond Aquifer

Water-laid deposits of sand and gravel fill a narrow, linear valley immediately west and to the south of Cobbetts Pond in Windham. This stratified-drift aquifer is currently undeveloped and was selected for evaluation because of its potential importance for public water supply. The location of this valley aquifer is shown in figure 16. The finite-difference grid used to model this area consisted of 67 columns and 26 rows with uniform cell dimensions of 200 ft on a side (fig. 15). Only the cells on the aquifer were considered "active" and were involved in the numerical computations. The total area of aquifer represented by active cells was 1.14 mi^2.

Boundary conditions

The eastern and western borders of the aquifer are defined by the contact between till or bedrock and stratified drift. This geologic contact was represented in the model by a "no-flow" boundary. Although termed a "no-flow" boundary, some flow does occur between the bedrock and stratified-drift aquifers and it may be significant in places. Results from an inventory of public-supply wells indicate that bedrock wells account for approximately one-fifth of the total water pumped from the study area (table 2). Because the bedrock aquifer can be a significant water producer, the flux across the bedrock stratified-drift boundary can be an important component of the total recharge to the stratified-drift aquifer. The exact location, direction, and quantity of flow between these aquifers will vary depending, in part, on the prevalence of water-bearing fractures in the rock and the absence of till semi-confining layers between aquifers. Because this investigation focused on the geohydrology of stratified-drift aquifers little is known about the hydraulic properties of bedrock and till and the effect on water availability in the stratified-drift aquifer. In a superposition model, the no-flow boundary assumes that pumping will not create additional flow across the boundary. This condition was not strictly met in the model because slight (3 ft or less) drawdowns produced by pumping reached the model "no-flow" boundaries in places. The model results, therefore, are slightly conservative in the estimate of aquifer potential yield and the calculated contributing area is slightly larger than what would be estimated if the model were simulated such that pumping could create additional flow across the boundaries.

Natural flux across the till or bedrock, stratified-drift no-flow boundary was accounted for in the model because the map of initial water-table altitudes (fig. 16), upon which drawdowns are superimposed, indicates the natural lateral flow from the till-covered valley walls. The model boundary was arbitrarily terminated southwest of Simpson Pond. This termination corresponds to a southeastern edge of the aquifer that is beyond the reach of drawdowns calculated by the model and, therefore, was simulated as a no-flow boundary.

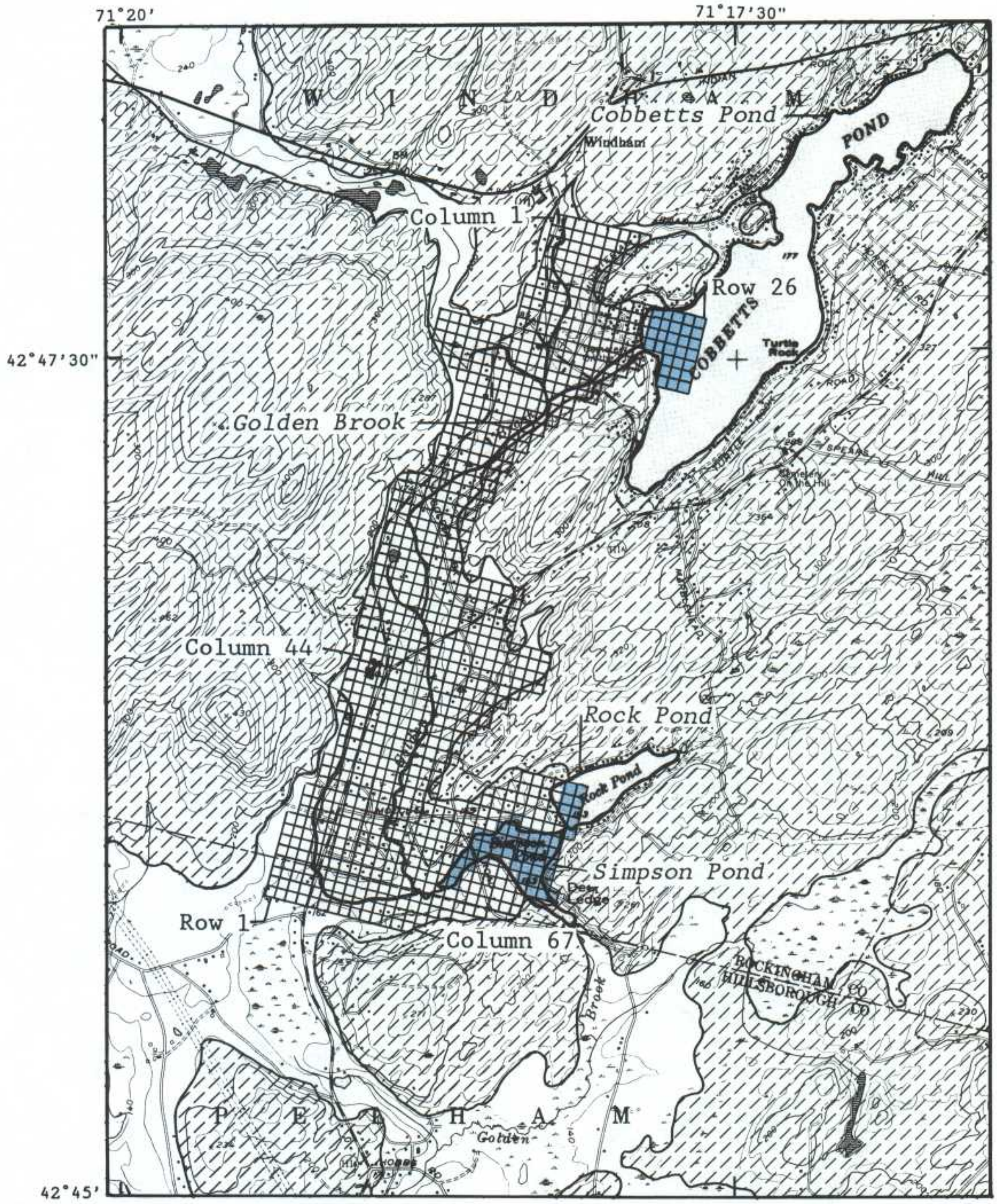
Three ponds, Cobbetts Pond in the northeastern corner and Rock and Simpson Ponds in the southeastern corner of the model, overlie part of the aquifer. The ponds were simulated in the model as head-dependent flux cells. This type of simulation allows leakage across a semipermeable pond bottom in response to a head gradient between water in the pond and in the aquifer.

The underlying till-bedrock surface was simulated as a no-flow boundary. Some leakage probably occurs across this boundary, but it was assumed to be small enough to be considered negligible in a water balance for the aquifer.

Aquifer parameters

The parameters of hydraulic conductivity, water-table altitude, aquifer-bottom elevation, and specific yield were assigned to each cell in the model. Appropriate values of hydraulic conductivity were determined from the maps of transmissivity and saturated thickness (pl. 4). The grid network is superimposed over these maps, and parameter values were calculated for the respective cells. For example, hydraulic conductivity was computed by dividing transmissivity by saturated thickness. Altitudes of the water-table and pond surface were set to an arbitrary initial value of zero feet, which created a continuous flat boundary suitable for analysis by superposition. Aquifer-bottom elevation was equivalent to the negative of the saturated thickness at each cell.

Parameters describing the hydrologic properties of the pond bottom were assigned to cells in the model that correspond to locations of Cobbetts and Simpson Ponds. Grid cells in which leakage between the pond and aquifer was simulated are shown in figure 16. Depths of the ponds range from 10 to 20 ft and were determined from bathymetric data obtained from seismic-reflection traverses across the



Base from U.S. Geological Survey
Windham, N.H. 1:24,000, 1953,
photorevised 1985

CONTOUR INTERVAL 20 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

0 1 2 MILES
0 1 2 KILOMETERS

EXPLANATION

STRATIFIED DRIFT

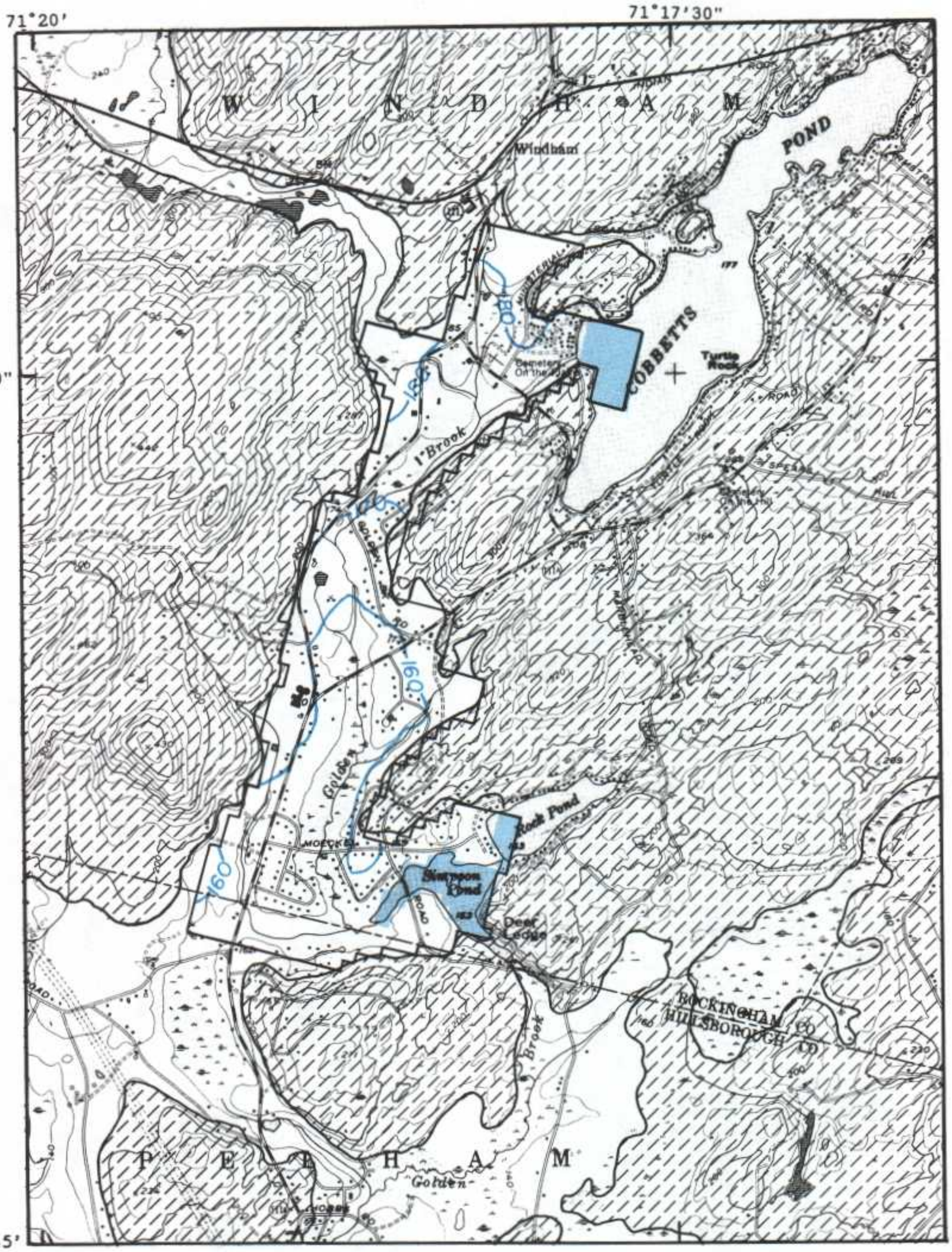
TILL AND BEDROCK

POND CELLS

MODEL CELL

MODEL BOUNDARY

Figure 15.--Finite-difference grid used to discretize the Windham-Cobbetts Pond aquifer.



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CONTOUR INTERVAL 20 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

0 1 2 MILES
0 1 2 KILOMETERS

EXPLANATION

STRATIFIED DRIFT

TILL AND BEDROCK

POND CELLS

MODEL BOUNDARY

—170— WATER-TABLE CONTOUR--Shows approximate average altitude of the water table under natural conditions in 1987. Contour interval 10 feet. National Geodetic Vertical Datum of 1929

Figure 16.--Initial water table for the Windham-Cobbetts Pond simulation.

ponds. Figure 13 shows a typical seismic-reflection profile for a traverse across the western shore of Cobbetts Pond in a region of hydrologic connection between pond and aquifer. Hydraulic conductivity of the pond bottom was assumed to be 2 ft/d), and the thickness of the material was assumed to be 2 ft. These estimates were based on values calculated for riverbed deposits (Haeni, 1978; de Lima, 1989), and were assumed to be representative of the pond-bottom hydrology.

The final parameter, specific yield, was estimated to be 0.2 for this unconfined aquifer and was assigned to the entire model area.

Application of numerical model

Five wells were simulated in the model and pumped at various rates until the limits for drawdown were attained at the end of 180 days. Five wells were needed because the model cells that contained the pumped wells went dry if the total discharge simulated was distributed among fewer wells. The locations of the wells and resultant drawdowns are shown in figure 17. The combined pumping rate of the five wells, 0.64 Mgal/d, represents the estimated potential yield of the basin. The potential yield as used in this report describes the rate at which water can be withdrawn from a basin under conditions of pumping for 180 days without recharge and without having adverse impacts on the water resource (see glossary).

Sensitivity analysis

A sensitivity analysis of some of the model parameters was done to show the effect these parameters have on estimates of potential yield. The analysis determined the relative importance of input data values on calculations of potential yield and provided a basis for assessing uncertainty in the simulations given the likely range in each value.

The principal input parameters of aquifer hydraulic conductivity, pond-bottom conductance, specific yield, and duration of pumping were independently increased and decreased by a constant factor throughout the modeled area while other parameters were left unchanged. A reference simulation was selected to represent the best estimate of the hydrologic properties of the aquifer. This reference serves as a standard from which subsequent simulations with different input values can be compared. The amount of adjustment of each parameter differed according to the likely range of each parameter.

The results of the analysis of each change in parameter value are shown in figures 18 and 19 for an east-west profile along column 44 (fig. 15). The profile includes the hypothetical production well of largest simulated discharge (0.135 Mgal/d) and represents an area of the model (column 44, row 11) where the greatest difference in drawdowns occurred between simulations. The computed percentage changes in storage and leakage and the drawdowns for each simulation are listed for comparison in table 5. It should be emphasized that these data represent changes in two of three components of recharge, aquifer storage, and pond and river leakage. Not represented is the change in recharge from till and bedrock uplands, which is commonly simulated in numerical ground-water flow models. The superposition technique, however, simplifies the flow regime by simulating the till-aquifer boundary as "no flow", where additional flow is not induced across this boundary. The tabulated results, therefore, are intended only to show relative differences in the simulations.

Aquifer hydraulic-conductivity (K_a) values were multiplied by factors of 1 (model standard), 2, and 0.5 in three separate simulations. Doubling the hydraulic conductivity of the aquifer resulted in a 32-percent overall reduction in drawdown at production wells and a decrease in the natural ground-water flow to the ponds. The reduction in drawdown extended generally to a distance of 1,500 ft from well locations, beyond which drawdowns were slightly greater than at corresponding cells in the model standard.

Reducing the hydraulic conductivity by 0.5 had the greatest effect on drawdown at well locations for these simulations. Overall, drawdown increased by 57 percent at production wells, and a greater percentage of water came from aquifer storage. Drawdowns decreased slightly relative to the model standard near the till-aquifer boundaries.

Pond-bottom conductance (K_b) values were multiplied by factors of 1 (model standard), 10, and 0.1 in three separate simulations. These changes resulted in computed heads that were identical to those of the model standard. No change in the proportions of water derived from the two sources (table 5) was observed. The insensitivity of the model shows that pond leakage is not the primary control on the availability of water to the simulated production wells, even though one simulated production well was within 600 ft of Cobbetts Pond. The results are probably a reflection of (1) limited

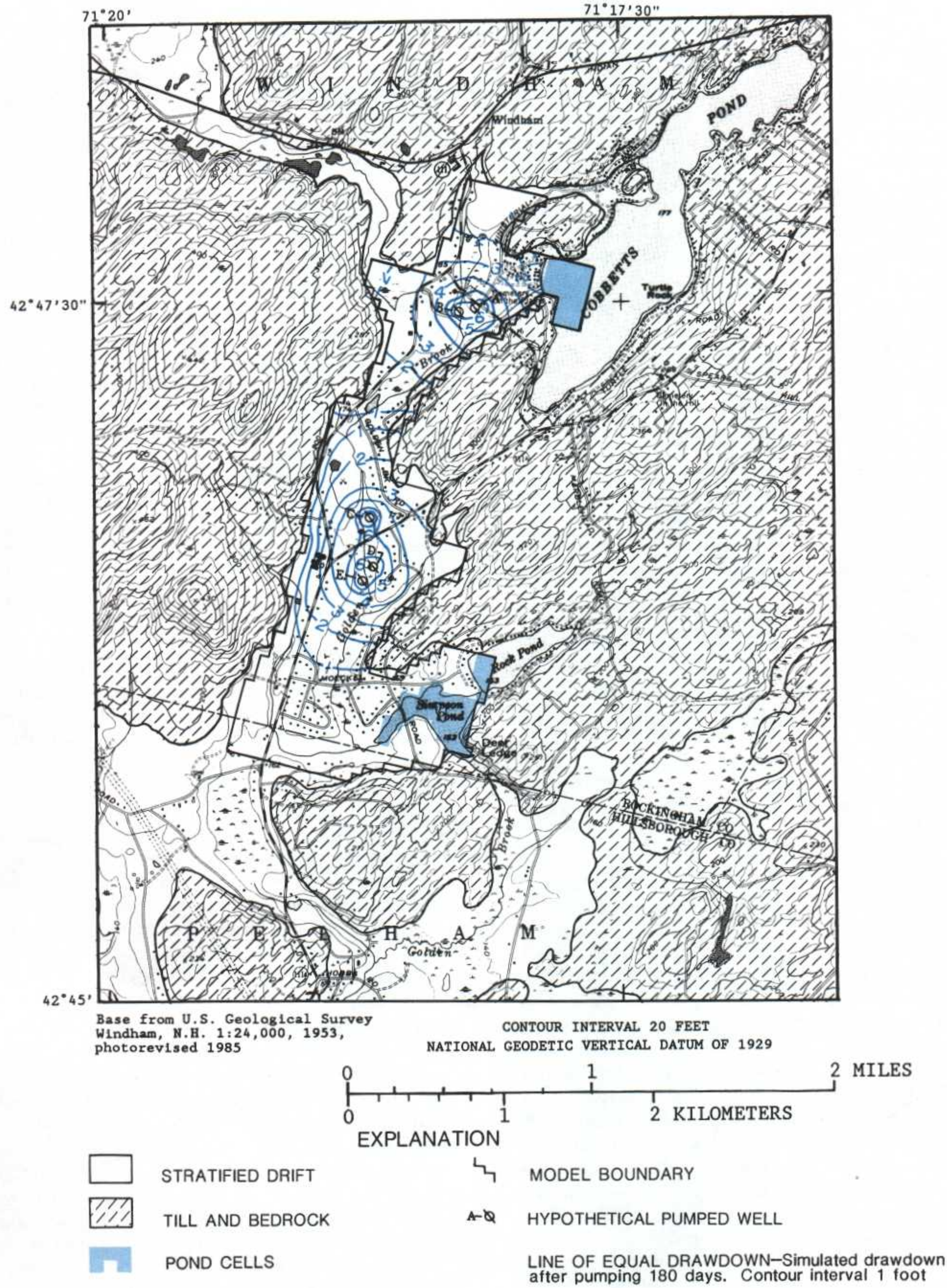


Figure 17.--Drawdown resulting from pumping five hypothetical wells completed in the Windham-Cobbetts Pond aquifer after pumping at a combined rate of 0.64 million gallons per day for 180 days.

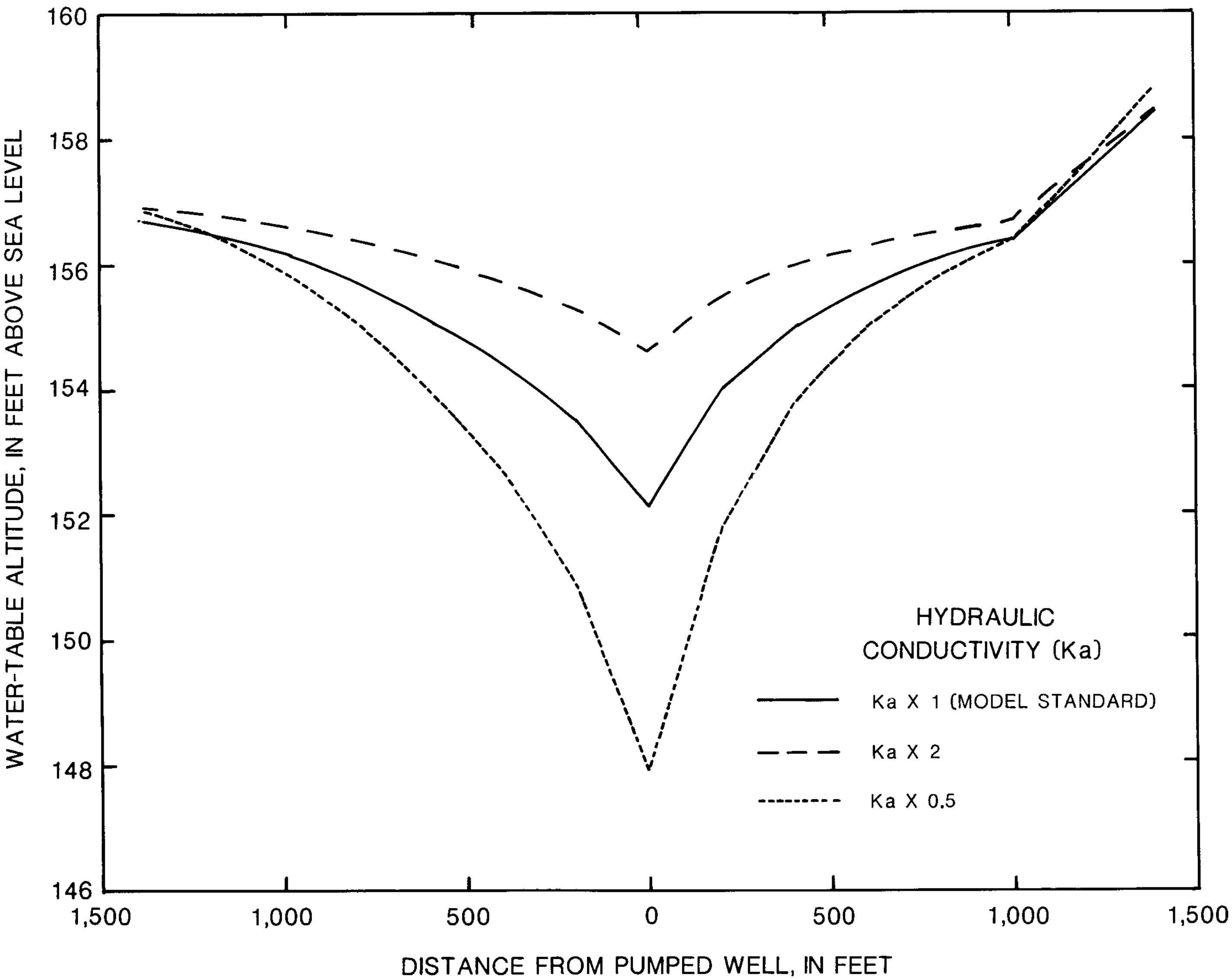


Figure 18.--Effects of varying hydraulic conductivity on results at hypothetical well D from the Windham-Cobbetts Pond model.

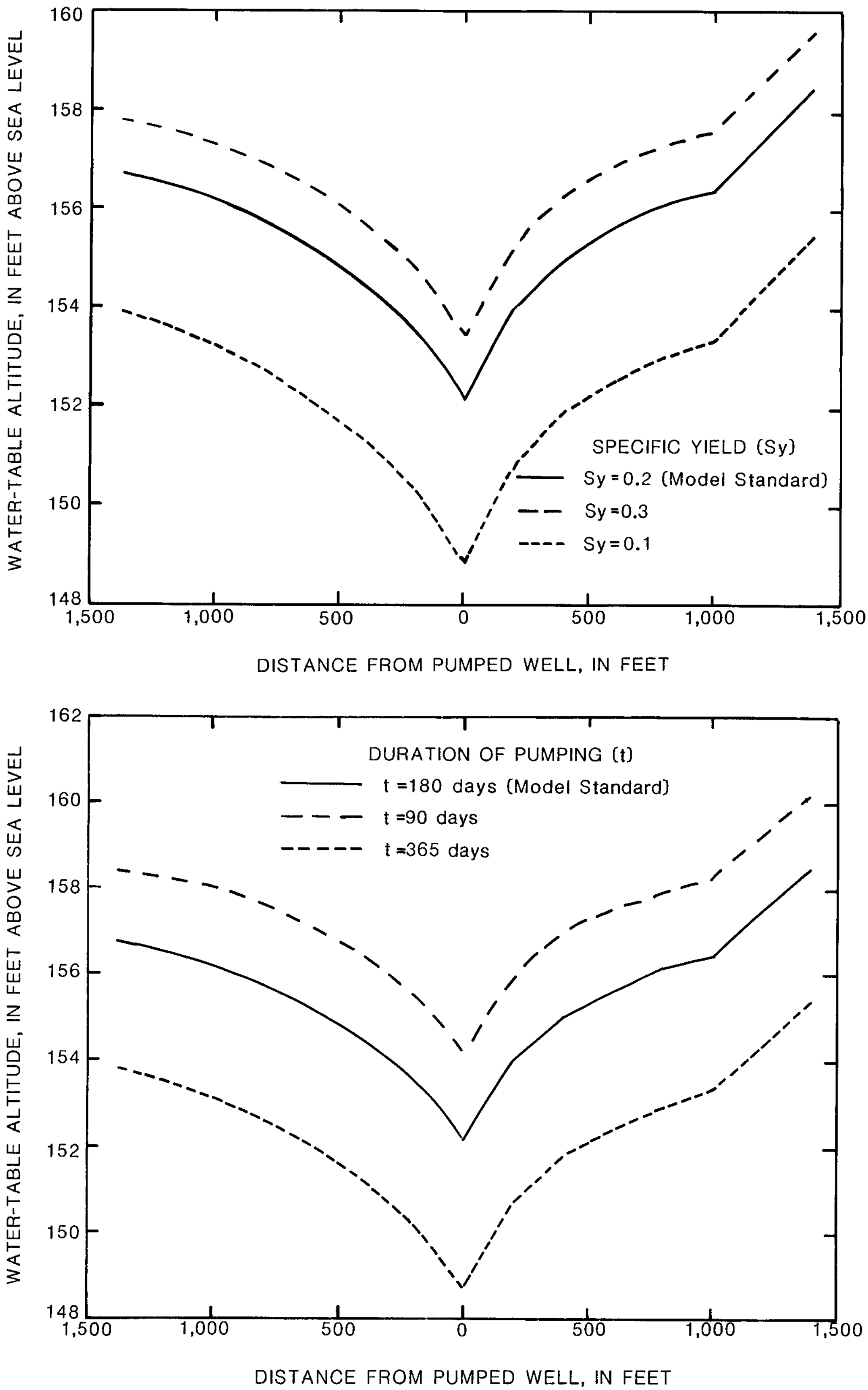


Figure 19.--Effects of varying specific yield and duration of pumping on results at hypothetical well D from the Windham-Cobbetts Pond model.

Table 5.--*Summary of aquifer-evaluation results showing sensitivity of model parameters*

[Mgal/d, million gallons per day; ft, feet; K_a, horizontal hydraulic conductivity; K_b, pond- and river-bottom conductance; S_y, specific yield; t, duration of pumping, in days; --, simulation failure, no values computed]

Model parameters	Change in storage (Mgal/d)	Change in flux to surface water[1] (Mgal/d)	Percentage of change in storage	Percentage of change in ground-water flux to surface water	Average drawdown at production wells[2] (ft)	Percentage difference from model standard in drawdown at production wells
			Windham-Cobbetts Pond aquifer			
Model standard[3]	0.60	0.04	94	6	7.6	--
$K_a \times 2$	.57	.07	90	10	5.2	32
$K_a \times 0.5$	.62	.02	97	3	12	-57
$K_b \times 10$	.60	.04	94	6	7.6	0
$K_b \times 0.1$	.60	.04	94	6	7.6	0
$S_y \times 0.3$	.61	.03	96	4	6.4	16
$S_y \times 0.1$	.57	.07	90	10	10.7	-41
t = 90	.62	.02	97	3	5.7	25
t = 365	.57	.07	89	11	10.3	-36
			Kingston-Powwow River aquifer			
Model standard[4]	.48	3.52	12	88	8	--
$K_a \times 2$	.36	3.64	9	91	4.2	48
$K_a \times 0.5$	--	--	--	--	--	--
$K_b \times 10$	.36	3.64	9	91	7.1	11
$K_b \times 0.1$	1.27	2.73	32	68	11.1	-39
$S_y = 0.3$	.63	3.37	16	84	7.8	3
$S_y = 0.1$	.29	3.71	7	93	8.2	-3
t = 90	.75	3.25	19	81	7.6	5
t = 365	.29	3.71	7	93	8.2	-3

[1] Includes induced infiltration and ground water captured before it reaches surface-water bodies.

[2] Computed (by use of equation 3) as the average drawdown for all production wells in the simulation.

[3] Simulation with five wells pumping at a combined discharge of 0.64 Mgal/d.

[4] Simulation with eight wells pumping at a combined discharge of 4.0 Mgal/d. Model parameters represent best estimates of the natural system, $K_a \times 1$, $K_b \times 1$, $S_y = 0.2$, and t = 180 days.

ground-water flow in the narrow section of stratified drift that connects Cobbetts Pond to the aquifer and (2) the distance separating the wells from Simpsons pond.

Specific yield (S_y) was set equal to 0.2 (model standard), 0.3, and 0.1 in three separate simulations. Simulated drawdowns were sensitive to small changes in the specific yield. An increase in specific yield to 0.3 had a large effect, reducing drawdowns not only at well locations but also throughout the modeled area (fig. 19). By decreasing the specific yield to a value of 0.1, drawdowns increased considerably throughout the aquifer as less water was held in storage, and pumping stress affected a large part of the aquifer.

Duration of pumping (t) values of 180 days (model standard), 90 days, and 365 days were used in three separate simulations. The effect of changing the transient simulation from 180 days to shorter and longer periods was also evaluated. As expected, the simulations indicated that overall drawdown in the aquifer was less after 90 days than after 180 days. The simulation for 365 days showed a significant decrease in head relative to the model standard as aquifer storage became depleted. Numerical oscillation and convergence were problems in the 365-day simulation as some model cells near till-aquifer borders went dry.

Application of analytical method

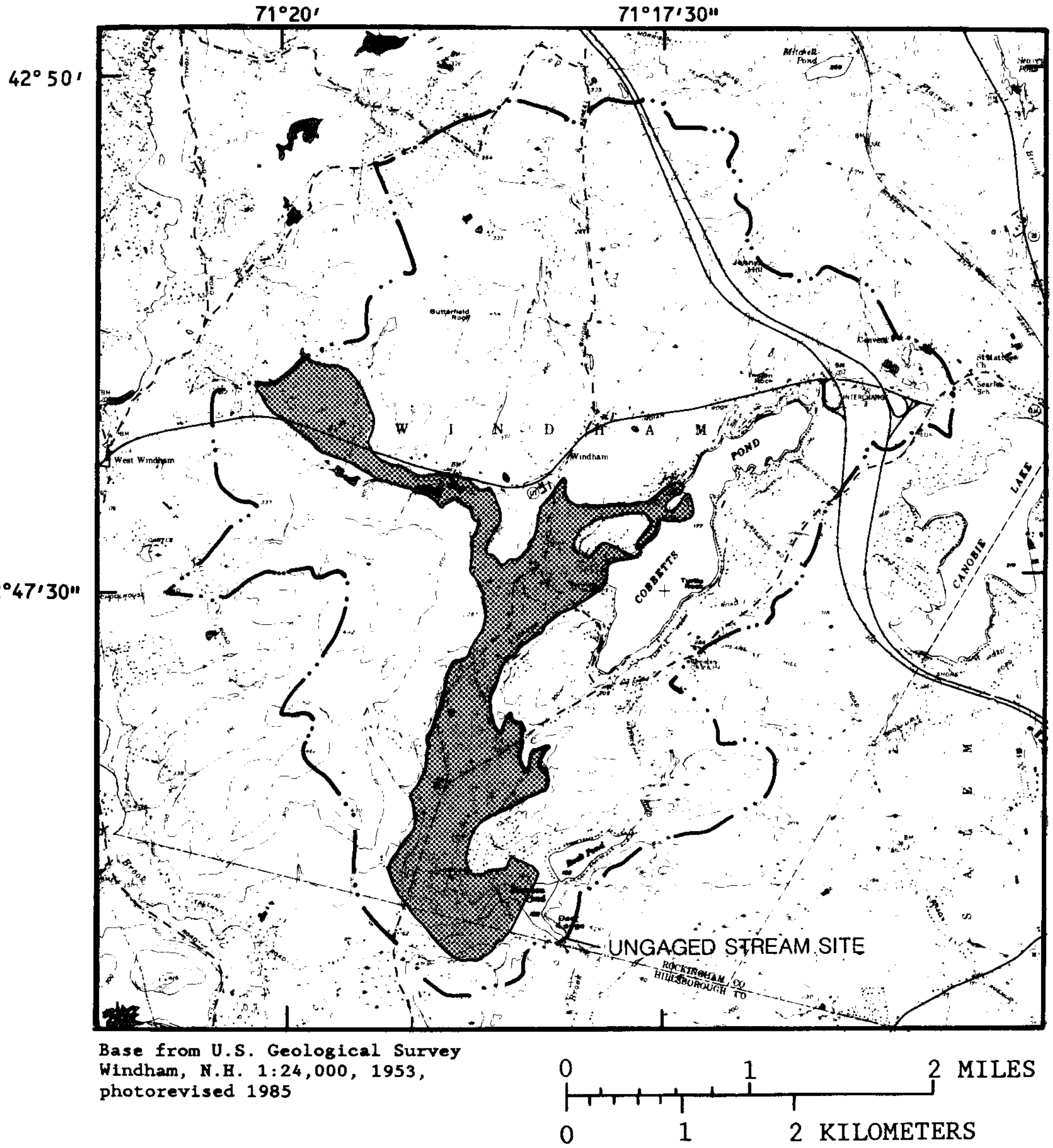
Application and results of the analytical method to estimate potential yield for this valley aquifer are shown in figure 20. The segment of the map used in figure 20 was taken from plate 1, which shows stratified-drift aquifer boundaries for the western part of the study area. Because this map has contours indicating altitude of land surface and shows areas underlain by stratified drift, it is the only map required for estimating aquifer yield. An estimate of 1.3 ft^3/s or 0.84 Mgal/d for the $Q_{7,10}$ is obtained by use of this method. This is slightly larger than the potential-yield estimate of 0.64 Mgal/d determined from the numerical model. Together, the analytical and numerical results indicate that this small basin of thin stratified drift is capable of yielding less than 1 Mgal/d but probably more than 0.5 Mgal/d under long-term pumping. These estimates are based on a conservative withdrawal scheme that makes use of available storage and does not influence pond stages.

Well-capture area

Well-capture areas were constructed by use of the method of superposition and information shown in figures 16 and 17. Figure 16 shows the configuration of the initial water table and figure 17 shows the drawdown contours constructed from drawdowns computed from the two-dimensional numerical model. The result of superimposing drawdowns on the initial water-table altitudes is shown in figure 21. Because topographic maps with a (10-20 ft) contour interval were used for vertical control to construct the water-table maps and natural water-level fluctuations up to 5 ft may occur in the coarse-grained stratified-drift aquifers (fig. 12) the uncertainty of water levels shown in figures 17 and 21 is approximately 10 ft. The shaded area in figure 21 is the area contributing ground water to the wells after 180 days of pumping. The contributing area is assumed to extend into the till uplands where the shaded areas reach the till-aquifer boundary. This assumption is considered reasonable because the drawdowns calculated by the model were minor (4 ft or less) at the "no-flow" boundaries such that the condition of no additional flow across the model boundary is reasonably met. The effect of allowing these minor (4 ft) or less drawdowns at model boundaries is to estimate a contributing area that is slightly larger than what would be estimated if no drawdowns occurred at model boundaries. The size of the contributing area is about 0.9 mi^2 within the model-area boundaries. An additional 1.6 mi^2 of till uplands outside of the model boundaries is estimated to contribute water to the wells. Most evident from this analysis is that the size of the estimated contributing area (2.5 mi^2) is much larger than the area encompassed by the 400-foot protective radius currently required by New Hampshire State law.

Kingston-Powwow River Aquifer

The Kingston-Powwow River aquifer, in Kingston is the largest continuous aquifer in the study area and is an example of an outwash plain composed of well-sorted glaciofluvial sand and gravel materials. Presently, this ground-water resource is undeveloped as a public supply; most town residents are served by individual home wells. A major hydrologic feature of the Kingston-Powwow River aquifer is the extensive area of surface water in contact with permeable stratified-drift deposits.



Base from U.S. Geological Survey
Windham, N.H. 1:24,000, 1953,
photorevised 1985

CONTOUR INTERVAL 20 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

EXPLANATION

COARSE-GRAINED STRATIFIED DRIFT

DRAINAGE-BASIN DIVIDE

EXAMPLE

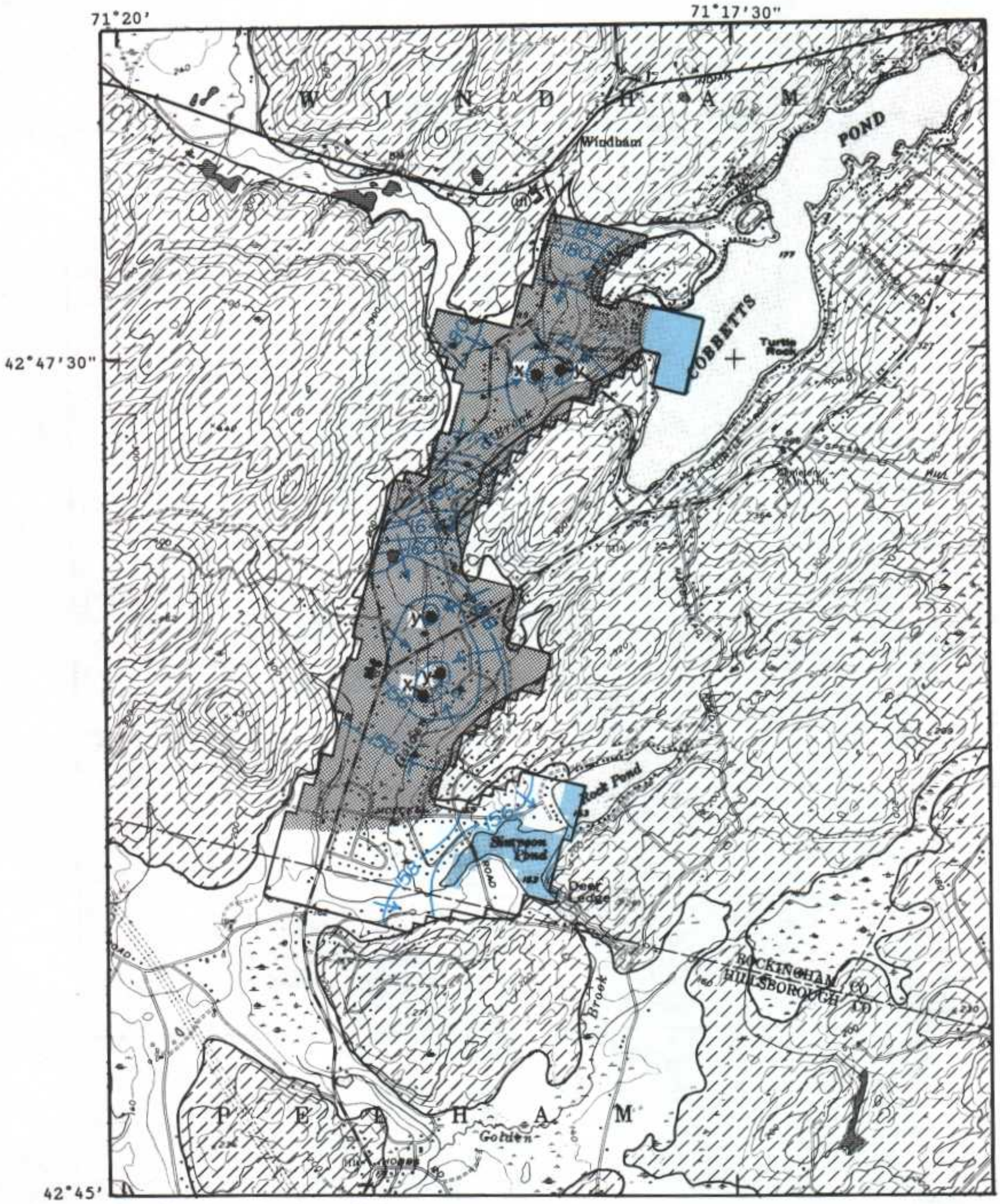
1. Drainage-basin divide is drawn on map
2. Area enclosed by divide is measured as 11.5 square miles
3. Area of coarse-grained statified drift is measured as 1.8 square miles
4. Using the following equation:

$Q_{7,10}$ is 0.67 A_{sd} + 0.01 A_{till},

$Q_{7,10}$ is 0.67(1.8) + 0.01(9.7)

$Q_{7,10}$ is 1.3 cubic feet per second or 0.84 millions gallons per day

Figure 20.--Method of determining potential yield of aquifer from the 7-day, 10-year low-flow estimate at an ungaged stream site.



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CONTOUR INTERVAL 20 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

0 1 2 MILES

0 1 2 KILOMETERS

EXPLANATION

	STRATIFIED DRIFT
	TILL AND BEDROCK
	AREA CONTRIBUTING WATER TO WELLS INSIDE OF THE MODEL AREA
	POND CELLS
	MODEL BOUNDARY
160	WATER-TABLE CONTOUR-Shows altitude of simulated water table after pumping for 180 days. Contour interval 2 feet. National Geodetic Vertical Datum of 1929. Arrows indicate approximate direction of ground-water flow
x x-0.120 y-0.135	HYPOTHETICAL PUMPING WELL-Small letter is pumping rate, in million gallons per day

Figure 21.--Calculated water-table configuration based on simulated drawdown after 180 days of pumping from the Windham-Cobbetts Pond aquifer.

Three ponds--Great, Powwow, and Country Ponds--overlie glaciofluvial stratified drift and cover 1.6 mi^2 or 17 percent of the total aquifer surface. The Powwow River connects the ponds and is regulated by the Trickling Falls dam at the eastern shore of Powwow Pond. The ponds and river are a major control of the regional ground-water-flow system and locally receive both surface-water and ground-water discharge (pl. 7A). Surface-water outflow from this system is regulated to maintain a constant water level in the ponds throughout the recreation season (from March through October). The river and the ponds could probably supply abundant induced recharge to properly located wells.

The Kingston-Powwow River aquifer was modeled and evaluated by use of the same numerical and analytical methods described for the Windham-Cobbetts Pond aquifer. The finite-difference grid used to discretize the aquifer is shown in plate 7B. The grid consisted of 122 rows and 118 columns with uniform cell dimensions of 200 ft on a side. The active model area was 9.4 mi^2.

Boundary conditions

The external boundaries of the model (pls. 7A and 7B) coincided with surface-water divides or with the geologic contact between the aquifer and either till or silts and clays (pl. 5). These areas were simulated as no-flow boundaries; no change in flow across the boundary was assumed to occur during pumping.

The bottom boundary of the aquifer is the contact between highly permeable stratified drift and the less permeable till, bedrock, or fine-grained marine deposits. This boundary also was treated as a no-flow boundary in the model. Some leakage probably occurs across this boundary in the aquifer, but it is assumed to be small relative to the flow in the aquifer.

The internal boundaries include the Powwow River, till and bedrock outcrops, and Great, Powwow, and Country Ponds. The river and ponds were treated as river cells that simulate a leaky boundary. Till and bedrock outcrops that rise above the outwash plain were simulated as no-flow boundaries. The locations and types of all boundaries simulated are shown in plate 7A.

Aquifer parameters

Parameters assigned to the model were derived from similar sources and procedures as those used for the Windham-Cobbetts Pond aquifer. Maps of transmissivity and saturated thickness (pl. 5) were used to assign values of hydraulic conductivity in the model. The water-table and surface-water elevations were set equal to zero throughout the model area. Depths of the river and ponds were determined from seismic-reflection data. Vertical hydraulic conductivities of river and pond-bottom sediments (river and pond-bottom conductance) were assumed to be 2 ft/d, and the thickness of material was assumed to be 2 ft. Specific yield was estimated to be 0.2 over the entire modeled area.

Application of numerical model

Eight wells were introduced to the model and pumped at various rates until the predetermined limits for drawdown were attained. Wells were located within 600 ft of surface-water bodies because of the increased recharge that would be available from induced infiltration. Plate 7C shows the location of these hypothetical production wells and the drawdown simulated after 180 days of pumping. The combined pumping rate of the eight wells, 4.0 Mgal/d, represents the estimated potential yield of the aquifer. The number of hypothetical wells was the maximum feasible given present knowledge and practical considerations. Production wells simulated elsewhere either yielded small volumes that would be impractical for public or commercial water systems or failed to meet the siting criteria.

Sensitivity analysis

A sensitivity analysis was also done for the Kingston-Powwow River model to test the sensitivity of model results to changes in input parameters. The parameters and ranges in values selected were the same as those used for the Windham-Cobbetts Pond aquifer model.

The results of the analysis of each change in parameter value are shown in figures 22 and 23 for an east-west profile along row 47. The profile includes the production well with the highest simulated discharge (1.0 Mgal/d) and represents an area of the model where the largest difference in drawdowns occurred between simulations. Changes in natural ground-water flow to surface water and storage, as well as drawdowns for each simulation, are listed for comparison in table 5. These data were computed in the same way as for the Windham-Cobbetts Pond aquifer and offer a basis

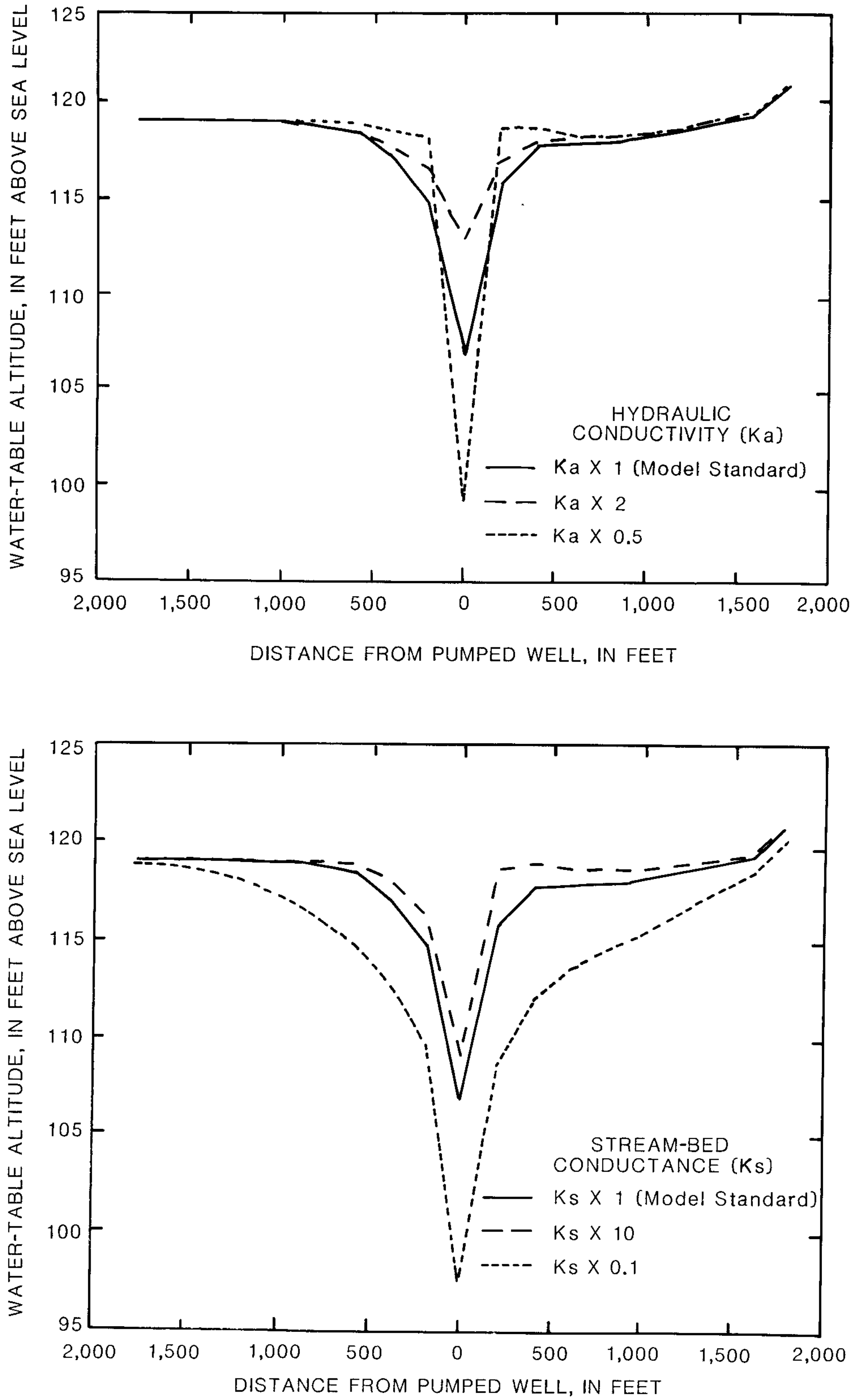
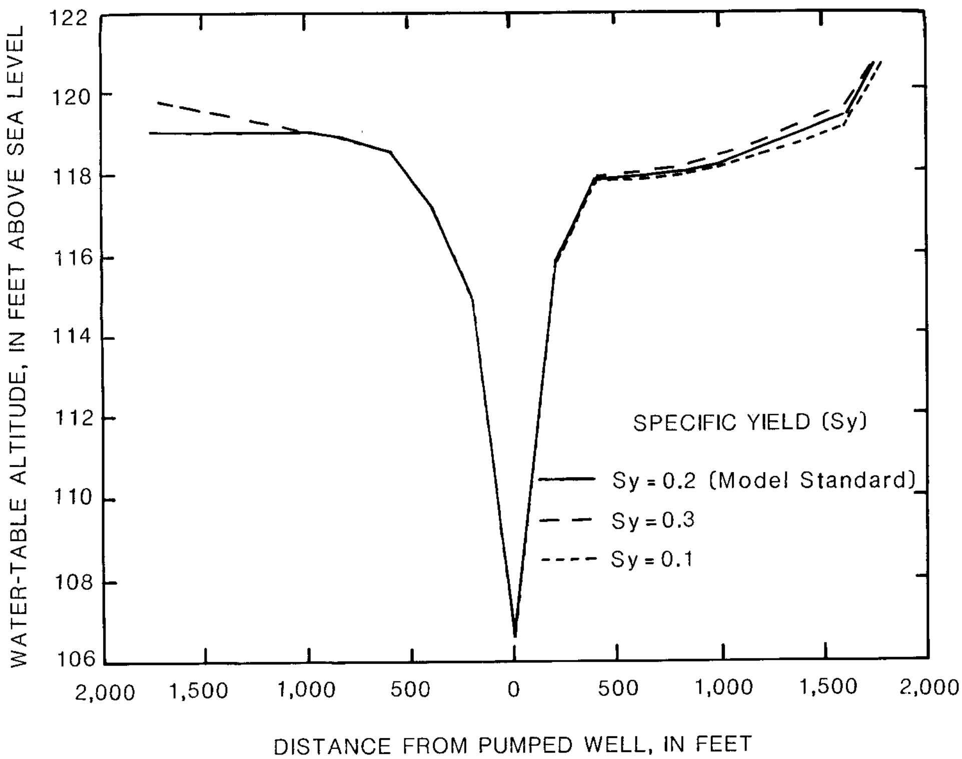


Figure 22.--Effects of varying hydraulic conductivity and streambed conductance on results from the Kingston-Powwow River model.



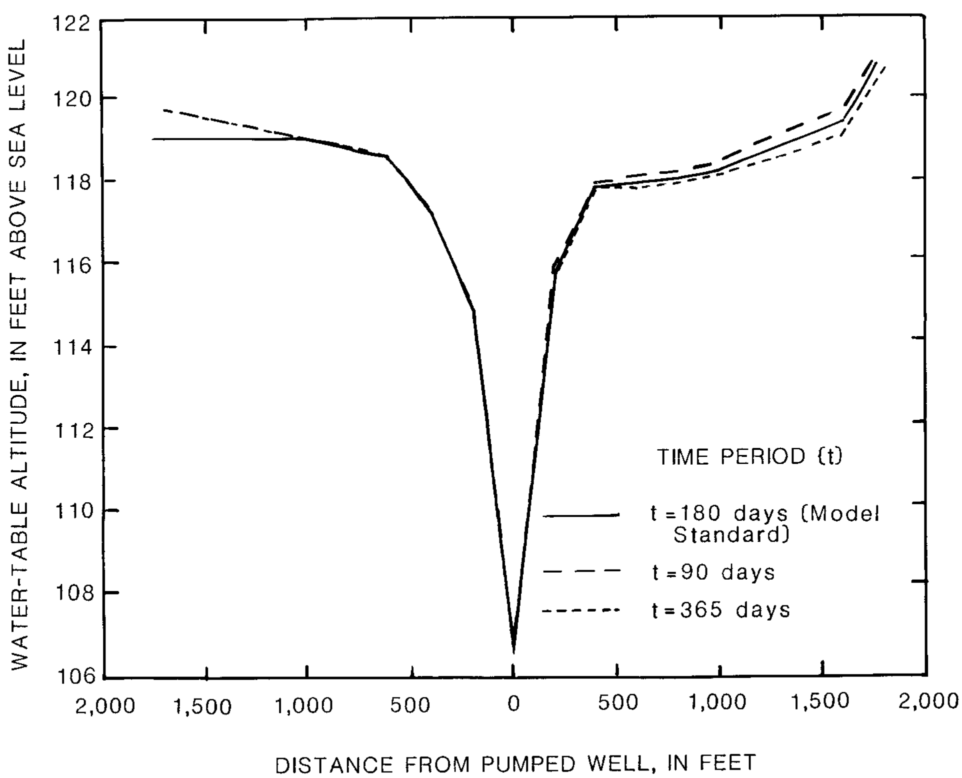


Figure 23.--Effects of varying specific yield and duration of pumping on results from the Kingston-Powwow River model.

for the comparison of results between the two aquifers.

Aquifer hydraulic-conductivity (K_a) values were multiplied by factors of 1 (model standard), 2, and 0.5 in three separate simulations. Results indicated that changes in hydraulic conductivity have a large effect on the ground-water flux to the river and ponds. An increase in hydraulic conductivity by a factor of 2 resulted in a slight reduction in the ground-water flow to the river and ponds and (or) a small increase in the induced recharge from these surface-water sources. This simulation had the greatest effect on reducing the drawdown at the pumping centers, a 48-percent reduction relative to the standard simulation.

Reducing the hydraulic conductivity by 0.5 resulted in drawdowns that exceeded the model constraints and dried up two of the eight wells. This model, therefore, appears to have been sensitive to reductions in hydraulic conductivity, as was the Windham-Cobbetts Pond aquifer model. In the Kingston-Powwow River aquifer, a smaller proportion of the recharge to wells came from aquifer storage than from the capture of ground-water flow before it reached the surface-water sources and (or) from induced infiltration. The siting of hypothetical production wells in thick saturated areas close to ponds and rivers, therefore, was necessary to achieve maximum yields.

River and pond-bottom conductance (K_b) values were multiplied by factors of 1 (model standard), 10, and 0.1 in three separate simulations. Increasing the bottom conductance by a factor of 1 and 10 had only a small effect. Simulated heads rose less than 1 ft, and the ground-water flux across the river and pond bottoms changed only slightly. The insensitivity of the model indicated that use of the standard conductance causes the leaky boundary to be, effectively, a constant-head boundary that poses no limit to the amount of surface water available for induced recharge to the wells.

Much greater changes in model results occurred when the bottom conductance was decreased by a factor of 10. Heads within 2,000 ft of the wells decreased by an average of 2 ft and, a greater proportion of water was derived from aquifer storage. These results contrast sharply with findings from the Windham-Cobbetts Pond model, for which bottom conductance had no affect on computed head values. The results underscore the importance of accurately determining bottom-conductance values for aquifer systems where induced infiltration is the primary source of water.

Specific yield (S_y) was set equal to 0.2 (model standard), 0.3, and 0.1 in three separate simulations. The change in specific yield had only a small effect on computed heads and ground-water discharge in the model. Specific yield equal to 0.3 resulted in a greater proportion of water being derived from aquifer storage and head values that were somewhat greater than for corresponding cells in the standard simulation. By decreasing specific yield to 0.1, heads decreased by less than 0.5 ft at well locations because less water was available from aquifer storage and a greater proportion was derived from capture of ground-water flow and (or) induced recharge from surface water.

Duration of pumping (t) values of 180 days (model standard), 90 days, and 365 days were used in three separate simulations. Duration of pumping had little effect on model results. Drawdowns simulated at well locations were slightly less after 90 days of pumping than after 180 days, and a greater percentage of the total withdrawal was derived from aquifer storage. Increasing the duration of pumping to 365 days had less effect on drawdowns at pumping centers; the average increase in drawdown was only 0.2 ft for the eight wells in the simulation. This minimal drawdown effect contrasts with the results from the Windham-Cobbetts Pond model, which was more sensitive to pumping duration because of the relative lack of hydrologic interconnection between ponds and aquifer.

Application of analytical method

The potential yield was also evaluated by use of the analytical method discussed previously. The percentage of drainage basin underlain by coarse-grained stratified drift is 32 percent and represents an area of 9.4 mi^2. The area of till-covered bedrock in the basin upgradient from the aquifer is 19.8 mi^2. By use of this information and equation 2, the potential yield for the Kingston-Powwow River aquifer is estimated to be 6.5 ft^3/s or 4.2 Mgal/d. This value compares favorably with the potential-yield estimate of 4.0 Mgal/d determined from the numerical model. These estimates indicate that this large aquifer is capable of supplying about 4.0 Mgal/d under long-term pumping.

Well-capture area

Simulated drawdowns after 180 days of pumping were superimposed on the initial water table to estimate the water-table configuration under long-term pumping (pl. 7D). The area of measurable drawdown extends to the external model boundaries and is similar to, but not identical with, the contributing area. The size of the contributing area is estimated to be 4.9 mi^2 and represents 52 percent of the active model area. Clearly, this exceeds the area determined by the 400-ft protective radius (0.144 mi^2 for eight wells) as required by New Hampshire regulations.

LOCATIONS AND DESCRIPTIONS OF SELECTED STRATIFIED-DRIFT AQUIFERS

Stratified-drift aquifers at Derry-Island Pond, Windham-Cobbetts Pond, Kingston-Powwow River, North Hampton-Knowles Pond and central Greenland (pls. 1-3), are considered to be favorable stratified-drift aquifers in the study area for developing new ground-water supplies. These favorable ground-water areas meet the following criteria: (1) the aquifer is generally composed of well-sorted sand and gravel, (2) the aquifer has a saturated thickness of 40 ft or more, and (3) the aquifer is either undeveloped or the full potential yield of the ground-water resource has not been attained by present pumpage. Many other areas underlain by well-sorted stratified drift may also yield large quantities of ground water; however, they either will probably not sustain yields of 0.5 Mgal/d or more or they are currently developed to near their maximum potential yields.

Preliminary estimates of the quantity of water potentially available in ground-water areas is considered to be the sum of (1) the amount of precipitation that falls directly on the aquifer and becomes ground water, (2) water from adjacent areas of till and bedrock that enters the sand and gravel aquifer, and (3) streamflow across the aquifer that might be induced to infiltrate the sand and gravel. Methods for evaluating each of these recharge sources have been discussed previously in the section on "Recharge."

Derry-Island Pond Aquifer

A delta consisting of well-sorted sand and gravel forms a flat-topped triangular plain at the confluence of Taylor Brook and Island Pond in eastern Derry (pl. 1). During deglaciation, meltwater streams flowed in the narrow linear valley of Taylor Brook and carried stratified sediments from the glacier and uplands into a former glacial lake now occupied by Island Pond. These proglacial sediments range from well-sorted sand and gravel deposits near the mouth of Taylor Brook to varved clay deposited some distance from the delta front in Island Pond. The stratified-drift aquifer is approximately 1.1 mi^2 in area and ranges from 10 to 90 ft in thickness. The aquifer is thickest and transmissivity is greatest along the west shore of the pond (pl. 4). In addition, permeable glacial materials and recent beach deposits along the west shore provide a strong hydrologic connection between pond and aquifer, making this section of the aquifer the most favorable for ground-water development.

The aquifer area includes many year-round residences and seasonal homes. Centralized water or sewer systems have not been built within the area. Each home maintains a private, on-site water well and a septic system. The collective effect of these homes and their septic systems on ground-water quality has not been evaluated and is a central issue in determining whether this aquifer can be developed for public water supply.

The aquifer configuration and sediments along the aquifer-pond boundary were investigated by use of seismic-reflection methods. One seismic-reflection profile (fig. 14 and pl. 2) shows an irregular bedrock surface for a north-to-south traverse across the outlet of Taylor Brook near the toe of the delta. Bedrock depths range from 12 to 125 ft below the pond surface. The transition between glacial lakebed materials and coarse-grained stratified-drift materials is also apparent from the profile. Fine-grained lakebed materials are laminar bedded and have a layer-cake appearance in contrast with the stratified-drift materials deposited along the flanks of bedrock knobs that have a chaotic pattern with less laminar definition.

A USGS well, DFW-424, was drilled in the stratified drift at the outlet of Taylor Brook after an inspection of the profile showed thick deposits of relatively coarse-grained material and a bedrock depth of about 80 ft below pond surface. The well log for DFW-424 confirms the seismic-reflection results in regard to the texture of materials and bedrock depth. An upper zone of coarse sand of glaciofluvial origin changes to a lower zone of fine and very fine sand of glacial-lake origin generally below 40 ft at the Taylor Brook outlet.

The quantity of ground water potentially available from this aquifer is a function of the recharge from precipitation and the amount of surface water from Island Pond that could be induced to infiltrate the aquifer. The average recharge from precipitation on the 1.1-mi^2 stratified-drift aquifer is estimated to be 1.2 Mgal/d. Indirect recharge from

2.9 mi^2 of adjacent till and bedrock is estimated to be 2.6 Mgal/d.

The amount of water available as induced recharge from Island Pond would largely be a function of the distance between a production well and the pond-aquifer boundary. By placing a hypothetical production well in the area between the 40- to 80-ft saturated-thickness contours near the pond, most of the water captured would be expected to come from induced infiltration and not from depletion of aquifer storage. Because well location plays such an important role in the amount of water captured by induced recharge, a more detailed analysis than that presented in this section would be needed to make estimates of potential yield for specific well-field arrangements.

Another potential source of induced recharge is Taylor Brook, which flows across the delta and discharges into Island Pond. The amount of water potentially available from this source during dry conditions can be estimated by solving equation 4 for the $Q_{7,10}$. The $Q_{7,10}$ for the Taylor Brook basin is estimated to be 0.41 ft^3/s on the basis of a drainage area of 5.3 mi^2, 10 percent of which is covered by stratified drift and 90 percent of which is covered by till. By comparison, low-flow discharge was 0.48 ft^3/s on August 26, 1987, near the outlet of Taylor Brook (table 3). The average flow duration on this date for three New England coastal rivers (Oyster River of southeastern New Hampshire, Parker River of northeastern Massachusetts, and Royal River of south-eastern Maine) was 97.5 percent. Flow at this duration is only slightly more than the $Q_{7,10}$ for streams in New England. If similar relations apply to Taylor Brook and the low flow (0.48 ft^3/s) is nearly equal to the $Q_{7,10}$ for this brook, an additional 0.3 Mgal/d of water from induced infiltration would be available for withdrawal from wells.

The amount of water available from precipitation (1.1 Mgal/d), induced infiltration (0.3 Mgal/d), and ground-water discharge from upland till and bedrock (2.6 Mgal/d) equals 4 Mgal/d. This estimate is based on the assumption that all of the recharge from precipitation could be captured by wells and that recharge from the pond is not considered.

Windham-Cobbetts Pond Aquifer

A valley train of well-sorted stratified drift material extends from the western shore of Cobbetts Pond in Windham southerly through a narrow, linear valley into the town of Pelham and then to Massachusetts. Sand and gravel that fills the valley was deposited by meltwater streams discharging from a glacier upvalley near Cobbetts Pond. This valley train originates from a head of outwash that was formed by deposition in contact with ice and appears as a distinct ridge of pebble-cobble gravel along the western rim of Cobbetts Pond.

Results from a seismic-reflection traverse along the western shore of the pond show a relatively thin zone of coarse boulder gravel that fills a narrow bedrock channel (fig. 13). The southern wall of the channel rises steeply and extends to just below the pond surface. The other buried channel wall, not shown, truncates at the boundary between till and stratified drift 500 ft to the north. The area of aquifer between these no-flow boundaries is the primary conduit for the water flow between the pond and aquifer.

Golden Brook is a small regulated stream that is the major drain for the valley. Sluice gates at the outlet of Cobbetts Pond are used to maintain the pond level for recreation, consequently, the brook often runs dry during periods of little or no precipitation, and the flow in the brook cannot be relied on as a source for induced infiltration.

Aquifer thickness is greatest near the channel of Golden Brook, where the thickness of the saturated zone averages 30 to 50 ft and is as much as 60 ft. The aquifer thins to the south and southeast of Moeckel Road, where 10 to 20 ft of saturated thickness is common.

The aquifer area primarily includes suburban residential and commercial land use and is thickly settled in most places. Most homes have an on-site well and a septic system; however, the Southern New Hampshire Water Company supplies water at an average of 75,000 gal/d to communities within the aquifer area by pumping from bedrock wells.

The potential yield of this pond-aquifer system was evaluated by applying the superposition method to a finite-difference model as described in a previous section of this report. Results from the model indicate that a potential yield of 0.6 Mgal/d is available from the pond-aquifer system on the basis of a simulation of five production wells pumped for 180 days during a period of no recharge.

Kingston-Powwow River Aquifer

A large outwash plain consisting of glaciofluvial stratified drift extends across the towns of Kingston, East Kingston, and Newton (fig. 2). This, the largest stratified-drift aquifer in the study area (10.5 mi^2), was built from a network of braided melt-water streams carrying sand and gravel downvalley from a melting glacier. The melting of remnant blocks of ice in the outwash plain left behind numerous kettles; the largest are now occupied by Great, Powwow, and Country Ponds. Connecting the ponds is the Powwow River, which follows the glacial drainage and outflows to Powwow Pond.

During deglaciation, sea level rose and the ocean inundated about one-third of the aquifer area, leaving behind marine silts and clays in a southeast-trending, broad, shallow basin. The boundary line, marked by open circles on plate 2, is the inferred western limit of the marine inundation for this aquifer and is based on well data and surficial geology of the basin. East of this marker, the aquifer consists of a thin layer of outwash and beach deposits (less than 20 ft thick) over relatively impermeable marine silts and clays. West of the boundary, the aquifer consists primarily of glaciofluvial stratified drift overlying a thin discontinuous mantle of till on bedrock.

One of two known productive zones of the aquifer is in a buried valley of thick glaciofluvial material along the axis of the Powwow River immediately south of Great Pond (pl. 2). Saturated thickness exceeds 100 ft in places and averages about 60 ft throughout the 1.5-mi length of the valley. Great Pond, the Powwow River, and Country Pond all connect to the buried valley and could provide large amounts of recharge to this lightly populated aquifer section.

Another productive zone of the aquifer is between Greenwood and Great Ponds. The topography of the area is that of a knob-and-kettle landscape characteristic of collapsed outwash formed from the melting of remnant ice blocks. Much of the coarse stratified drift was deposited against glacial ice and averages from 40 to 60 ft in saturated thickness. State ownership of land along the northeastern shore of Great Pond has kept this aquifer section relatively undeveloped.

Water use for the entire aquifer is from on-site wells that supply individual homes, businesses, and schools. Potential yield was estimated for this aquifer by use of the numerical model mentioned in the previous section. Results from eight wells pumping continuously for a 180-day period of no recharge indicate that this aquifer is capable of yielding about 4 Mgal/d.

North Hampton-Knowles Pond Aquifer

The aquifer in North Hampton is an elongate low-relief kame delta consisting of coarse ice-contact stratified drift (pl. 3). The site is about 0.7 mi^2 in area and is primarily bordered by impermeable fine-grained marine deposits that separate the aquifer from nearby sources of recharge, specifically the Winnicut River and the extensive Cornelius swamp. The headwaters of Cornelius Brook and several small ponds are within the aquifer, but, because they are underlain by marine sediments, limited surface-water recharge is available to the aquifer.

Water levels in USGS observation well NSW-69 and seismic-refraction results for a 1,500-ft survey near Knowles Pond indicate that saturated thickness is 40 to 60 ft along the Cornelius Brook channel. Saturated materials composed of permeable sand, gravel, and cobbles form a zone of high transmissivity. The area is moderately developed with residences and is presently undeveloped as a public water supply. The yield for the 0.7-mi^2 aquifer is estimated to be 0.6 Mgal/d; however, this value could be less if the North Hampton-Knowles Pond aquifer is hydraulically connected with the aquifer to the north of Route 95, where two gravel-packed wells currently withdraw ground water at a combined rate of 0.8 Mgal/d. Potential yield for the combined aquifers is estimated to be 1.3 Mgal/d on the basis of increased land area of stratified drift. Ground-water withdrawal of 0.8 Mgal/d leaves 0.5 Mgal/d available for additional ground-water development. These preliminary estimates indicate that additional pumping from this aquifer is possible, although more detailed work is needed to determine the effects of current pumpage on water levels and the water balance in the aquifer.

Aquifers that lack contact with streams, such as at Knowles Pond, could be used as seasonal storage reservoirs. The aquifer could be pumped heavily and water levels drawn down in the summer with little effect on streamflow. For the remainder of the year, when water supplies could be obtained from sources sustained by induced infiltration, the aquifer would remain idle and recover from the heavy use. This concept would be of practical significance only in the context of a regional water system that interconnected several surface and (or) ground-water sources (Randall and others, 1988b).

Greenland Aquifer

The aquifer in central Greenland is a large kame delta completely within marine deposits adjacent to Great Bay, a saltwater body (pl. 3). The site is 2.5 mi^2 in area and consists of unconfined and confined aquifers separated by discontinuous layers of marine silt and clay. The largest and most productive part of this aquifer is unconfined.

A municipal well, Greenland number 5 (GTW1), is the only large-production well currently tapping the unconfined aquifer. This well is 1,400 ft west of Interstate 95 in one of two productive zones of the aquifer and has a maximum rated yield of 0.7 Mgal/d. Observations from the drilling of a 2.5-in. test well and results from a 12-day aquifer test on an 8-in. well at this well site indicate that the transmissivity for the aquifer section is 4,100 ft^2/d and that saturated thickness averages 40 ft. Drawdowns were noted to continue at a predictable rate on the 12th and last day of the test as the well was pumped at 524 gal/min. These drawdowns indicate that stabilization had not occurred and that ground water was continually being removed from storage with little or no contribution from surface-water recharge. The aquifer is partially protected from saltwater intrusion by a ridge of bedrock that crops out near the mouth of the Winnicut River and by the surrounding impermeable marine deposits. This configuration limits recharge to the aquifer by induced infiltration.

Another small but productive area of the aquifer is immediately east of Interstate 95 near Breakfast Hill Road. Aquifer thickness averages 40 ft, and the materials consist of coarse ice-contact gravel interfingering with marine silt and clay. A 10-day pump test was done at well GTW-49 by the Portsmouth Water Department to determine the feasibility of the site for a municipal-well installation. Results indicate a transmissivity of 4,500 ft^2/d. The water was principally derived from aquifer storage with no recharge by induced infiltration. Although the aquifer has the potential to supply significant amounts of water, the site has not been developed because of its proximity to the Coakley landfill hazardous-waste site, where the extent of contaminant migration is uncertain.

Potential yield for the 2.5-mi^2 aquifer is estimated to be 2.3 Mgal/d. Subtracting the 0.7 Mgal/d withdrawn from the Greenland number 5 well leaves a total estimated aquifer yield of 1.6 Mgal/d. Because of the uncertainty in the flow and the potential for migration of contaminants from the Coakley landfill to the Breakfast Hill Road area, the aquifer section most promising for further consideration is near the State-owned gravel pit west of Interstate 95.

GROUND-WATER QUALITY

Water in the stratified-drift aquifers of the lower Merrimack River and coastal river basins is generally suitable for drinking and other domestic purposes. Concentrations of dissolved constituents are low, and turbidity and color are generally absent. Ground-water-quality degradation has occurred near at least 16 sites in the 327 mi^2 study area (fig. 24 and pls. 1-3). Six of these sites are included on the National Priority List (NPL) of hazardous-waste sites by the U.S. Environmental Protection Agency (1986) and will be evaluated under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980. Ten hazardous-waste sites require monitoring of ground-water quality under the Federal Resource Conservation and Recovery Act (RCRA) of 1976. Contaminants in the shallow stratified-drift aquifers at these sites limit the availability of potable water for municipal and domestic uses.

Ground-water samples were collected from 24 USGS observation wells and 6 municipal wells, in April and August 1987, to characterize background water quality of the stratified-drift aquifers. These samples were collected at wells where the water quality is most likely to reflect natural conditions. The only exception is municipal well PXW-2, which serves Pease Air Force Base (AFB) in the towns of Newington and Portsmouth. The water from this well is known to be contaminated with trichloroethylene (TCE) (Bradley, 1982). Because of the well's high yield, Pease AFB decided to treat the water and continue to use it as a drinking-water supply.

Methods described by Fishman and Friedman (1989) were used in the collection and the analysis of ground-water samples. All samples were analyzed by the USGS National Water Quality Laboratory in Arvada, Colo. Statistical results of the chemical analysis of the ground-water samples are summarized in table 7 and presented for comparison with the U.S. Environmental Protection Agency (1989) and New Hampshire Water Supply Engineering Bureau (1990) drinking-water regulations.

Dissolved constituents commonly found in ground water from the stratified-drift aquifers are calcium, magnesium, sodium, bicarbonate, sulfate, chloride, and silica. They are derived from many sources: calcium, bicarbonate, and silica are derived primarily from soil and rock weathering; sulfate is contributed by precipitation; organic material is derived from sediments; and sodium and chloride come from soil and rock weathering and precipitation. Elevated concentrations of sodium and chloride also commonly result from salt used to deice roads.

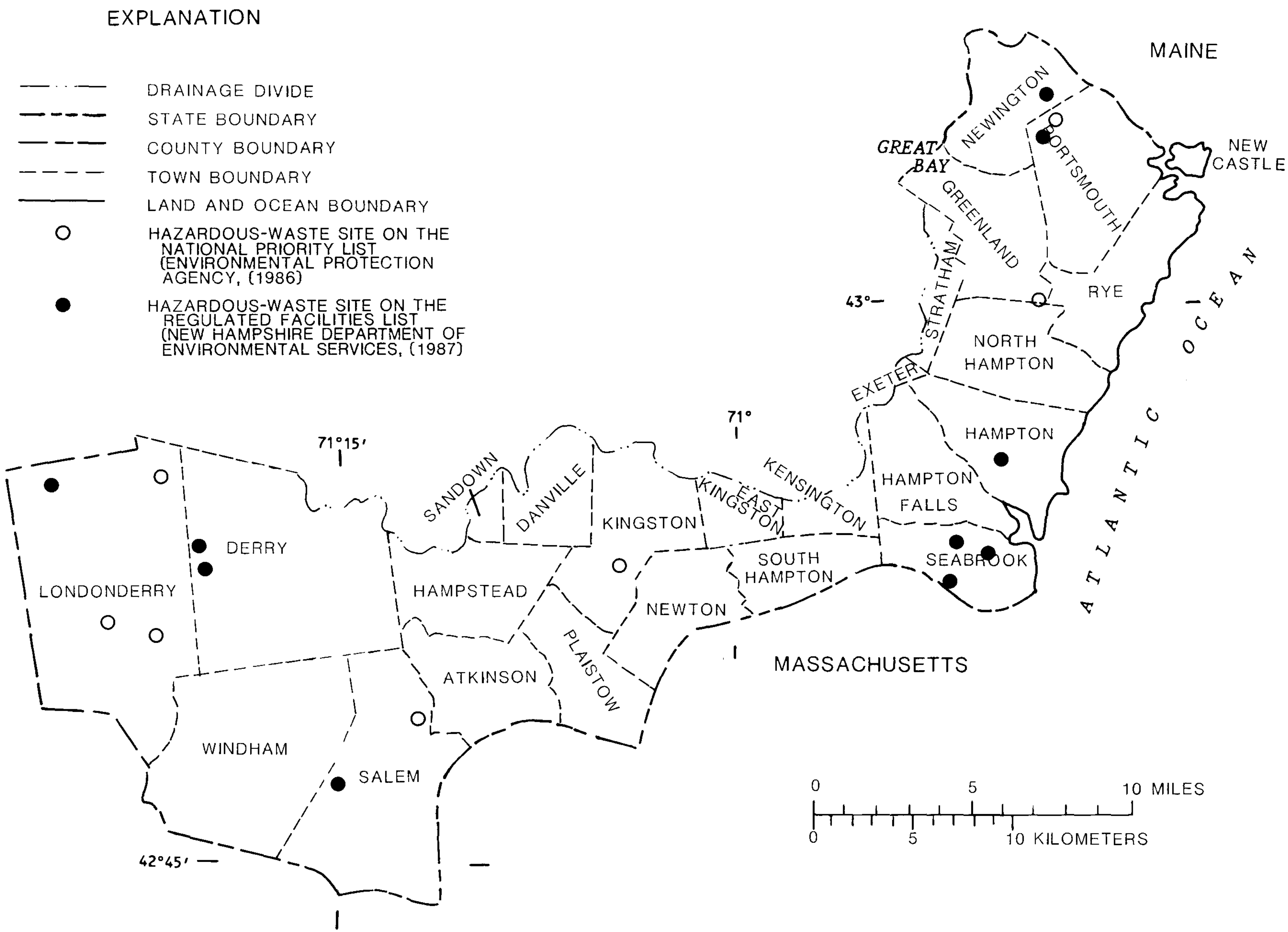


Figure 24.--Locations of hazardous-waste sites.

Physical and Chemical Properties

Graphical representations of the chemical analyses are presented on plates 1-3 and show variations in the chemistry of aquifer water. Concentrations of dissolved constituents (expressed in milliequivalents per liter) are plotted at the appropriate well site, and the points are connected to form irregular polygons called Stiff diagrams (Stiff, 1951). Four cations, sodium (Na), potassium (K), magnesium (Mg), and calcium (Ca), are plotted along the axis to the left of the zero point. Five anions, chloride (Cl), fluoride (F), sulfate (SO_4), bicarbonate (HCO_3), and carbonate (CO_3), are plotted along the axis to the right of the zero point. The shape of the closed figure characterizes the water composition. Dissolved-solids concentration, as indicated by the width of the figures, tends to increase from the west to the east. This variation may be caused by the deposition of salt aerosols from ocean storms, the presence of saline connate residues in the marine silts and clays of the seacoast region, and (or) greater contact time for mineral-water reactions in the more impermeable marine deposits that comprise most of the seacoast aquifers.

Total Dissolved Solids

Total dissolved solids in water includes all ionized and nonionized dissolved solids in solution, but excludes colloids and dissolved gases (Davis and DeWiest, 1966). Concentration of total dissolved solids in the samples ranged from 22 mg/L (milligrams per liter) to 500 mg/L, and the mean was 149.3 mg/L. The concentration in one water sample (from well PXW-5) equalled the recommended limit of 500 mg/L for total dissolved solids established by the New Hampshire Water Supply Engineering Bureau (1990) for public drinking water. Water from this well also had the highest specific conductance. If total dissolved solids are unknown, specific conductance can be used to estimate the value. One equation used is

$$KA = S, \qquad (5)$$

where K is specific conductance in μS/cm (microsiemens per centimeter at 25 degrees Celsius);

A is a constant (for natural waters, A ranges from 0.55 to 0.75) (Hem, 1985); and

S is total dissolved solids, in milligrams per liter.

Specific Conductance

Specific conductance, a measure of the ability of water to conduct electrical current, ranged from 24 to 860 μS/cm, and the mean was 252 μS/cm. For all samples, the median (215 μS/cm) and maximum (860 μS/cm) exceeded the median (132 μS/cm) and maximum (469 μS/cm) specific conductance of waters from large municipal-supply wells tapping stratified-drift aquifers Statewide (Morrissey and Regan, 1987).

Three wells yielding water with elevated total dissolved solids and specific conductance are close to roads or airport runways that have been salted. Well NIW-35 is near a Pease Air Force Base runway, well PXW-5 is next to New Hampshire State Highway 101 in Portsmouth, and well SAW-49 is near Town Farm Road in Salem. The data from this study indicate that past or present road-salting practices continue to influence ground-water chemistry in shallow stratified-drift aquifers.

pH

The pH of water is a measure of the water's hydrogen-ion activity. The pH scale ranges from 0 to 14; each unit increase in the scale represents a tenfold decrease in hydrogen-ion activity. Water having a pH of 7.0 is neutral, less than 7.0 is acidic, and greater than 7.0 is alkaline. At a pH below 6.5, some metals in metallic piping can dissolve and a metallic taste can be imparted to the water (U.S. Environmental Protection Agency, 1989). The pH of 30 samples measured in the field ranged from 5.80 to 8.48 and the median pH was a slightly acidic 6.6. In addition, there is a definite trend of increasing pH from the western section towards the eastern section of the study area. The most acidic ground-water samples (pH from 5.80 to 5.86) were from wells LRW-70, WPW-37, and WPW-38 in the towns of Londonderry and Windham. The most basic ground-water sample (pH 8.48) was from well NSW-69 in the seacoast town of North Hampton.

Alkalinity

Alkalinity is a measure of the capacity of a solution to resist a change in pH due to the addition of acid and is also a measure of the concentrations of carbonate ($CO_3^{=}$), bicarbonate (HCO_3^-), and hydroxide (OH^-) ions. The relatively low alkalinity of the ground water in the stratified-drift aquifers indicates little buffering capacity or ability to resist acidification. Alkalinity determined in the field ranged from 3 to 158, expressed as mg/L of $CaCO_3$ (calcium carbonate), and the mean was 51 mg/L. The sample with the highest alkalinity (158 mg/L) was obtained from well NSW-70. The highest alkalinities were determined in waters from wells in the eastern part of the study area. In general, the stratified-drift aquifers and bedrock do not contain significant carbonate minerals; consequently, water associated with them has a low alkalinity and low buffering capacity.

Calcium, Magnesium, and Hardness

Calcium and magnesium are common elements of alkaline-earth minerals. Calcium and magnesium are also the principal cations in most natural ground water (Hem, 1985). Concentrations of calcium ranged from 1.4 to 78 mg/L, and the mean was 22 mg/L. Concentrations of magnesium in the samples ranged from 0.4 to 18 mg/L, and the mean was 5.0 mg/L.

Hardness of water, expressed in mg/L as $CaCO_3$, is caused by divalent metallic cations dissolved in water. In fresh water these cations primarily are calcium and magnesium, but iron, strontium, and manganese may also contribute to hardness. Hardness ranged from soft (5 mg/L) to very hard (270 mg/L). (Table 6 describes hardness classification.)

Seventeen samples with a hardness of less than 60 mg/L were classified as soft water (table 6). Ten samples were moderately hard water from 72 to 120 mg/L and three wells contained hard water (from 130 to 180 mg/L). Water from wells NSW-70 and PXW-5 was very hard (concentrations of 220 mg/L and 270 mg/L). Water from these last two wells also had the highest concentrations of calcium and magnesium, the two principal components of hardness.

Sodium

Concentrations of sodium for all samples ranged from 1.7 to 88 mg/L, and the mean was 19 mg/L. The concentration of sodium (88 mg/L) in the water sample from well SAW-49 was the highest determined. All of the sodium concentrations were less than the secondary drinking-water standard (100 mg/L) established by the New Hampshire Water Supply Engineering Bureau (1990) for drinking water. At present, sodium concentrations pose a potential health problem for people who require sodium-restricted diets and who have wells near, or down-gradient from, heavily salted roads or salt-storage areas.

Chloride

Concentrations of chloride for all samples ranged from 2.2 to 200 mg/L, and the mean was 36.8 mg/L. All of the concentrations of chloride were below the secondary drinking-water standard of 250 mg/L (New Hampshire Water Supply Engineering Bureau, 1990).

Table 6.--*Classification of hardness of water*

[Modified from Durfor and Becker, 1964, p. 27]

Descriptive rating	Range of hardness, as $CaCO_3$ (milligrams per liter)
Soft	0 – 60
Moderately hard	61 – 120
Hard	121 – 180
Very hard	181 or greater

Sulfate

The sulfate (SO_4) ion is one of the major anions in natural waters. Sulfate is reduced to hydrogen sulfide (H_2S) gas under anaerobic conditions, and its odor can be detected at only a few tenths of a milligram per liter of H_2S. Presence of H_2S could be a problem in stratified-drift aquifers that are near, under, or overlain by peat bogs or swamps. Concentrations of sulfate for all the samples ranged from 3.5 to 65 mg/L, and the mean was 17 mg/L. None of the samples had concentrations that exceeded the New Hampshire Water Supply Engineering Bureau secondary drinking-water standard of 250 mg/L.

Iron and Manganese

High concentrations of iron and manganese were the most common water-quality problems found during this investigation. Iron concentrations above the New Hampshire Water Supply Engineering Bureau secondary drinking-water standard of 300 μg/L (micrograms per liter) (New Hampshire Water Supply Engineering Bureau, 1990) were measured in samples from seven wells--7,400 μg/L at KTW-42, 5,300 μg/L at KTW-78, 5,300 μg/L at DFW424, 5,000 μg/L at KTW-39, 3,600 μg/L at KTW-41, 2,400 μg/L at KTW-77, and 460 μg/L at SAW-50. Five of these seven samples came from wells in Kingston. Elevated concentrations of iron and manganese are not known to be harmful to humans, but they can stain clothing and plumbing fixtures and give water an objectionable taste and color. Two-thirds of all the samples had concentrations of manganese above the New Hampshire Water Supply Engineering Bureau secondary drinking-water standard of 50 μg/L. Concentrations of manganese ranged from less than 1 μg/L (HEW-7) to 1,100 μg/L, and the mean was 391 μg/L.

Trace Elements

Aluminum is the third most abundant element in the Earth's outer crust, but it rarely occurs in solution in natural water at concentrations greater than about a few tens of micrograms per liter (Hem, 1985, p. 73). The exceptions are waters that are highly acidic. Aluminum concentrations for all the samples ranged from less than 10 μg/L to 210 μg/L, and the mean was 28 μg/L. Aluminum concentrations that exceeded the New Hampshire Water Supply Engineering Bureau secondary drinking-water standard of 50 μg/L were determined in samples from four wells--210 μg/L at KTW-40, 190 μg/L at KTW-42, 160 μg/L at KTW-45, and 60 μg/L at DFW-424.

Arsenic in ground water can originate from geologic or anthropogenic sources. Geologic sources of arsenic include dissolution of minerals such as arsenopyrite. An example of an anthropogenic source is use of pesticides that contain arsenic, which can enter ground water through waste disposal or agricultural drainage. Because arsenic can be toxic to humans in trace amounts, the USEPA (1988) set a Maximum Contaminant Level[2] (MCL) of 50 μg/L. This level was not exceeded by any of the samples collected for this study. The highest arsenic concentration determined was 14 μg/L in a sample from well DFW-424. Although arsenic is not a major concern in these stratified-drift aquifers, about 10 to 15 percent of water from bedrock wells tested in New Hampshire exceeded the U.S. Environmental Protection Agency's MCL for arsenic (Morrissey and Regan, 1987).

Strontium is chemically similar to calcium, and replaces calcium or potassium in igneous-rock minerals in minor amounts. Natural concentration of strontium in water is usually limited by ion exchange with calcium-rich clays (Hem, 1985). Concentrations of strontium ranged from 20 μg/L to 350 μg/L, and the mean was 116 μg/L. At present, no Federal or New Hampshire drinking-water regulations or standards have been set for strontium.

2

MCL = Maximum Contaminant Level: Enforceable, health-based regulation that is to be set as close to the level at which no known or anticipated adverse effects on the health of a person occur as is feasible. The definition of feasible means the use of best technology, treatment techniques, and other means that the Administrator of the U.S. Environmental Protection Agency finds, after examination for efficacy under field conditions and not solely under laboratory conditions, are generally available (taking cost into consideration).

Organic Compounds

Water samples from selected USGS observation wells drilled during this investigation were analyzed for 36 priority volatile organic compounds summarized in table 7. The five wells not sampled for organic compounds--HEW-7, NSW-70, PXW-5, RYW-38, and SGW-1--are municipal wells that are routinely sampled by the New Hampshire Water Supply and Pollution Control Division. The only municipal well that was sampled for volatile organic compounds was PXW-2 (also known as the Haven Supply well), which serves Pease Air Force Base.

Volatile organic compounds (VOC) were detected at trace concentrations in water from four wells and at low concentrations in a fifth well. Water from well SAW-50, in Salem, contained 0.2 μg/L of tetrachloroethylene; water from KFW-17, in Kensington, contained 1.3 μg/L of 1,1,1-dichloroethylene; water from KTW-42, in Kingston, contained 0.2 μg/L of trichloroethylene; and water from KTW-46, also in Kingston, contained 0.3 μg/L of toluene. The concentrations are all close to the detection limits of the analytical procedures used, and, because only one volatile organic compound was found in such small amounts at each of these wells, contamination is unlikely. If ground water is contaminated, a number of constituents will commonly be observed in an analysis as, for example, PXW-2 contained three contaminants--0.7 μg/L chloroform, 2.4 μg/L 1,2-transdichloroethene, and 5.7 μg/L trichloroethylene. Trichloroethylene is the only constituent whose concentration in water from PXW-2 exceeds the New Hampshire Water Supply Engineering Bureau drinking-water standards for volatile organic compounds.

Contamination Sources

Contamination of ground water from human activities can come from many sources. Activities that may degrade the water quality of ground water include landfill disposal of household and industrial wastes; storage and spreading of road deicing salt; agricultural practices, which include spreading of commercial fertilizers and spraying of pesticides; spreading or landfill disposal of sludge from municipal sewage systems; or leakage from fuel, septic (especially in densely populated areas), and chemical-storage tanks. Overpumping of wells can induce saltwater intrusion in coastal areas by increasing the hydraulic gradient between the saltwater and freshwater interface. Evidence is increasing that "acid rain" can lower the pH in ground water, especially in New England, where soils and rocks have little buffering effect. With a decrease in pH, concentrations of dissolved trace metals such as aluminum could increase in ground water.

Extensive ground-water contamination has occurred at seven uncontrolled hazardous-waste sites. Six sites--the Auburn Road Landfill site in Londonderry, the Tinkham Garage/Woodland Village Condominiums site in Londonderry, the Ottati and Goss/Great Lakes Container Corporation site in Kingston, the Coakley Landfill site in North Hampton, the Holton Circle site in Londonderry, and the Pease Air Force Base of Newington-Portsmouth (pls. 1-3)--are on the U.S. Environmental Protection Agency's National Priority List of hazardous-waste sites (U.S. Environmental Protection Agency, 1986) (fig. 24). In addition, the Duston Road site of Salem is classified by the State of New Hampshire as a high priority hazardous-waste site warranting remedial cleanup activities (New Hampshire Water Supply and Pollution Control, W.A. Healy, written commun., April 1985).

The Auburn Road Landfill site is in the northeastern corner of Londonderry near the towns of Auburn (to the north) and Derry (to the east). A study of this site by a private consultant identified about 1,000 buried drums containing VOCs (NUS Corporation, 1986). Another private consultant, under contract to the USEPA, is conducting a final Remedial Investigation/Feasibility Study (RI/FS) that will identify the nature and extent of site contamination and the remedial action needed to clean up the site. Currently, the only remedial action taken has been the removal of the buried drums, which was scheduled to be completed by 1989.

The Tinkham Garage/Woodland Village Condominiums site is in the town of Londonderry near the intersection of Interstate 93 and State Route 102. The Tinkham Garage was first used as an area for storage, maintenance, and cleaning of tanker trucks. In 1982, contaminants were detected in the soil behind the garage and the condominium complex. Further tests detected contaminants in septic tanks and ground water from nearby bedrock wells. A draft RI/FS was prepared that characterized ground-water flow in the bedrock aquifer and identified the extent of the plume of contamination (NUS Corporation, 1985). The major volatile organic compounds detected in the ground water were 1,2-dichloroethane and trichloroethylene (NUS Corporation, 1985). The New Hampshire Water Supply and Pollution Control Division authorized the installation of a municipal drinking-water supply for the residences

Table 7.--*Summary of results of water-quality analyses*

[A "less than" symbol (<) precedes a value if a concentration is less than detection limit (reporting limit) indicated for that analysis. °C, degrees Celsius; μS/cm, microsiemens per centimeter; mg/L, milligrams per liter, μg/L, micrograms per liter; --, no data]

Property or constituent	MCL[1]	SMCL[2]	NHMCL[4]	NHSMCL[5]	Number of samples	Mean[6]	Median	Standard deviation[6]	Minimum	Maximum
Specific conductance, field (μS/cm at 25 °C)	--	--	--	--	30	252.1	215	199.4	24	860
Temperature (°C)	--	--	--	--	29	10.4	10	2.0	8	16.5
Oxygen dissolved, (mg/L as O_2)	--	--	--	--	17	4.6	4.3	3.5	0	11.3
pH, field (standard units)	--	6.5 - 8.5	--	6.5 - 8.5	30	--	6.66	--	5.80	8.48
Color (platinum-cobalt units)	--	15	--	15	30	10.9	2	26.1	1	110
Alkalinity, field (mg/L as $CaCO_3$)	--	--	--	--	30	51.0	36.0	44.8	3	158
Hardness, total (mg/L as $CaCO_3$)	--	--	--	--	30	74.5	54.5	64.6	5	270
Solids, sum of constituents, dissolved (mg/L)	--	500	--	500	30	149.3	122	107.8	22	500
Calcium, dissolved (mg/L as Ca)	--	--	--	--	30	21.48	17.0	18.36	1.4	78
Magnesium, dissolved (mg/L as Mg)	--	--	--	--	30	5.02	3.55	4.59	.4	18
Chloride, dissolved (mg/L as Cl)	--	250	--	250	30	36.8	19.5	46.67	2.2	200
Sodium, dissolved (mg/L as Na)	--	20	250	100 - 250	30	19.38	10	22.73	1.7	88
Nitrogen, ammonia, dissolved (mg/L as N)	--	--	--	--	30	.019	.004	.054	<.01	.26
Potassium, dissolved (mg/L as K)	--	--	--	--	30	3.05	2.65	1.57	.3	7.5
Sulfate, dissolved (mg/L as SO_4)	--	250	--	250	30	16.52	14	12.75	3.5	65
Fluoride, dissolved (mg/L as F)	4	2	4	2	30	.10	.1	.092	<.1	.5
Carbon, organic, dissolved (mg/L as C)	--	--	--	--	30	1.71	1.1	1.55	.7	8.3
Silica, dissolved (mg/L as SiO_2)	--	--	--	--	30	14.76	13.5	5.08	7.3	28
Arsenic, dissolved (μg/L as As)	50	--	50	--	29	1.73	.75	2.77	<1	14
Barium, dissolved (μg/L as Ba)	1,000	--	5,000	--	23	21.48	23	12.09	4	53

Table 7.--*Summary of results of water-quality analyses*--Continued

Property or constituent	MCL[1]	SMCL[2]	NHMCL[4]	NHSMCL[5]	Number of samples	Mean[6]	Median	Standard deviation[6]	Minimum	Maximum
Beryllium, dissolved (μg/L as Be)	--	--	--	--	30	--	--	--	< 10	--
Boron, dissolved (μg/L as B)	--	--	--	--	30	13.65	10	10.43	< 10	50
Cadmium, dissolved (μg/L as Cd)	10	5	5	--	30	--	--	--	< 1	4
Chromium, dissolved (μg/L as Cr)	[3]50	--	100	--	30	--	--	--	< 10	20
Cobalt, dissolved (μg/L as Co)	--	--	--	--	30	1.77	1	2.1	< 1	9
Copper, dissolved (μg/L as Cu)	--	1,000	--	1,000	30	2.07	1	2.11	< 1	10
Iron, dissolved (μg/L as Fe)	--	300	--	300	26	1,183.0	84.5	2,179.0	< 3	7,400
Lead, dissolved (μg/L as Pb)	50	--	50	20	30	--	--	--	< 5	--
Manganese, dissolved (μg/L as Mn)	--	50	--	50	28	391.1	235	409.4	< 1	1,100
Molybdenum, dissolved (μg/L as Mo)	--	--	--	--	30	.63	.3	1.68	< 1	8
Mercury, dissolved (μg/L as Hg)	2	--	2	--	30	--	--	--	< .1	--
Nickel, dissolved (μg/L as Ni)	--	--	--	--	30	3.16	2	3.19	< 1	13
Silver, dissolved (μg/L as Ag)	50	--	50	90	30	--	--	--	< 1	1
Strontium, dissolved (μg/L as Sr)	--	--	--	--	30	115.6	90.5	86.27	20	350
Zinc, dissolved (μg/L as Zn)	--	5,000	--	5,000	23	4.61	4	3.38	< 3	13
Antimony, dissolved (μg/L as Sb)	--	--	--	--	30	--	--	--	< 1	2
Aluminum, dissolved (μg/L as Al)	--	50	--	50	30	27.8	5.92	56.49	< 10	210
Lithium, dissolved (μg/L as Li)	--	--	--	--	23	4.92	3.59	3.96	< 4	16
Selenium, dissolved (μg/L as Se)	10	--	50	--	30	.66	.59	.855	< 1	4
Dichlorobromomethane, total (μg/L)	--	--	--	--	25	--	--	--	< .2	--
Carbon tetrachloride, total (μg/L)	5	--	5	5	25	--	--	--	< .2	--
1,2-Dichloroethane, total (μg/L)	--	--	--	--	25	--	--	--	< .2	--

Table 7.--*Summary of results of water-quality analyses*--Continued

Property or constituent	MCL[1]	SMCL[2]	NHMCL[4]	NHSMCL[5]	Number of samples	Mean[6]	Median	Standard deviation[6]	Minimum	Maximum
Bromoform, total (µg/L)	--	--	--	--	25	--	--	--	<.2	--
Chlorodibromomethane, total (µg/L)	--	--	--	--	25	--	--	--	<.2	--
Chloroform, total (µg/L)	--	--	--	--	25	--	--	--	<.2	.7
Toluene (µg/L)	--	--	2,000	40	25	--	--	--	<.2	.3
Benzene, total (µg/L)	5	--	5	--	25	--	--	--	<.2	--
Chlorobenzene, total (µg/L)	--	--	--	--	25	--	--	--	<.2	--
Chloroethane, total (µg/L)	--	--	--	--	25	--	--	--	<.2	--
Ethylbenzene, total (µg/L)	--	--	700	30	25	--	--	--	<.2	--
Methylbromide, total (µg/L)	--	--	--	--	25	--	--	--	<.2	--
Methylchloride, total (µg/L)	--	--	--	--	25	--	--	--	<.2	--
Methylene chloride, total (µg/L)	--	--	--	--	25	--	--	--	<.2	--
Tetrachloroethylene, total (µg/L)	--	--	5	--	25	--	--	--	<.2	.2
Trichlorofluoromethane, total (µg/L)	--	--	--	--	25	--	--	--	<.2	--
1,1-Dichloroethane, total (µg/L)	--	--	--	--	25	--	--	--	<.2	--
1,1-Dichloroethylene, total (µg/L)	--	--	70	--	25	--	--	--	<.2	--
1,1,1-Trichloroethane, total (µg/L)	--	--	200	--	25	--	--	--	<.2	1.3
1,1,2-Trichloroethane, total (µg/L)	--	--	--	--	25	--	--	--	<.2	--
1,1,2,2 Tetrachloroethane, total (µg/L)	--	--	--	--	25	--	--	--	<.2	--
1,2-Dichlorobenzene, total (µg/L)	--	--	--	--	25	--	--	--	<.2	--
1,2-Dichloropropane, total (µg/L)	--	--	5	--	25	--	--	--	<.2	--
1,2-Transdichloroethene, total (µg/L)	--	--	--	--	25	--	--	--	<.2	2.4
1,3-Dichloropropene, total (µg/L)	--	--	--	--	25	--	--	--	<.2	--

Table 7.--*Summary of results of water-quality analyses*--Continued

Property or constituent	MCL[1]	SMCL[2]	NHMCL[4]	NHSMCL[5]	Number of samples	Mean[6]	Median	Standard deviation[6]	Minimum	Maximum
1,3-Dichlorobenzene, total (μg/L)	--	--	600	10	25	--	--	--	<.2	--
1,4-Dichlorobenzene, total (μg/L)	--	--	--	5	25	--	--	--	<.2	--
2-Chloroethylvinylether, total (μg/L)	--	--	--	--	25	--	--	--	<.2	--
Dichlorodifluoromethane, total (μg/L)	--	--	--	--	25	--	--	--	<.2	--
Trans-1,3-dichloropropene, total (μg/L)	--	--	--	--	25	--	--	--	<.2	--
Cis-1,3-dichloropropene, total (μg/L)	--	--	--	--	25	--	--	--	<.2	--
1,2-Dibromoethylene, total (μg/L)	--	--	--	--	25	--	--	--	<.2	--
Vinylchloride, total (μg/L)	--	--	2	--	25	--	--	--	<.2	--
Trichloroethylene, total (μg/L)	--	--	5	--	25	--	--	--	<.2	5.7
Styrene, total (μg/L)	5	--	5	10	25	--	--	--	<.2	--
Xylene, total (μg/L)	--	--	10,000	20	25	--	--	--	<.2	--

1 MCL (Maximum contaminant level) is an enforceable, health-based maximum level (concentration) for contaminants in public drinking-water supplies as defined in the national primary and secondary drinking-water regulations established by the U.S. Environmental Protection Agency [U.S. Environmental Protection Agency, 1989].

2 SMCL (Secondary maximum contaminant level) is a nonenforceable, aesthetically-based maximum level (concentration) for contaminants in public drinking-water supplies as defined in the national primary and secondary drinking-water regulations established by the U.S. Environmental Protection Agency [U.S. Environmental Protection Agency, 1989].

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

4 New Hampshire Maximum Contaminant Levels (NHMCL) set by the New Hampshire Water Supply Engineering Bureau [New Hampshire Water Supply Engineering Bureau, 1990].

5 New Hampshire Secondary Maximum Contaminant Levels (NHSMCL) set by the New Hampshire Water Supply Engineering Bureau [New Hampshire Water Supply Engineering Bureau, 1990].

6 Statistics involving values less than detection limit were assigned values calculated by means of a technique described by Gilliom and Helsel (1986).

whose wells were contaminated or threatened by contamination from this site.

The Ottati and Goss/Great Lakes Container Corporation hazardous-waste site is on land west of State Route 125 in Kingston. The site was used for the storage and reconditioning of drums from 1955 through 1980. By 1980, the site contained an estimated 4,300 drums of unknown chemical waste (Goldberg-Zoino and Associates, 1986). Most of these drums were stored outdoors with no protection from the weather. Clean-up activities began in 1981, and drum-removal operations were completed by the summer of 1982. A preliminary hydrogeologic investigation, by a private consulting firm (Ecology and Environment, Inc., 1982) has indicated an extensive ground-water-contaminant plume that extends from the site towards Country Pond to the southeast. Another private consulting firm is completing a final RI/FS that will define the nature and extent of site contamination and identify the remedial action needed to complete clean-up activities at the site.

The Coakley landfill covers 20 acres in a residential area in North Hampton. The landfill borders the towns of Greenland to the northwest and Rye to the northeast. Originally a sand and gravel quarry, the site was converted to a landfill in 1971. Thirteen residential wells, to the north, east, and south of the site, have been closed because of contamination by VOCs from the landfill (New Hampshire Water Supply and Pollution Control Division, 1985a). A private consultant completed a draft RI/FS in 1988 that defined the nature and extent of site contamination and remedial action needed to clean up the site (Roy F. Weston, Inc., 1988-1989). As of 1990, no remedial action has been taken at the site except to cap the landfill and install catchment drains around its perimeter.

The Holton Circle site is in a residential cul-de-sac off Pillsbury Road in the town of Londonderry. Small concentrations of VOCs were detected in water samples from the unconsolidated and bedrock aquifers in 1988.

Pease Air Force Base is on a peninsula between Great Bay and the Piscataqua River in the towns of Portsmouth and Newington. A private consultant, under contract to the U.S. Air Force, did an Installation Restoration Program, Phase II Stage 1 Confirmation/Quantification Study at Pease Air Force Base during 1986. In this study, 20 sites were investigated for possible contamination. Past activities at Pease Air Force Base in support of aircraft maintenance has resulted in the generation of small quantities of hazardous wastes, including spent degreasers, solvents, paint strippers, and contaminated jet fuels (Roy F. Weston, Inc., 1986).

The Duston Road site is near the intersections of Duston Road, Eyssi Drive, and Atkinson Road in Salem. Ground water near the Duston Road site was determined to be contaminated with VOCs in October 1983 (New Hampshire Water Supply and Pollution Control Division, 1985b). The source of contamination proved to be drums buried in the overburden layer. In August 1984, more than 63 barrels, as well as debris and contaminated soil, were removed. Contamination at the site extends into the thin, sandy aquifer and the crystalline bedrock aquifer (New Hampshire Water Supply and Pollution Control Division, 1985b). In addition, some contaminants were found in Dietal Pond and Providence Hill Brook. Because ground water was contaminated in many nearby domestic wells, including wells finished in unconsolidated deposits and bedrock, a town water line was extended to the affected area in October 1984 to provide potable water.

Ten facilities (fig. 24 and pls. 1-3) are on the New Hampshire Water Supply and Pollution Control Division and New Hampshire Waste Management Divisions's RCRA Regulated Facilities List (New Hampshire Department of Environmental Services, 1987). Three of these sites are in Seabrook, two are in Derry, two are in Newington, one is in Salem, one is in Hampton, and one is in Londonderry.

SUMMARY AND CONCLUSIONS

The lower Merrimack and coastal river basins in southeastern New Hampshire encompass 327 mi^2, of which 24 percent is covered by stratified-drift deposits. About 79 percent of the water pumped by high-capacity wells is derived from wells screened in coarse-grained stratified drift. Population for the 25 communities of the study area was 228,495 in 1987, and is projected to increase at an average annual rate of 3.32 percent to the end of the century. The quantity and quality of ground-water resources are generally sufficient for immediate water needs, however, stresses from a rapid population increase have caused local deterioration in quality and shortages that have forced some communities to seek water from increasingly distant sources.

At present, the maximum yield of all community water-supply systems that withdraw water from the stratified drift is estimated to be 6 Mgal/d. Towns served by high-yielding gravel-packed wells include

Hampton, North Hampton, Portsmouth, Rye, and Seabrook. Many of the shallow aquifers within these towns are developed at or near their full potential yields and, as a result, additional sources are sought from the bedrock aquifer or from aquifer areas outside of town boundaries. Maximum well yield averaged 328 gal/min for 8 municipal wells tapping crystalline bedrock and 377 gal/min for 19 municipal wells tapping stratified drift.

Two types of topography define the stratified-drift deposits found in the study area. West of and including the Spicket River drainage basin are low, rounded hills and ridges with local topographic relief of 100 to 200 ft between interstream divides and stream bottoms. The most extensive stratified-drift aquifers are confined within well-defined valley walls and consist of valley trains, deltas, and kame terraces.

East of the Spicket River basin, topographic relief is less than 100 ft with sluggish streams flowing in broad valleys cut into predominantly sand, silt, and clay units. The most productive aquifers are outwash plains and kame plains that are often underlain by fine-grained marine deposits. In some areas, a small confining layer composed of clay and silt is interbedded with stratified drift and separates the aquifer into an upper unconfined part and a lower confined part.

Total thickness of sand and gravel sediments ranges from 0 at the boundary of till or marine deposits and stratified drift to more than 120 ft at one location in Kingston. The average seasonal water-table fluctuation is 3 to 5 ft. Hydraulic conductivity generally ranges from 3 to 300 ft/d. Transmissivity ranges from near 0 to greater than 4,000 ft^2/d.

A total of 19 aquifers have transmissivities greater than 1,000 ft^2/d. Of these, 8 are currently used for public water supply and 11 are unused. Because the aquifers of the eastern report area are contained by fine-grained marine sediments that isolate them from surface-water bodies, long-term ground-water-supply potential is limited.

Aquifers that have the greatest potential for supplying additional amounts of water include the Kingston outwash plain in the Powwow River valley, the Windham valley-train deposit south of Cobbetts Pond, the delta at Island Pond in Derry, and the kame deltas in central Greenland and in central North Hampton.

Two aquifers that are currently undeveloped and of potential importance were selected for a detailed hydrologic analysis. The yield and contributing recharge areas to hypothetical wells in the Windham-Cobbetts Pond and Kingston-Powwow River aquifers were evaluated by use of a computer model that simulates ground-water flow. These hypothetical wells were simulated at sites considered favorable for future pumping centers. The principle of superposition was used to superimpose drawdowns, computed by the flow model, on the mapped water-table surface. Total well yields, representing maximum development at the Windham-Cobbetts Pond and Kingston-Powwow River aquifers, were estimated to be 0.6 and 4.0 Mgal/d. Potential yields derived from an analytical procedure based on surficial geology agree with the computer-model estimates for these aquifers.

Simulations of the Windham-Cobbetts Pond model indicate that, at maximum development, the contributing area approaches the full extent of the aquifer and far exceeds the area affected by drawdown in the Kingston-Powwow River model.

Sensitivity analyses of the models indicate that the Kingston-Powwow River model was most sensitive to changes in river- and pond-bottom conductance and the Windham-Cobbetts Pond model to changes in specific yield. These findings emphasize the importance of accurately determining bottom conductance for aquifer systems for which induced infiltration is the primary source of water (Kingston-Powwow River model) and specific yields for aquifers where ground-water storage is the primary source (Windham-Cobbetts Pond model).

The ground-water quality from 30 well sites is suitable for drinking and other domestic uses except at a few sites where natural aquifer composition or human activities have degraded water quality. Ground water in the region is generally soft, slightly acidic, and low in total dissolved solids. Ground-water-quality samples meet the USEPA's primary drinking-water regulations except for an elevated level of trichloroethylene in water from one supply well that has ongoing treatment for this constituent.

Inorganic constituents that exceed New Hampshire Water Supply Engineering Bureau's (written commun., 1988) secondary drinking-water standards and the USEPA's (1989) secondary drinking-water regulations are iron, manganese, and aluminum. Seven samples had iron concentrations greater than 300 $\mu g/L$, 19 samples had manganese concentrations greater than 50 $\mu g/L$, and 4 samples had aluminum concentrations greater than 50 $\mu g/L$. Most ground water in the area contains enough dissolved manganese to cause stains on plumbing fixtures and laundry, thus restricting its use without treatment. Concentrations of iron in some ground water is high enough to cause similar problems. Treatment can reduce manganese and iron concentrations.

Water samples were also analyzed for 36 volatile organic compounds. Of 25 wells sampled, water samples from four wells had trace concentrations and water samples from a fifth well had small concentrations of volatile organic compounds. Trichloroethylene in water samples from well PXW-2 was the only constituent whose concentration exceeds New Hampshire Water Supply Engineering Bureau's (1990) drinking-water standards for volatile organic compounds.

Extensive ground-water contamination at seven hazardous-waste sites has seriously decreased the amount of reliable, safe withdrawals from selected aquifers in some areas.

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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.

Basal 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.

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.

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 that of the aquifer itself.

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

Cubic foot 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.

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 degrees Celsius; 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 at which 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 millimeter 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 man-made 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: 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 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, 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.

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 plain: Moderately flat-topped hills of sand and gravel; surrounded or nearly surrounded by ice-contact slopes.

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.

Kettle: A steep-sided, basin- or bowl-shaped hole or depression, commonly without surface drainage, in stratified-drift deposits; formed by the melting of a large, detached block of stagnant ice left behind by a retreating glacier.

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

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.

Outwash plain: A broad, gently sloping sheet of outwash deposited by meltwater streams flowing in front of or beyond a glacier.

pH: The negative logarithm of the hydrogen-ion concentration. A pH of 7.0 indicates neutrality; values below 7.0 denote acidity, and 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. (4 mm = -2 phi, 2mm = -1 phi, 1 mm = 0 phi, 0.5 mm = 1 phi, and so on)

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.

Potential yield: The potential yield, defined for the purposes of this report, is the rate at which water can be withdrawn from a basin by pumping for 180 days without recharge without producing an undesirable result. An undesired result is an adverse situation such as progressive lowering of the water table resulting in depletion of the ground-water reserves, excessive lowering of pond levels and streamflow by induced infiltration such that water resources are adversely affected, the intrusion of water of undesirable quality, the deterioration of the economic advantages of pumping, and land subsidence caused by lowered ground-water levels. Any prolonged water withdrawals in excess of the potential yield will result in the mining of the water resource and have negative impacts on environmental, social, or economic conditions.

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; that is, the spaces naturally occurring between the grains or particles of which the rock or sediment is formed. 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 activities 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 created by altering the original condition of a rock or sediment by such phenomena as solution, fracturing, or faulting.

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.

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--that 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, the value at which 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.

Valley train: A long, narrow body of sand and gravel deposited by meltwater streams far beyond the margin of an active glacier and confined in the walls of a valley below the glacier; it may or may not emerge from the mouth of the valley to join an outwash plain.

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

APPENDIX

Geohydrologic sections based on seismic-refraction data

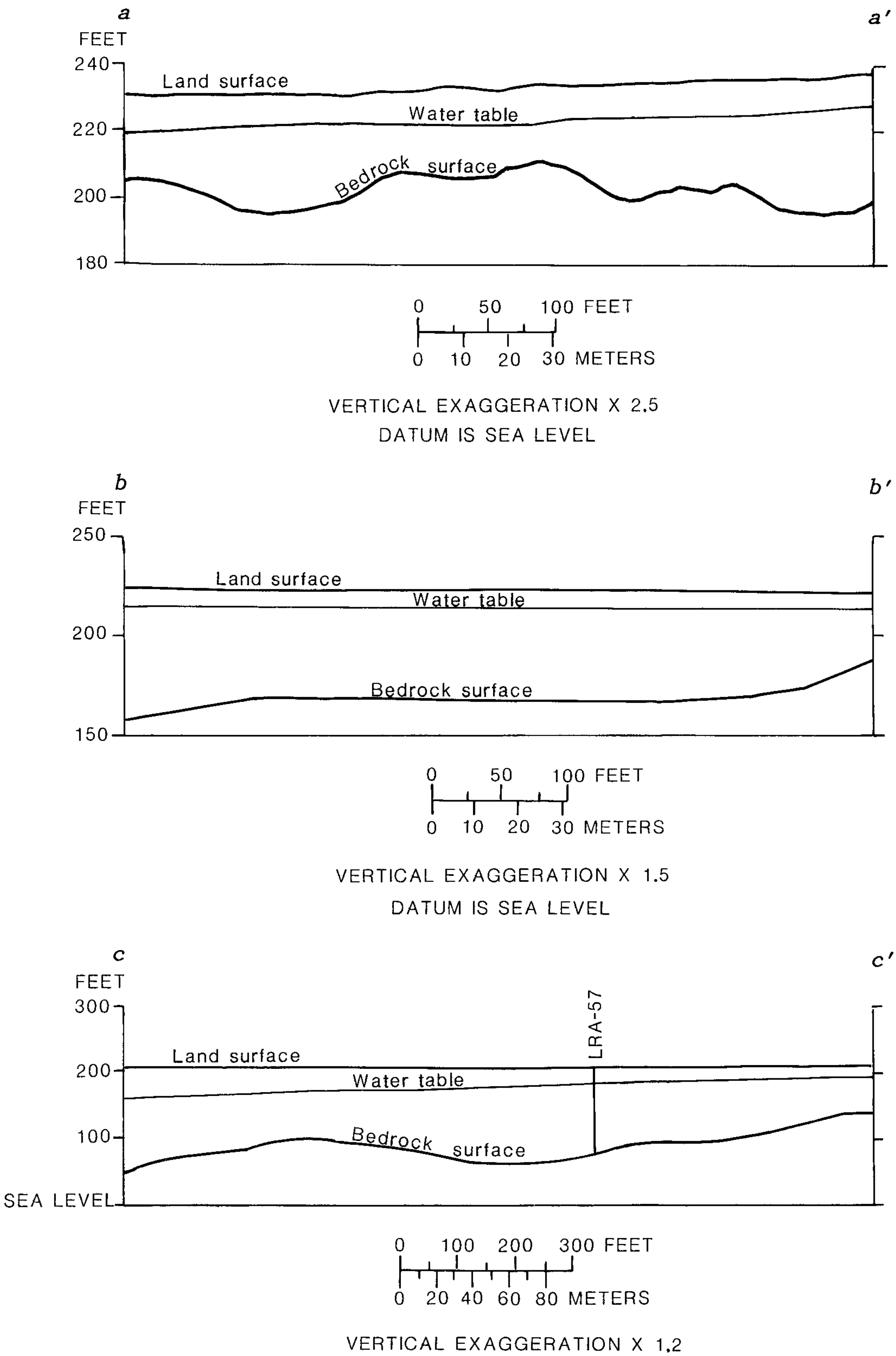


Figure A1.--Geohydrologic sections based on seismic-refraction data for Londonderry a-a′, b-b′, and c-c′. Lines of section are shown on plate 1.

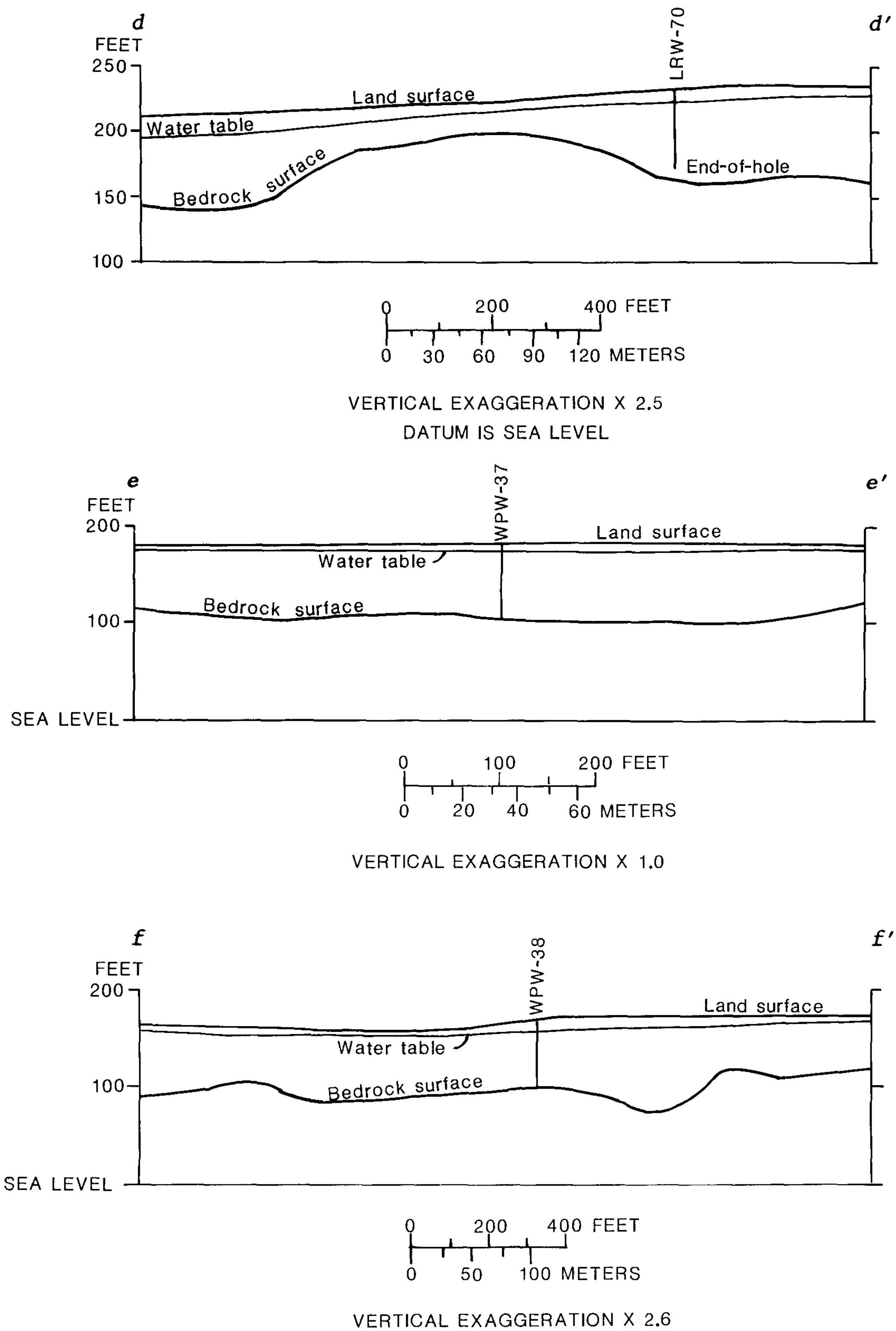


Figure A2.--Geohydrologic sections based on seismic-refraction data for Londonderry d-d', Windham e-e', and f-f'. Lines of section are shown on plate 1.

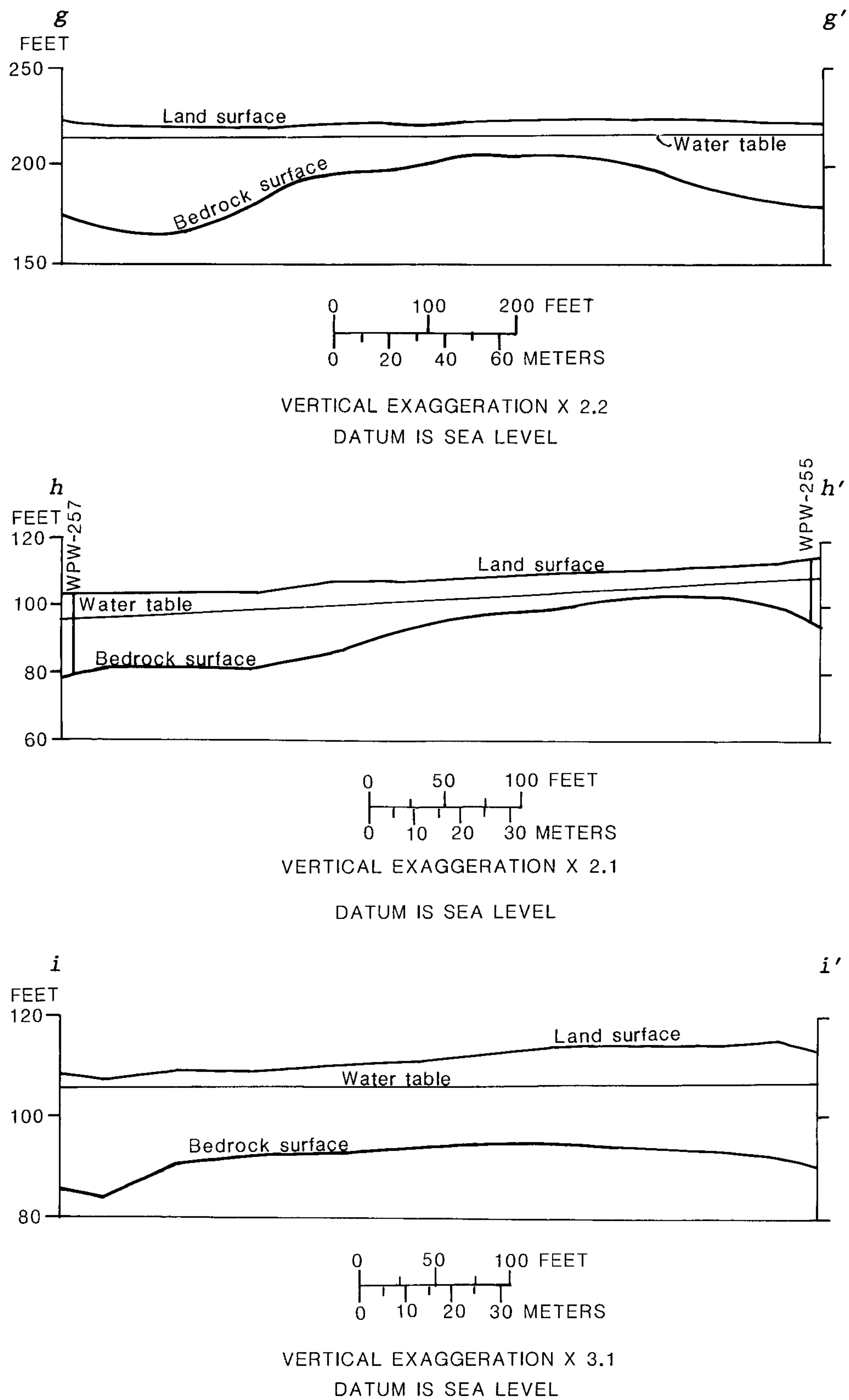


Figure A3.--Geohydrologic sections based on seismic-refraction data for Windham g-g′, h-h′, and i-i′. Lines of section are shown on plate 1.

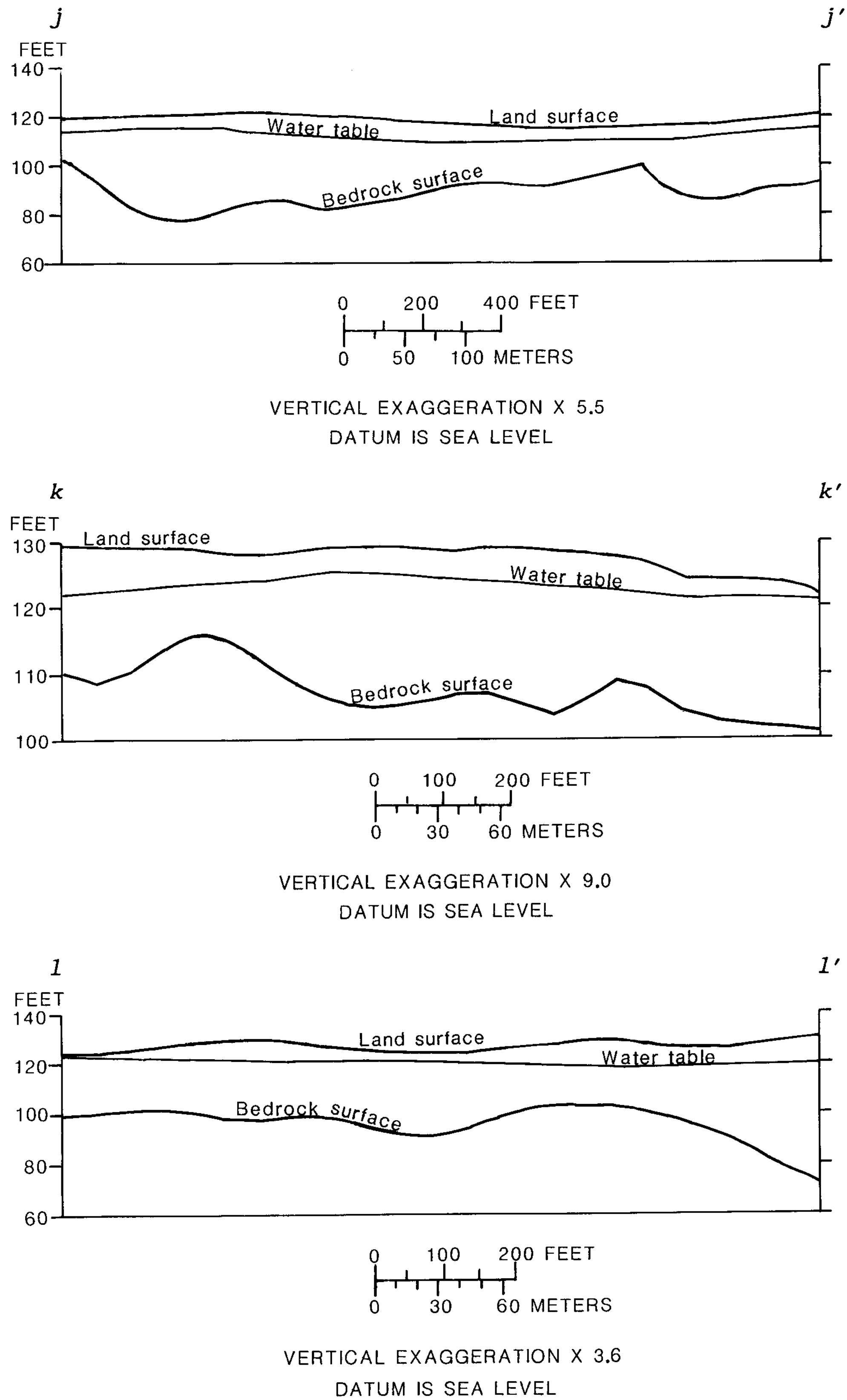


Figure A4.--Geohydrologic sections based on seismic-refraction data for East Kingston j-j′ and Kingston k-k′ and l-l′. Lines of section are shown on plate 2.

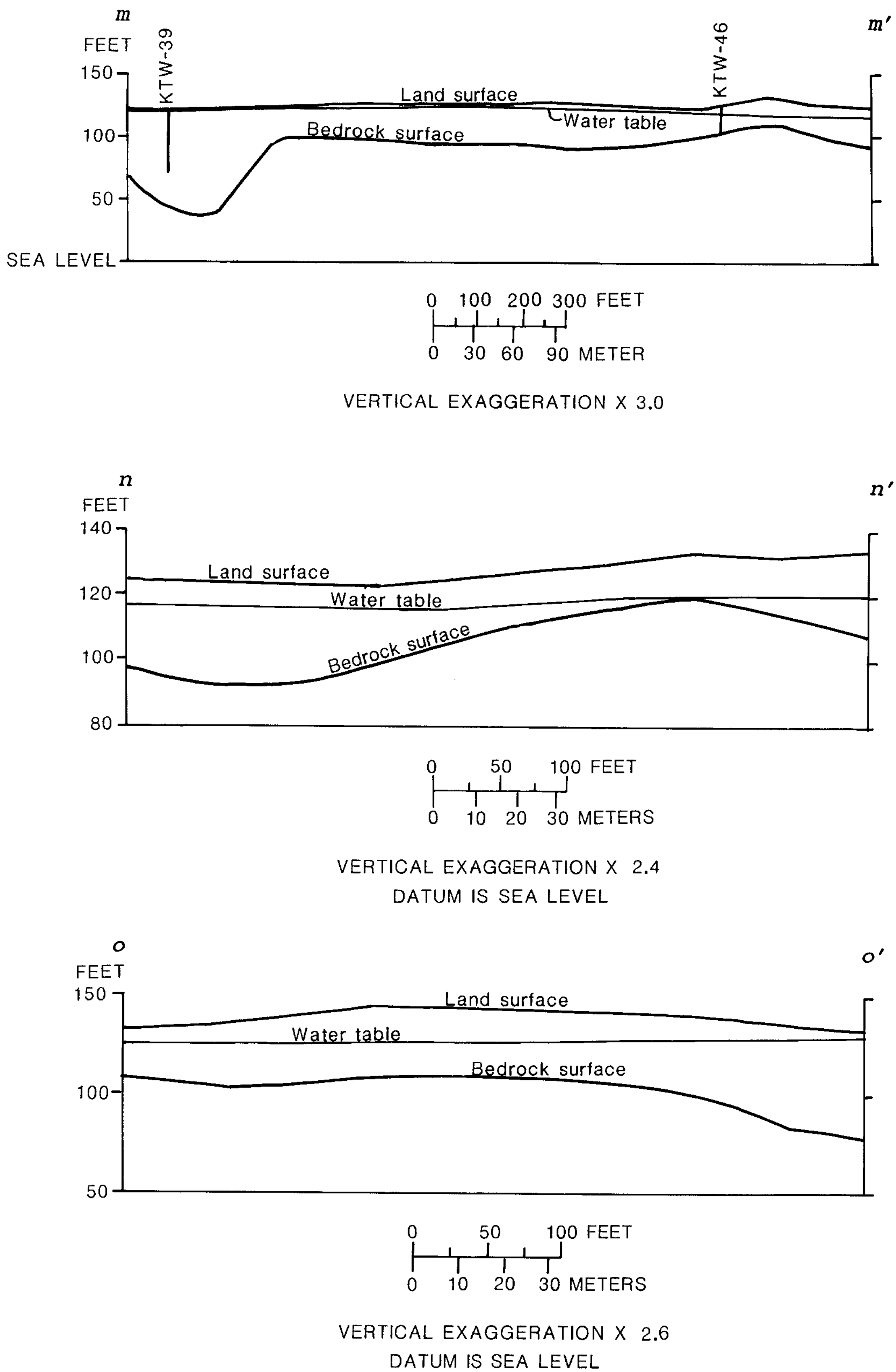


Figure A5.--Geohydrologic sections based on seismic-refraction data for Kingston m-m′, n-n′, and o-o′. Lines of section are shown on plate 2.

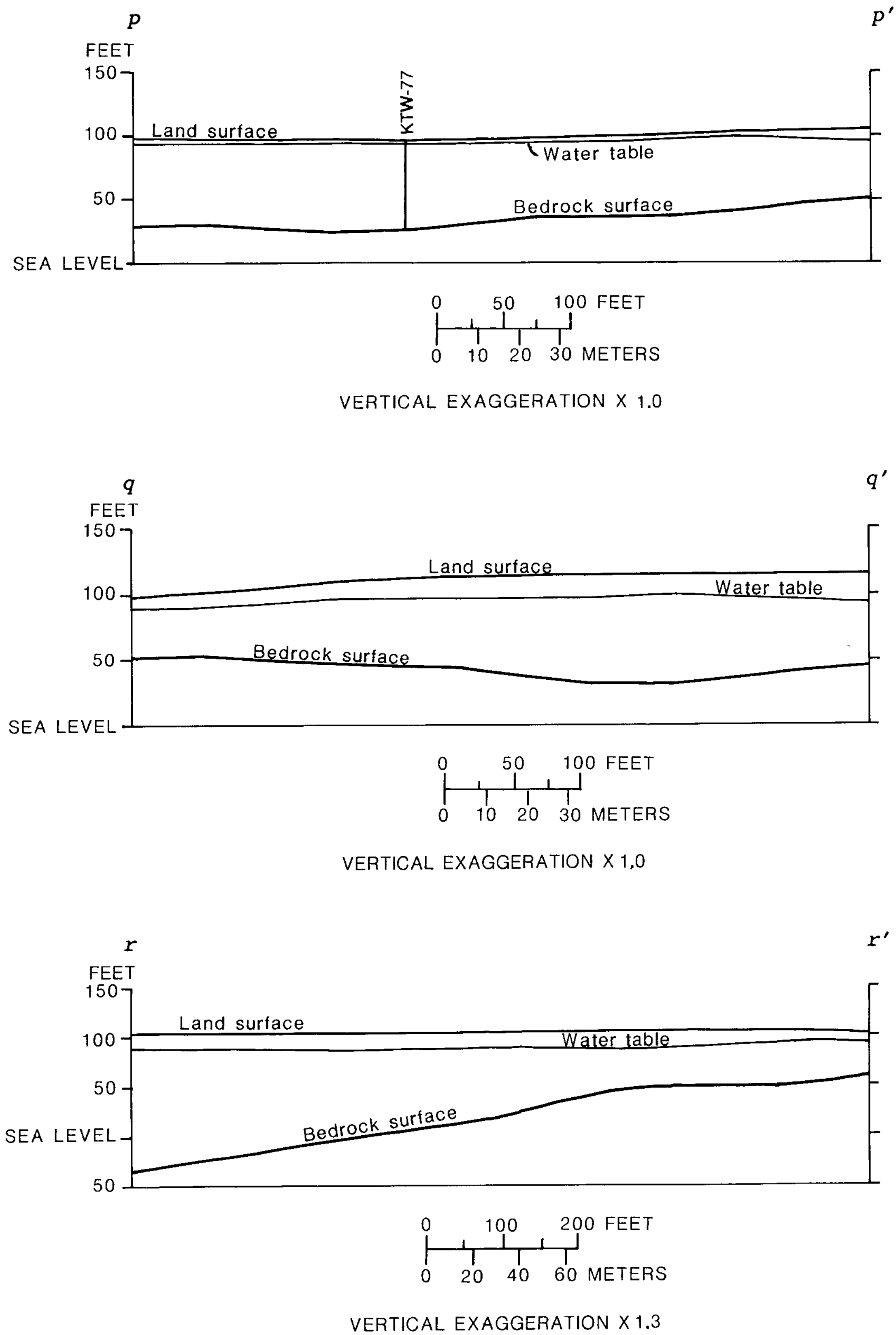


Figure A6.--Geohydrologic sections based on seismic-refraction data for Kingston p-p′, q-q′, and r-r′. Lines of section are shown on plate 2.

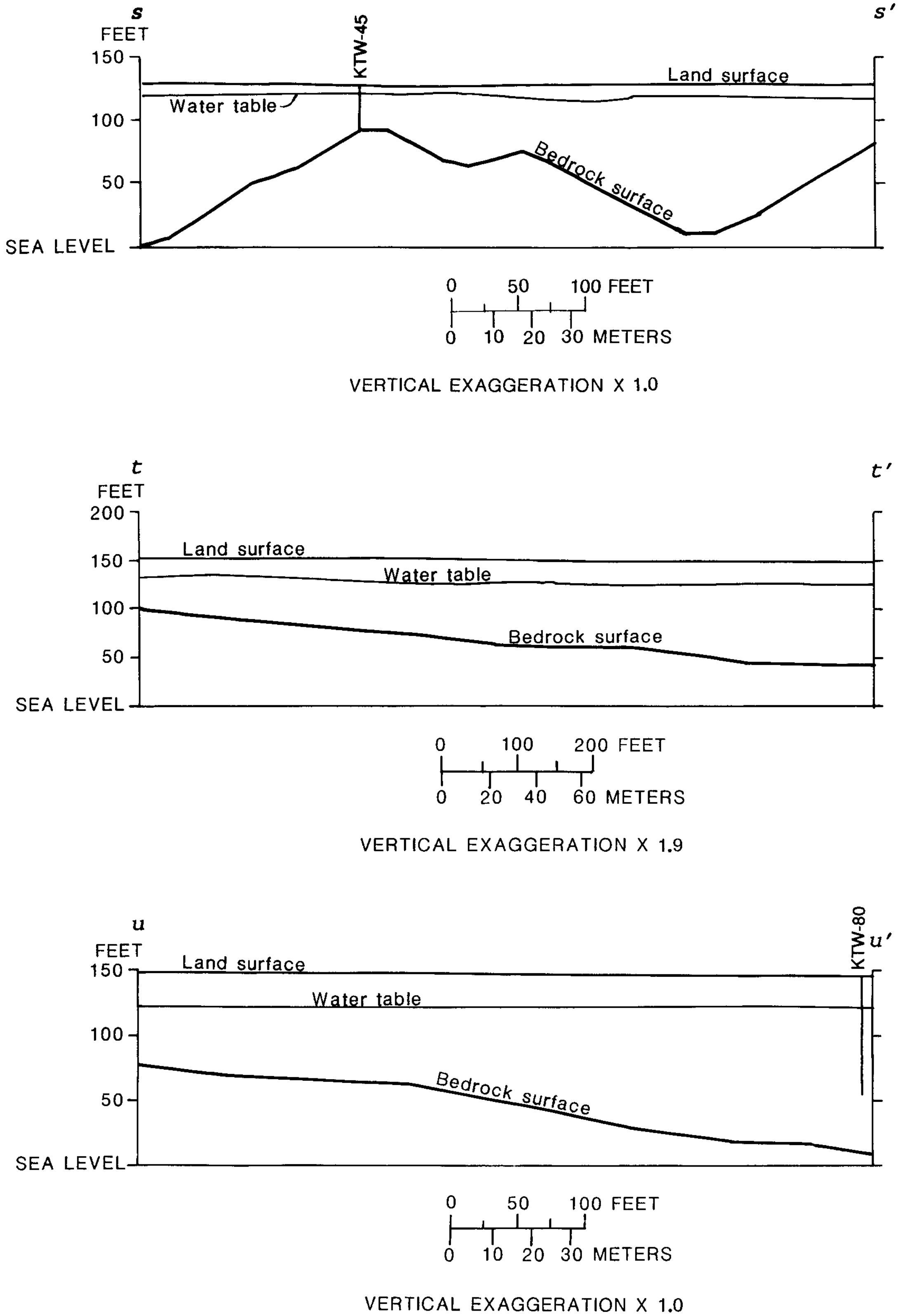


Figure A7.--Geohydrologic sections based on seismic-refraction data for Kingston s-s', t-t', and u-u'. Lines of section are shown on plate 2.

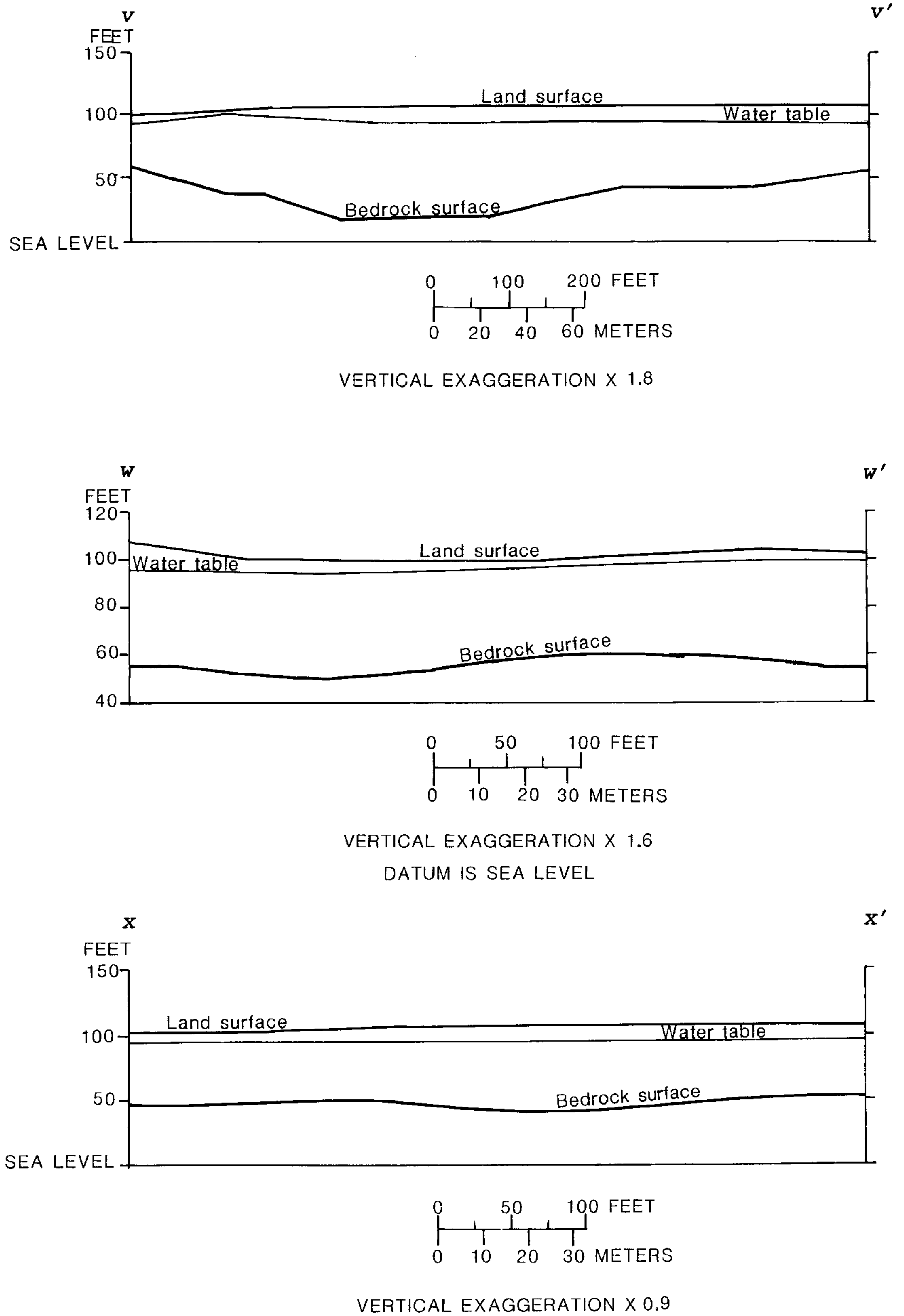
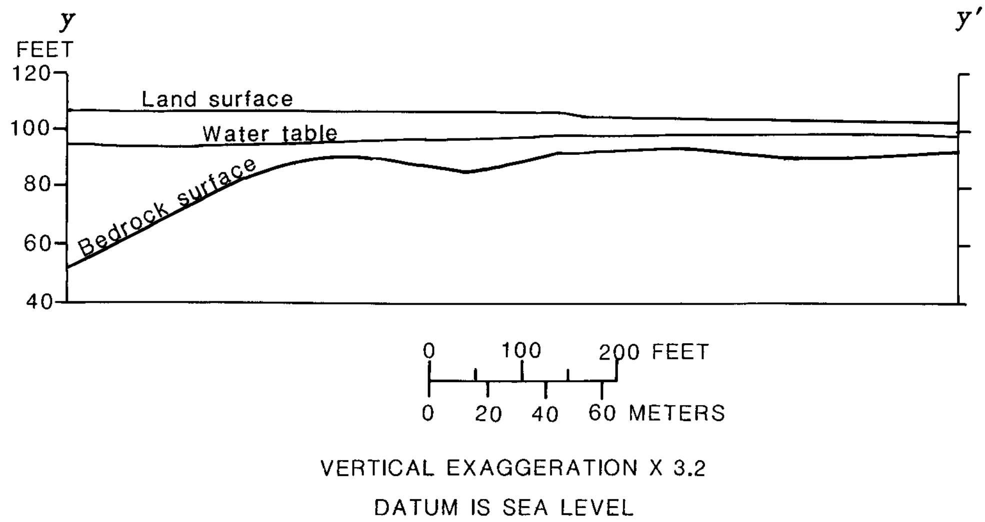
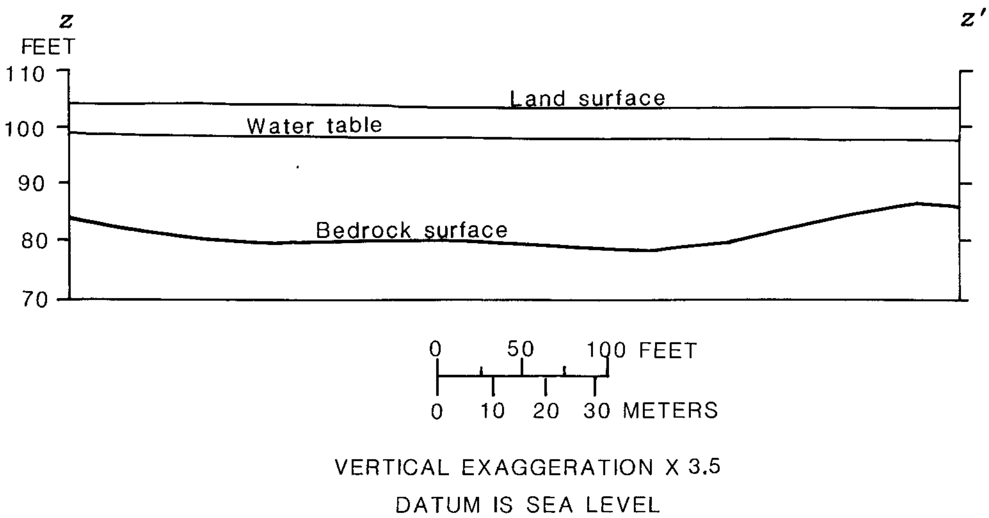


Figure A8.--Geohydrologic sections based on seismic-refraction data for Kingston v-v′, w-w′, and x-x′. Lines of section are shown on plate 2.





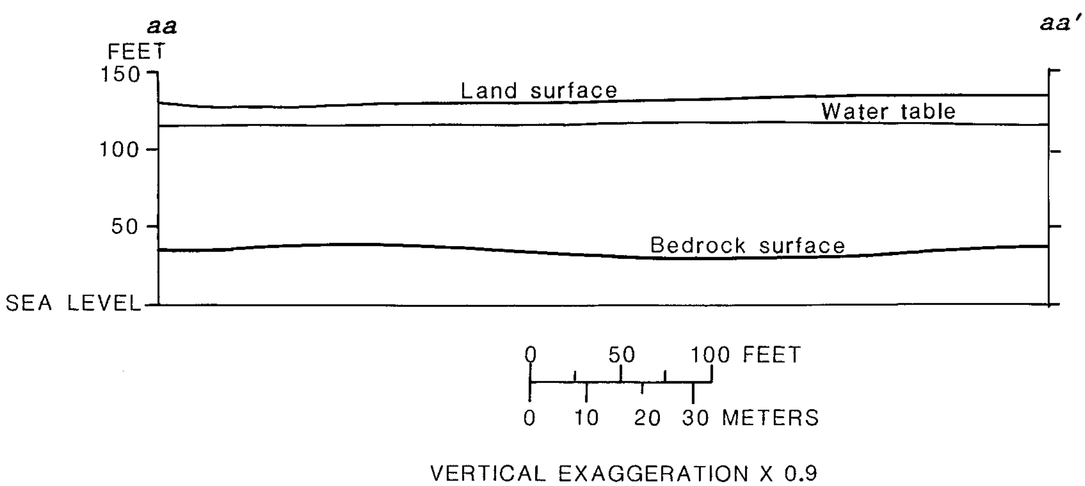


Figure A9.--Geohydrologic sections based on seismic-refraction data for Kingston y-y', z-z', and aa-aa'. Lines of section are shown on plate 2.

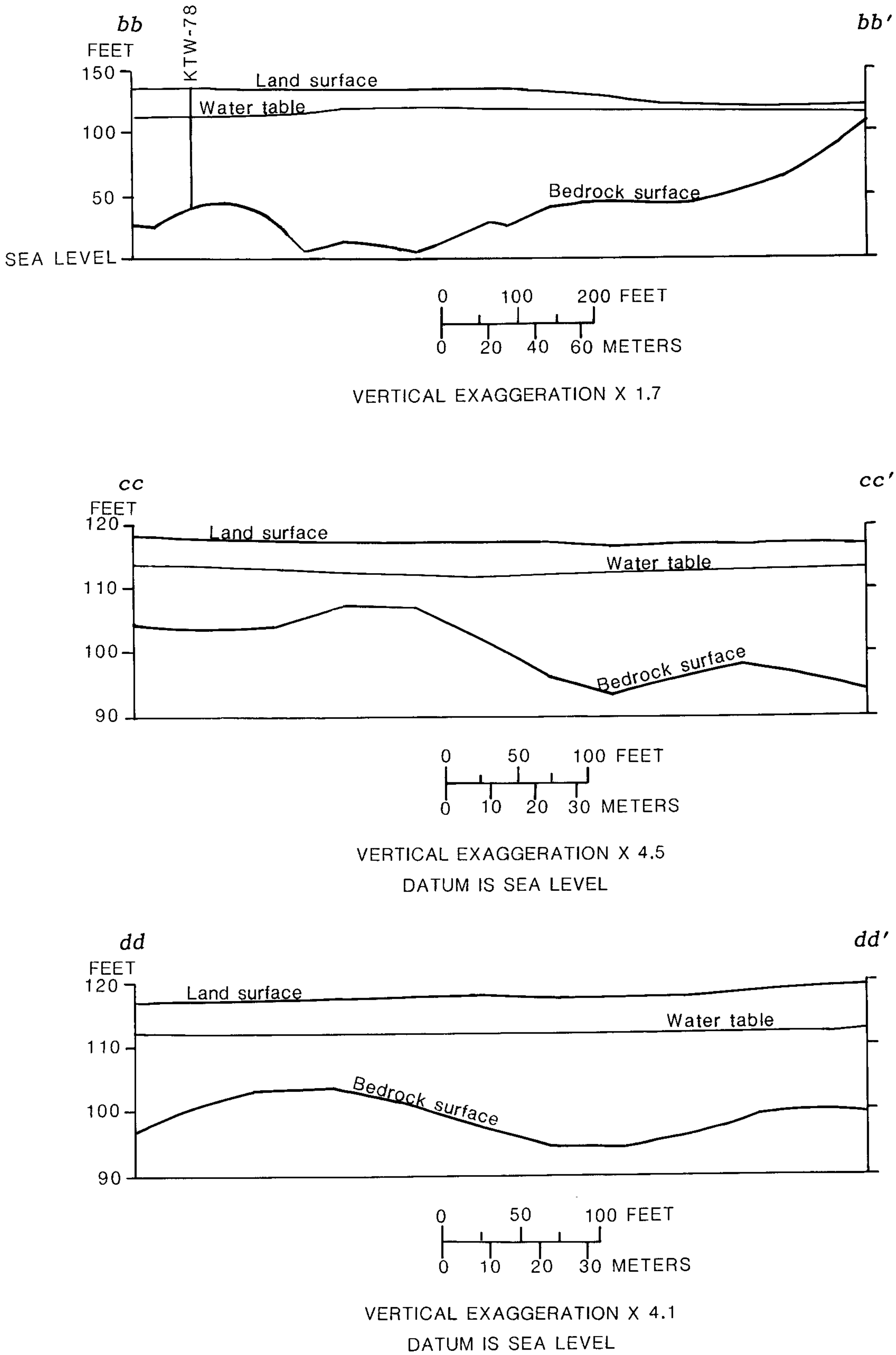


Figure A10.--Geohydrologic sections based on seismic-refraction data for Kingston bb-bb′, cc-cc′, and dd-dd′. Lines of section are shown on plate 2.

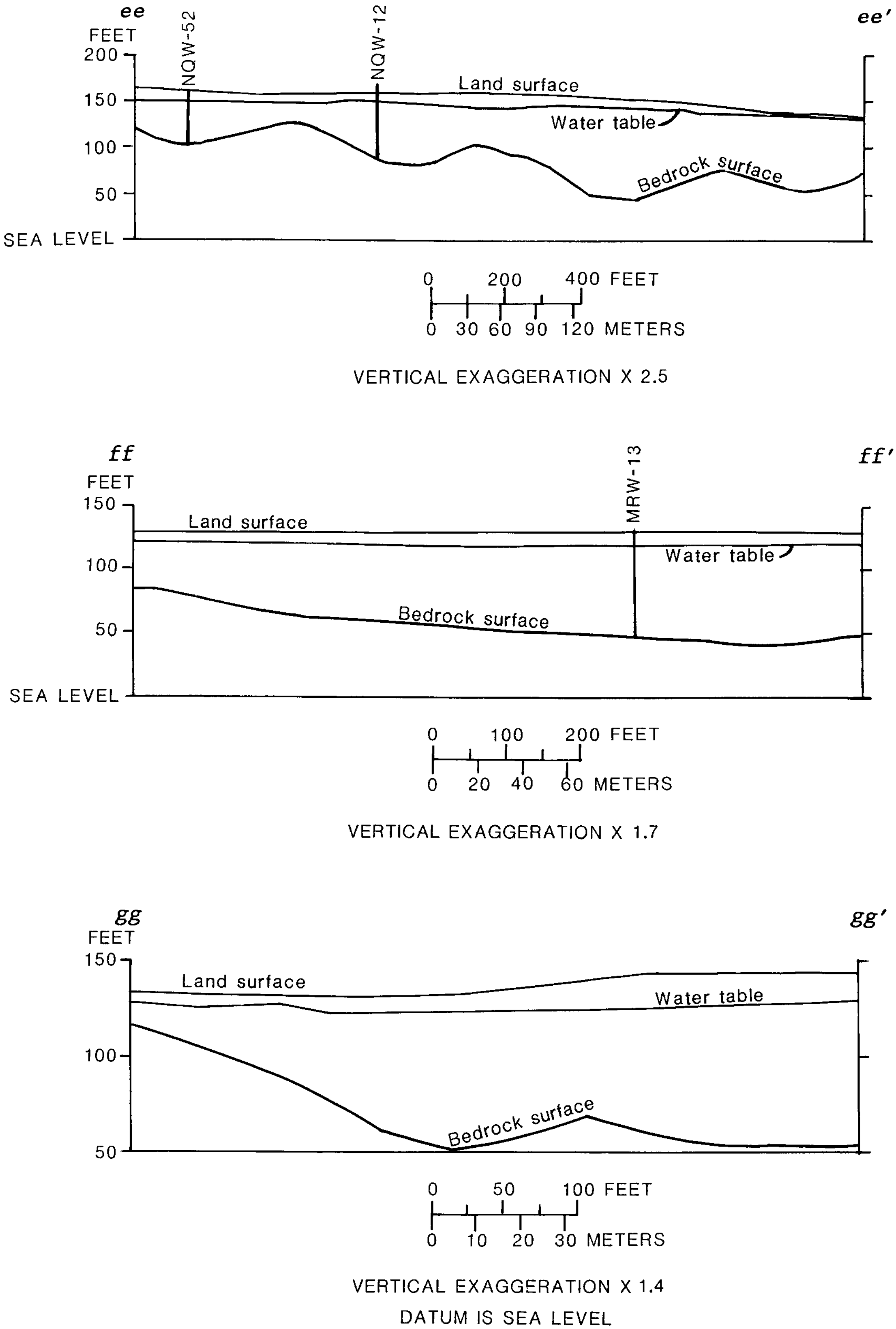


Figure A11.--Geohydrologic sections based on seismic-refraction data for Newton ee-ee', ff-ff', and gg-gg'. Lines of section are shown on plate 2.

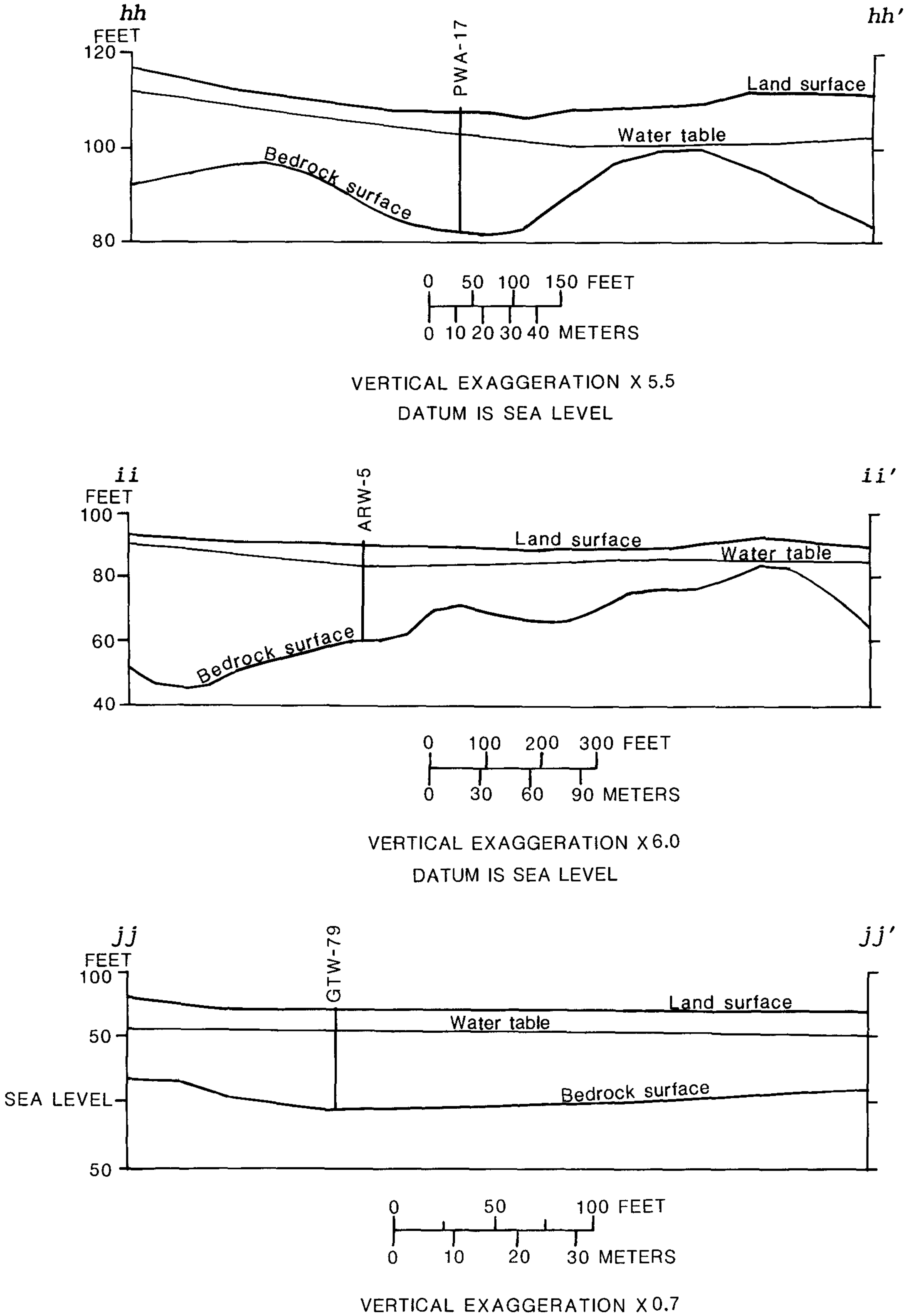


Figure A12.--Geohydrologic sections based on seismic-refraction data for Plaistow hh-hh′ and ii-ii′ and Greenland jj-jj′. Lines of section are shown on plates 2 and 3.

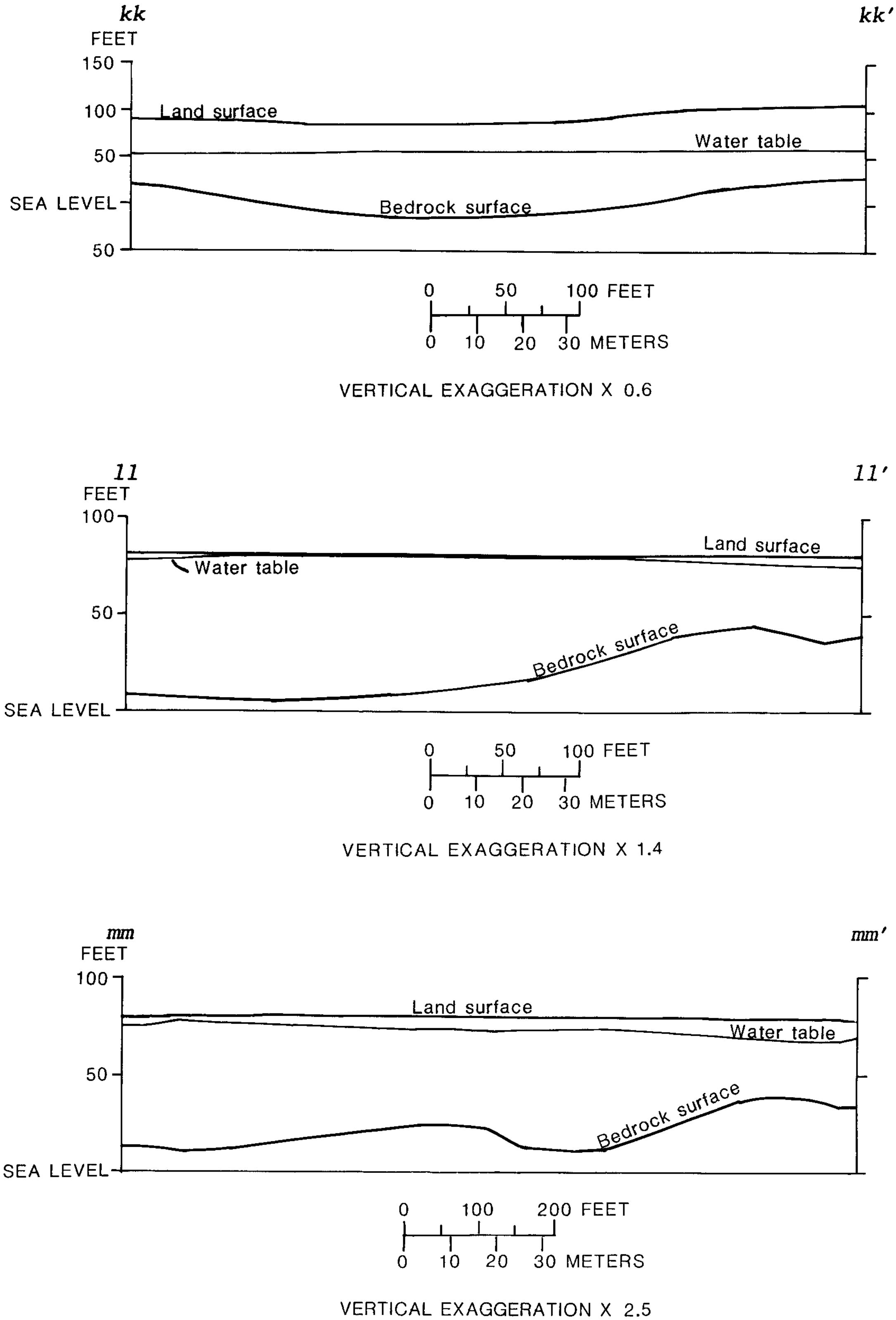


Figure A13.--Geohydrologic sections based on seismic-refraction data for Greenland kk-kk'and Kensington ll-ll' and mm-mm'. Lines of section are shown on plate 3.

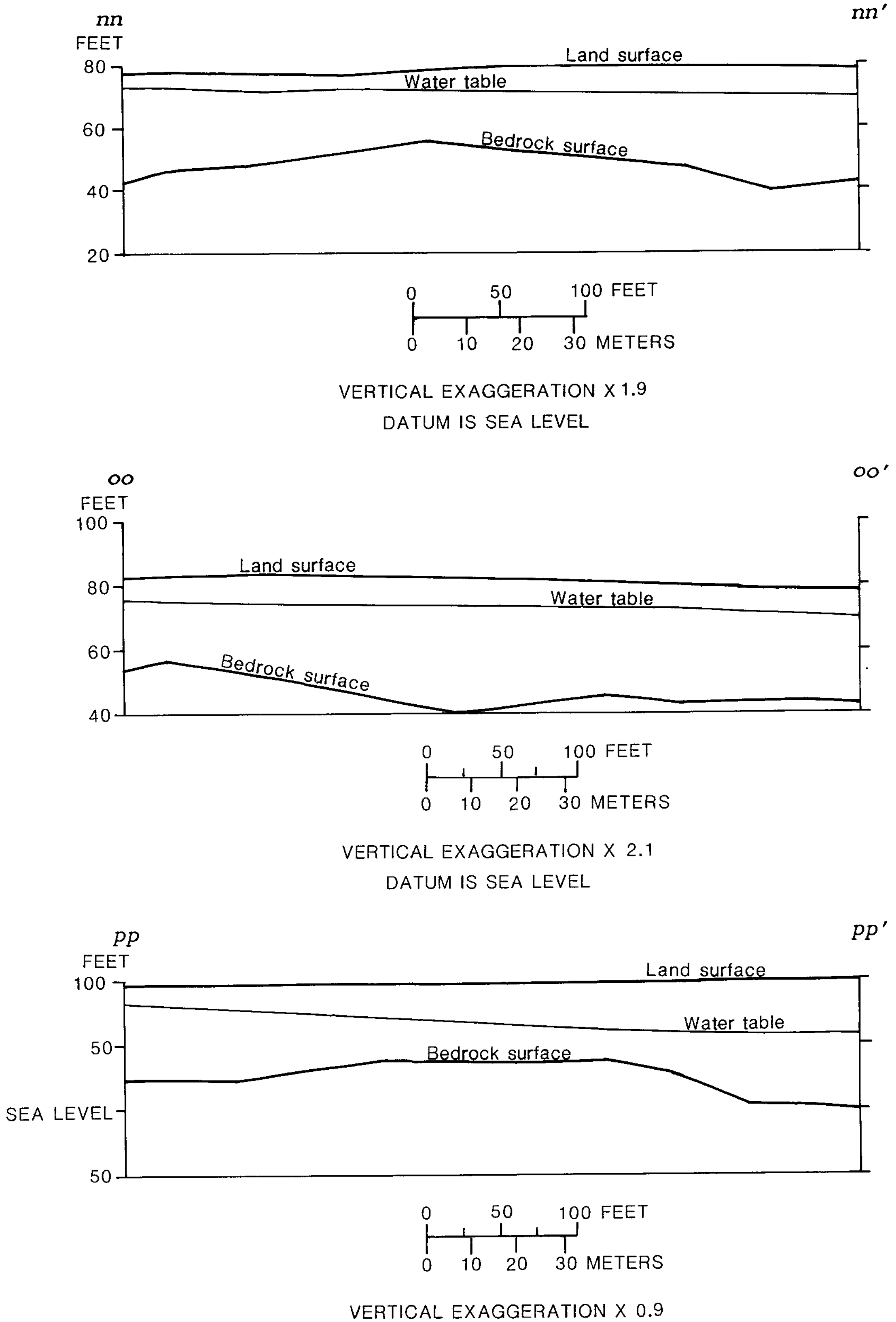


Figure A14.--Geohydrologic sections based on seismic-refraction data for Kensington nn-nn′ and oo-oo′ and Newington pp-pp′. Lines of section are shown on plate 3.

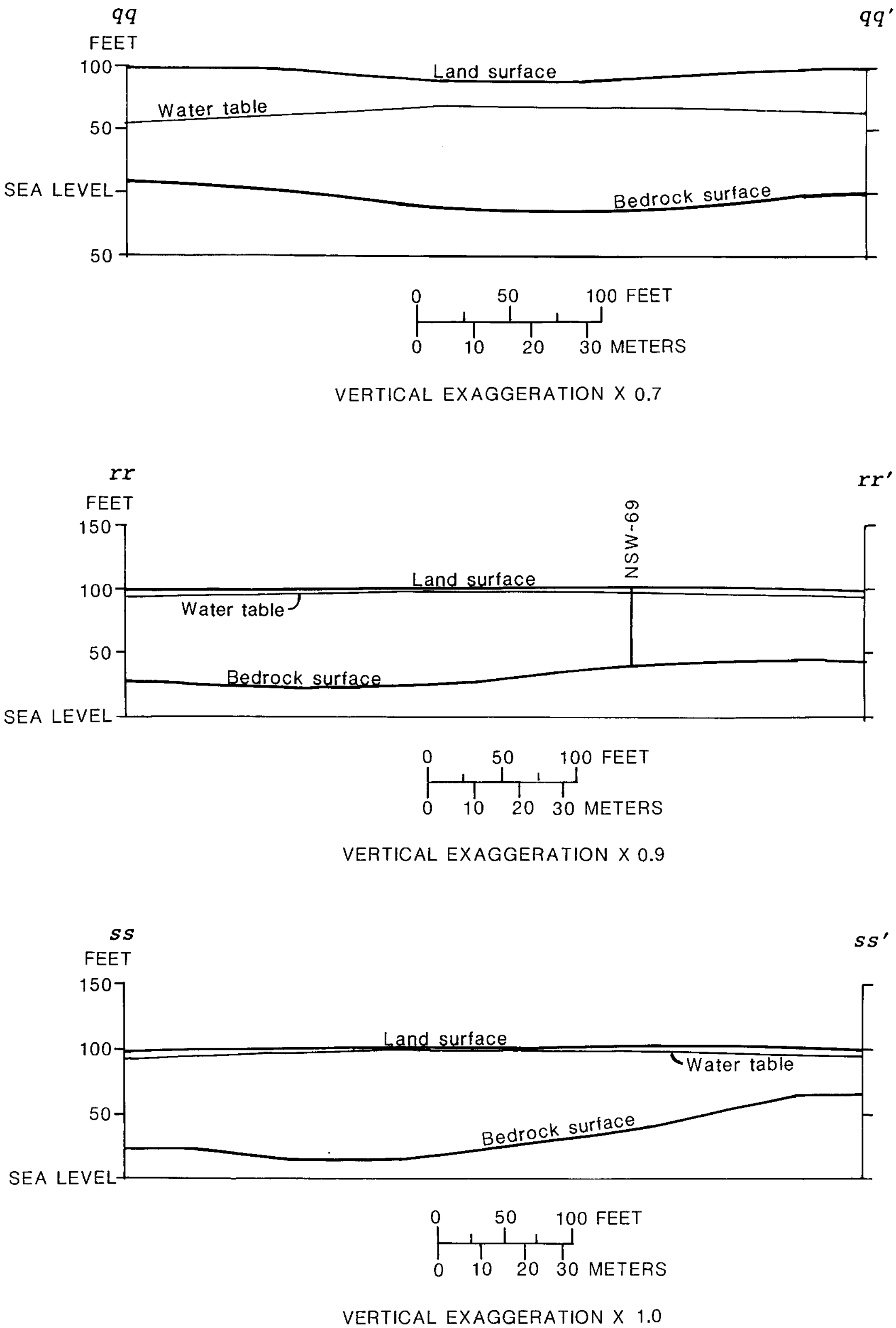


Figure A15.--Geohydrologic sections based on seismic-refraction data for Newington qq-qq′ and North Hampton rr-rr′ and ss-ss′. Lines of section are shown on plate 3.

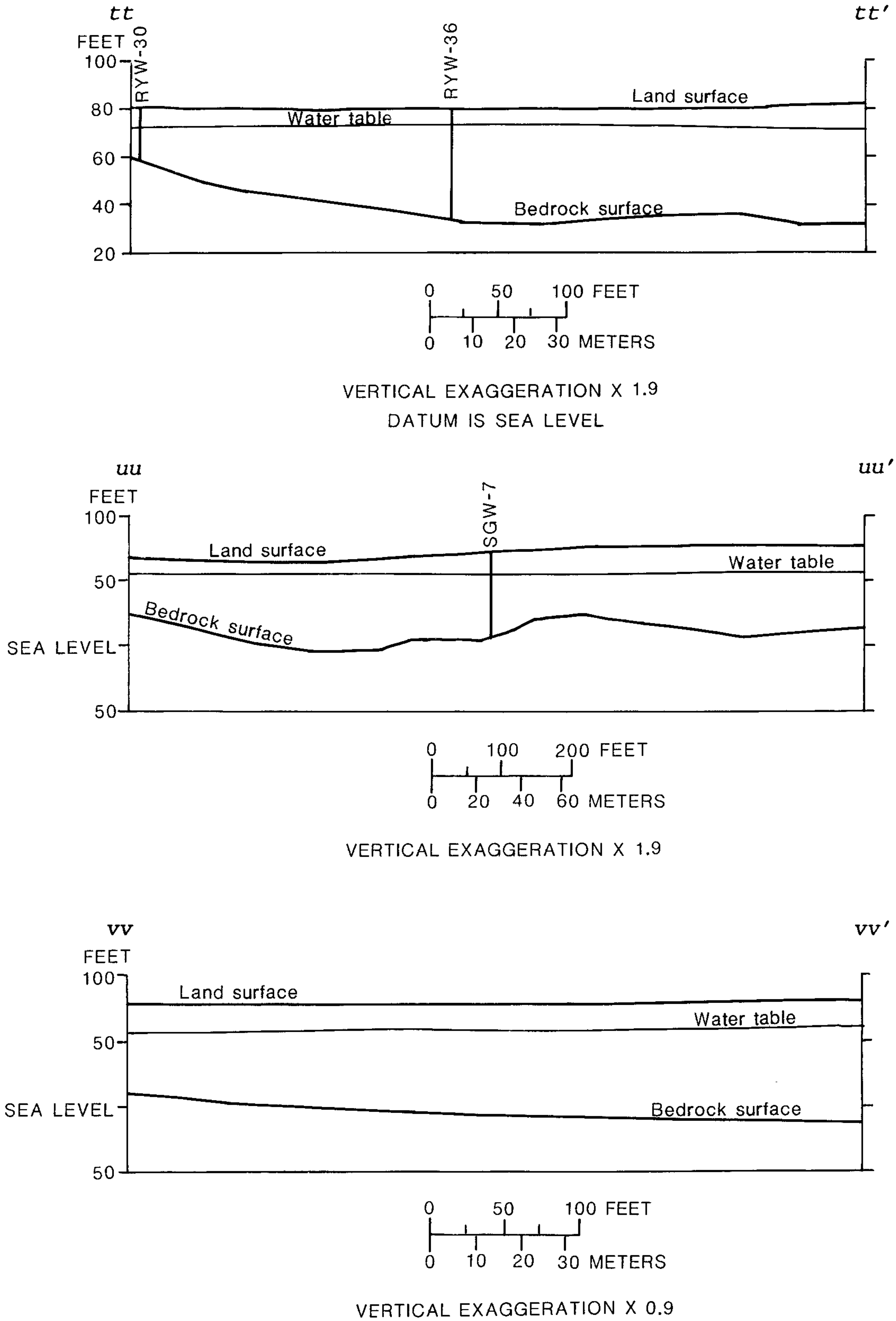


Figure A16.--Geohydrologic sections based on seismic-refraction data for Rye tt-tt′ and Seabrook uu-uu′ and vv-vv′. Lines of section are shown on plate 3.

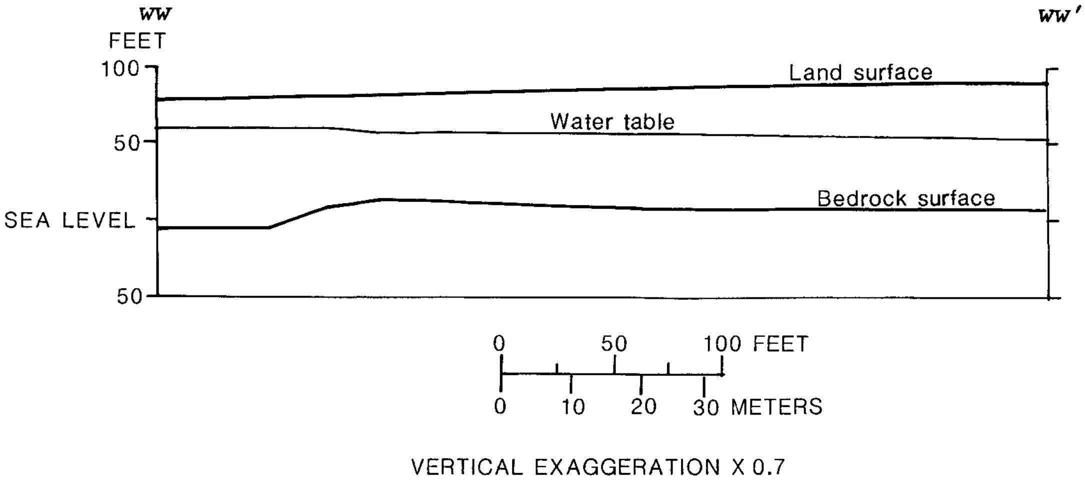


Figure A17.--Geohydrologic sections based on seismic-refraction data for Seabrook ww-ww'. Lines of section are shown on plate 3.