GROUND-WATER RESOURCES OF RHODE ISLAND

By Elaine C. Todd Trench

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	by	To obtain
	<u>Length</u>	
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	<u>Area</u>	
acre	4,047	square meter
square foot (ft^2)	0.09290	square meter
square mile (mi^2)	2.590	square kilometer
	<u>Volume</u>	
gallon (gal)	3.785	liter
million gallons (Mgal)	3,785	cubic meter
cubic foot (ft^3)	0.02832	cubic meter
million gallons per square mile ($Mgal/mi^2$)	1,460	cubic meters per square kilometer
	<u>Flow</u>	
foot per second (ft/s)	0.3048	meter per second
foot per day (ft/d)	0.3048	meter per day
gallon per minute (gal/min)	0.06309	liter per second
million gallons per day (Mgal/d)	0.04381	cubic meter per second
	<u>Hydraulic Conductivity</u>	
foot per day (ft/d)	0.3048	meter per day
	<u>Transmissivity</u>	
foot squared per day (ft^2/d)	0.09290	meter squared per day

<u>Temperature</u>

For temperature conversions between degrees Celsius (°C) and degrees Fahrenheit (°F), the following formulas may be used:

$$°C = 5/9 \times (°F - 32)$$
$$°F = (1.8 \times °C) + 32$$

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

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ABSTRACT

This general-interest report appraises the occurrence, source, flow, and quality of ground water in Rhode Island. Ground water, withdrawn from all major geologic units in Rhode Island, provided drinking water for about one-fourth of the State's population in 1985.

Ground water, mostly unconfined, is found in unconsolidated glacial till and stratified drift and in the underlying fractured bedrock. Thick deposits of stratified sand and gravel are the most productive aquifers in the State for public supply. Most private wells tap bedrock aquifers.

Ground water flows from upland recharge areas toward valley discharge areas. Most of the land surface is a recharge area. Large-capacity wells, located in permeable sediments near streams, commonly induce surface water to flow from streams into aquifers.

Concentrations of dissolved solids in ground water are generally less than 200 milligrams per liter, as compared to the National Secondary Drinking-Water Regulation of 500 milligrams per liter. Natural contaminants include iron, manganese, and radon. Withdrawals in coastal areas have caused saltwater intrusion.

Waste-disposal sites, industrial spills, leaking underground storage tanks, road salt, agricultural chemicals, and septic systems have contaminated ground water at some locations with metals, nitrate, bacteria, radionuclides, excessive concentrations of common ions, and more than 50 synthetic organic chemicals and petroleum products. Contamination by volatile organic compounds has been the major cause of public-well closings.

The rural Pawcatuck River basin contains nine high-yield stratified-drift aquifers. Southeastern Rhode Island, covered by clayey till, has no major aquifers. Stratified-drift aquifers in urbanized northeastern Rhode Island have a large potential yield but many water-quality problems. Rural western areas depend on ground water.

INTRODUCTION

The Importance of Ground Water

The earth's water resources include saltwater and freshwater. Saltwater constitutes about 94 percent of the total volume. The remaining 6 percent is freshwater, which is distributed among the following sources, in descending order of total volume:

* Ground water
* Ice caps and glaciers
* Lakes, swamps, reservoirs, and river channels
* Soil moisture
* Water in the atmosphere
* Water contained in plants and animals

If ice caps and glaciers are excluded, then ground water accounts for almost all of the world's freshwater (Freeze and Cherry, 1979, p. 5).

Nationally, ground water accounted for 35 percent of all freshwater used in 1985, excluding freshwater used for thermoelectric power generation (Solley and others, 1988, p. 65, 67). Ground water supplied between 16 and 30 percent of the freshwater used in 1985 in the six New England States.

Ground water is an abundant resource in Rhode Island. It has been widely used since colonial times, when it was withdrawn from springs and hand-dug wells. In 1985, ground water supplied approximately 18 percent of the freshwater used for all purposes in the State, including domestic, industrial, and agricultural uses (Solley and others, 1988, p. 59). Ground water provided drinking water for 24 percent of the State's residents, and it was the only source of drinking water for 12 towns. Untapped ground-water resources are available in several areas of the State.

Ground water in Rhode Island is generally suitable for human consumption and other uses that require high-quality water; however, ground-water contamination in Rhode Island and nationwide has increased public awareness of the risks to drinking-water supplies. Contaminants from a variety of sources have affected private and public ground-water supplies in Rhode Island.

Citizens understandably want safe drinking water. Information about ground-water resources can help citizens in their efforts to prevent contamination. The U.S. Geological Survey's mission is to collect, interpret, and disseminate geologic and hydrologic information that contributes to the wise management of the Nation's natural resources and promotes the well-being of its people (U.S. Geological Survey, 1986, p. 2). The Rhode Island Department of Environmental Management (RIDEM) is the regulatory agency responsible for developing a ground-water protection program for the State. The complementary responsibilities of RIDEM and the U.S. Geological Survey led to the cooperative project that has produced this report.

Purpose and Scope of the Report

This report provides Rhode Island's citizens with a broad overview of the State's ground-water resources and ground-water-contamination problems. The intended audience includes interested citizens, teachers, State and local government boards and agencies, and private organizations involved in water-resources issues.

The following questions were posed in developing the report:

* What is the importance of ground water in Rhode Island?
* What is ground water?
* Where does it come from?
* Where does it go?
* How does ground water become contaminated?
* Where are the major ground-water resources and contamination problems in Rhode Island?

The geographic area covered in the report includes Rhode Island and nearby parts of Connecticut and Massachusetts. Many of the concepts presented are also applicable to other areas within the glaciated northeastern United States.

The report presents the basic concepts of ground-water hydrology and describes the occurrence, source, flow (or movement), and quality of ground water in Rhode Island. Some complex ground-water problems that are frequently matters of interest and responsibility at the local level also are discussed. Technical concepts are applied to the major features or problems of individual drainage basins and other regions in the State. These concepts are presented in nontechnical language wherever possible, and technical terms that are used are explained in the text and defined in a glossary at the back of the report.

References are provided for interested readers who desire detailed hydrogeologic information for specific locations. Many of the references listed are available for inspection or distribution at the Rhode Island Office of the U.S. Geological Survey. Other publications are available from publishers and from the U.S. Government Printing Office.

Previous Studies

Numerous technical and nontechnical publications on ground-water resources and ground-water contamination provided background for the concepts presented in this report. A partial list includes Morrissey (1989), Harrison and Dickinson (1984), U.S. Environmental Protection Agency (1984a), U.S. Geological Survey (1984), Heath (1983), Pye and others (1983), Todd (1980), Freeze and Cherry (1979), Handman and others (1979), Cohen and others (1968), Baldwin and McGuinness (1963), Langbein and Iseri (1960), and Meinzer (1942; 1923). Publications on Rhode Island's water resources were consulted for information on local ground-water resources and contamination problems.

Statewide reports on the ground-water resources of Rhode Island include those by Lang (1961) and Allen (1953). Information on ground-water contamination problems in Rhode Island is summarized by the Rhode Island Department of Environmental Management (1988), and by Johnston and Barlow (1988); specific incidents are described in numerous other publications.

Acknowledgments

Margaret G. Dein Bradley and Ernest C. Panciera of the RIDEM Groundwater Section reviewed the report and provided information on agency responsibilities related to ground water, ground-water-contamination problems in Rhode Island, and local ground-water-protection programs. Sofia M. Bobiak of the Groundwater Section provided data on radon concentrations in private well water in Rhode Island.

Assistance in map compilation was provided by the Environmental Data Center (EDC) in the Department of Natural Resources Science at the University of Rhode Island. The EDC, under contract to RIDEM, compiled information for most of the maps in the report through the Rhode Island Geographic Information System (RIGIS). Carol Pringle Baker, RIGIS Groundwater Coordinator at the EDC, was most helpful and resourceful in developing these illustrations.

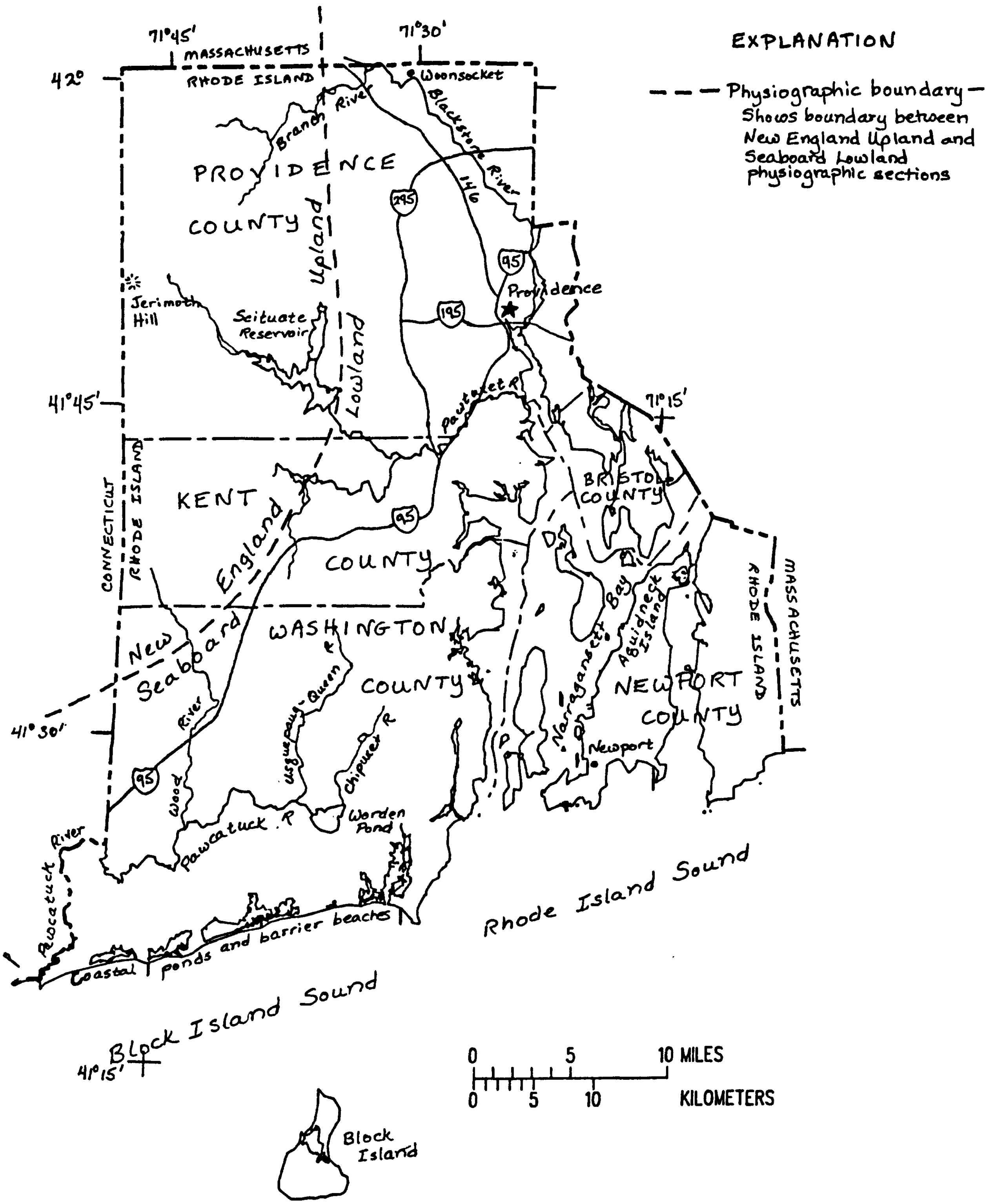
Bryan F. Barrette, Division of Drinking Water Quality, Rhode Island Department of Health, provided water-quality data for public water systems. Grace Beiser and John J. Deary, Jr., Division of Planning, Rhode Island Department of Administration, provided land-use information. Marc Tremblay, Providence Water Supply Board (PWSB), provided location information for the PWSB weather and rain-gage stations. Arthur J. Gold, of the University of Rhode Island Department of Natural Resources Science, provided information on root zones in Rhode Island.

Special thanks are extended to the following citizens who donated their time to review and comment on the report: Dr. Carol Hagglund, Providence; Robert W. Coker, Warwick; and Karen L. Dingley, East Greenwich. Their perspective and comments have been very helpful.

PHYSICAL AND CULTURAL SETTING

Rhode Island (fig. 1) is in southeastern New England and has a land area of 1,028 square miles. The State lies within two major physiographic sections of the New England province (Fenneman, 1938). The northwestern part of the State is in the New England Upland section, where altitudes generally range from 400 to 800 feet. Southern and eastern parts of the State are in the Seaboard Lowland section, an area of flat or gently rolling land that includes coastal areas, Narragansett Bay, and the Bay islands. Altitudes in the Seaboard Lowland section are generally less than 500 feet; swamps, ponds, and small lakes are numerous.

Despite its small size, Rhode Island has regions with distinct physical and cultural differences. The Blackstone, Pawtuxet, and Pawcatuck Rivers are the largest rivers in the State (fig. 1). The Blackstone and Pawtuxet Rivers have played a major role in the industrial development of the State for more than 200 years, as is reflected in the urban character of northeastern Rhode Island. Narragansett Bay and its resources dominate the landscape and the economy of the eastern third of the State. Woodlands and agricultural land form the landscape of the Pawcatuck River basin in southwestern Rhode Island. The southwestern coast, with its coastal ponds and long barrier beaches, is an important natural and recreational area. Hilly western parts of the State are mostly undeveloped.



Base and hydrology from the Rhode Island Geographic Information System

Figure 1.--Major physical and cultural features of Rhode Island. (Source: Boundary between New England Upland and Seaboard Lowland from Fenneman, 1938, pl. 1.)

Water Use in the 1980's

Fresh surface water and ground water are used by Rhode Island residents for drinking and other purposes. Surface-water sources include streams, lakes, ponds, and artificially impounded reservoirs. Ground water is withdrawn from wells and also is obtained from springs at some locations.

Total freshwater use in Rhode Island averaged 147 million gallons per day in 1985 (Solley and others, 1988, p. 59). Water use is shown in figure 2 for various categories of use. Rhode Island's 39 cities and towns and their sources of water in 1985 are shown in figure 3.

Daily use of surface water in 1985 averaged approximately 120 million gallons and use was concentrated in the northeastern and eastern parts of the State (fig. 3). Public supplies accounted for about 84 percent of the surface water used (Solley and others, 1988, p. 13). Drinking water for 76 percent of the State's 968,000 residents was provided by surface-water sources, including the Scituate Reservoir system, which provided water for half of the State's population (Solley and others, 1988, p. 13, 17; H.E. Johnston, U.S. Geological Survey, written commun., 1988).

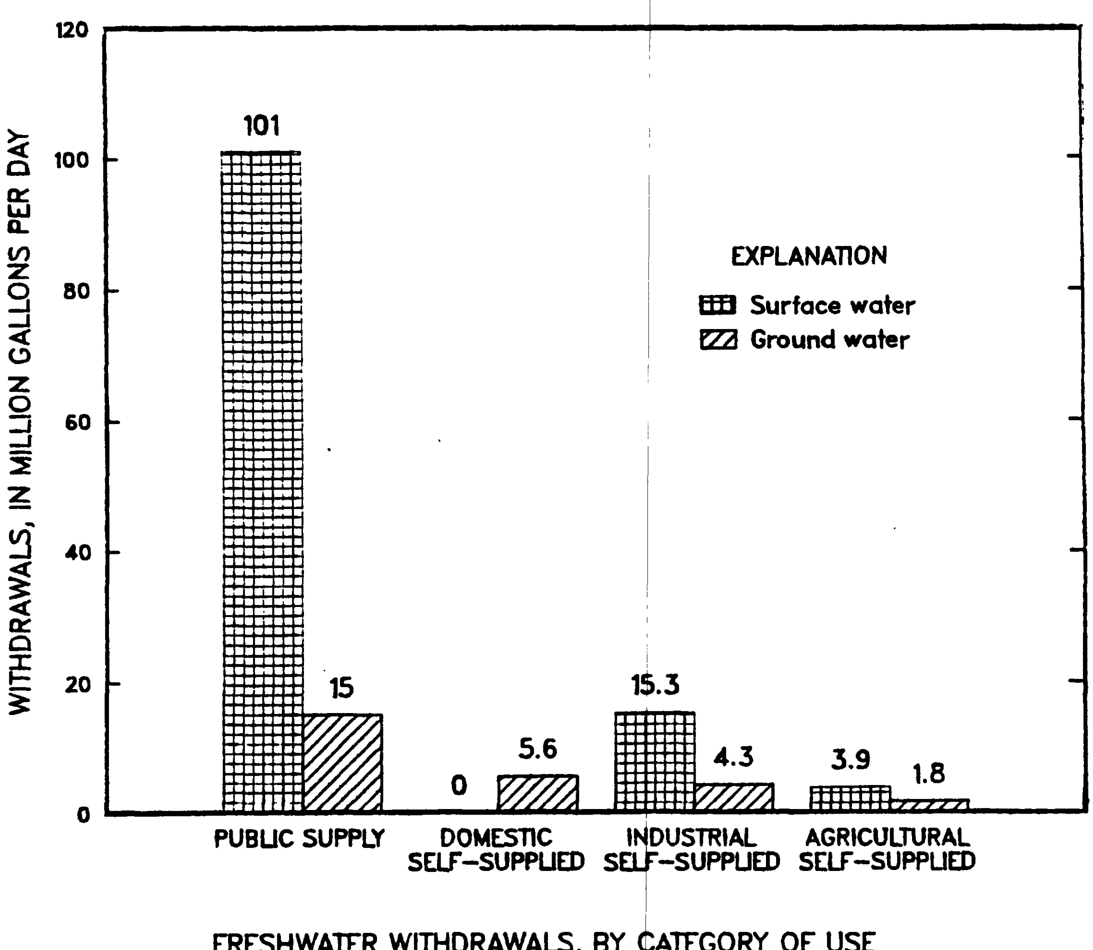


Figure 2.--Water use in Rhode Island in 1985. Public supply includes domestic, commercial, and industrial users. The other uses are self-supplied. (Source: Data from Solley and others, 1988, p. 65, 67. Compiled by R.W. Bell, U.S. Geological Survey.)

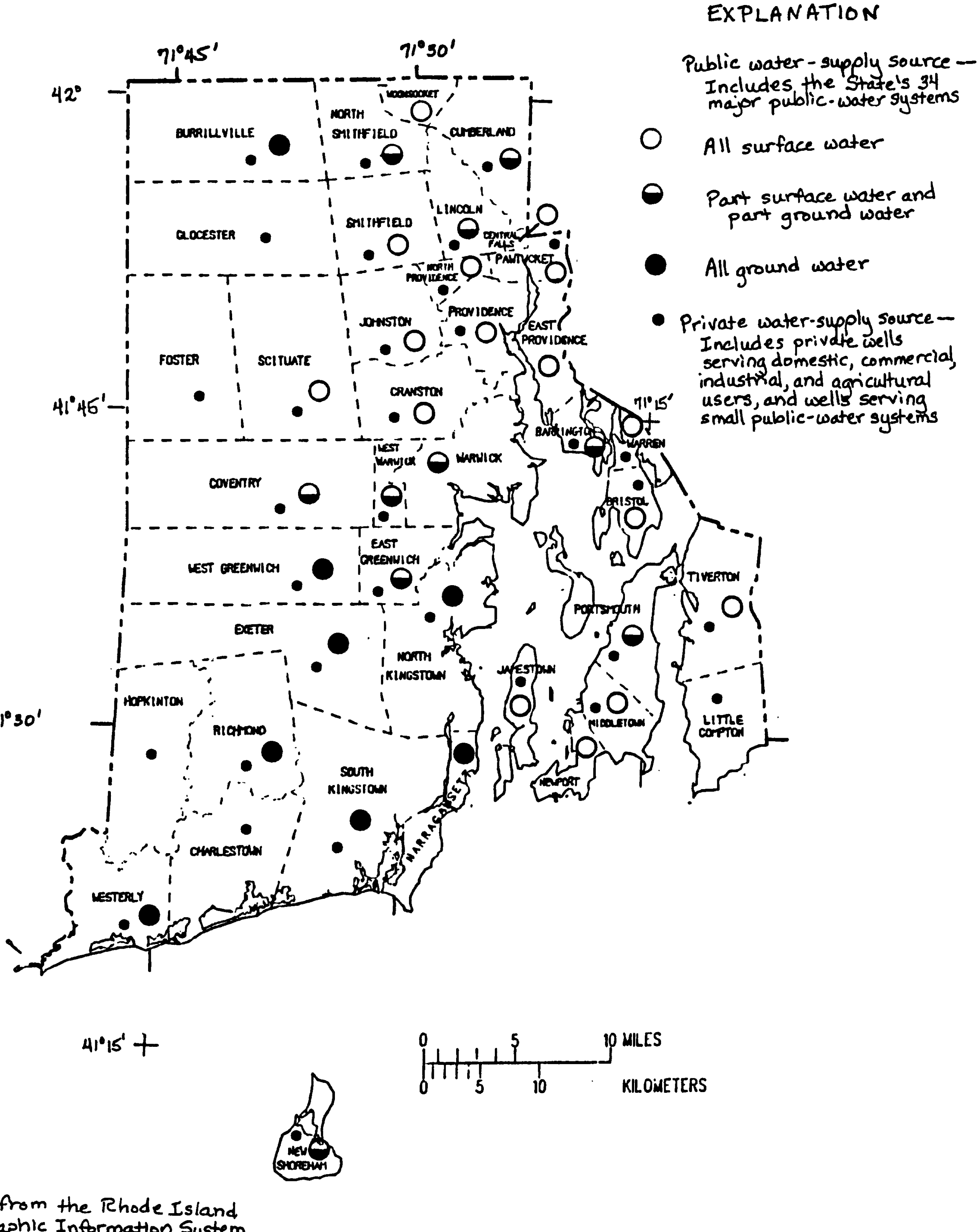


Figure 3.--Sources of water for Rhode Island cities and towns in 1985. (Source: Data from water suppliers. Compiled by E.C.T. Trench, R.W. Bell, and K.D. Mulvey, U.S. Geological Survey.)

Ground-water withdrawals averaged approximately 27 million gallons per day in 1985, and were distributed among the following uses (fig. 2):

Public supply--------------------	56 percent
Domestic (self-supplied)---------	21 percent
Industrial (self-supplied)-------	16 percent
Agricultural (self-supplied)-----	7 percent

Ground-water sources provided drinking water for 236,000 residents, or 24.4 percent of the total population in 1985 (Solley and others, 1988, p. 13, 17). About 152,000 people, or 16 percent of the population, used ground water from public water systems, and another 84,000 people, or 9 percent of the population, were served by private wells. Eighteen cities and towns used ground water for some or all of their public supply in 1985 (fig. 3). The city of Pawtucket, which supplies water to Central Falls, has public-supply wells that were not used in 1985.

The southern and western parts of Rhode Island rely most heavily on ground water (fig. 3). Ground water was the only source of public or private drinking water for 12 towns in 1985. Ground water is used throughout the State, however, and public or private wells serve people and industries in at least 35 of the State's 39 cities and towns (fig. 3).

Population Growth and Ground-Water Development

Rhode Island ranked second in population density among the 50 States in 1985 (Rhode Island Department of Administration, 1989). The population of Rhode Island grew from 604,000 in 1920 to 968,000 in 1985 (Rhode Island Department of Economic Development, 1987, p. 28, 35).

In the early part of the 20th century, the population was concentrated in a few cities. In 1920, the city of Providence accounted for almost 40 percent of the State's population. Providence, Pawtucket, and Woonsocket (fig. 3), the State's three largest cities in 1920, accounted for about 57 percent of the population (Rhode Island Department of Economic Development, 1987, p. 35). Since World War II, the population has grown dramatically in formerly rural areas. A comparison of population data for 1970 and 1985 shows that suburbs and rural towns have the fastest growth rates in the State (Rhode Island Department of Economic Development, 1987, p. 28, 31). In 1985, Providence, Pawtucket, and Woonsocket accounted for only 28 percent of the total population (Rhode Island Department of Economic Development, 1987, p. 28). Suburban growth has stimulated the use of ground water, initially from private wells in sparsely settled areas and eventually from public-supply wells as residential densities have increased.

Effects of Land Use on Ground-Water Quality

Most of the ground-water contamination in Rhode Island has been caused by human activities at or near the land surface. Recent studies in Connecticut also indicate that subtle changes in ground-water quality can commonly be related to land use (Grady and Weaver, 1988). Rhode Island's surface water and ground water are interconnected bodies of freshwater, and the water quality of one can affect the quality of the other. Consequently, some land-use and waste-disposal practices may contaminate surface water and ground water.

Generalized land use and projected changes in Rhode Island are shown in figure 4 for the period 1960-2010. Land-use percentages shown are approximate because of changes in planning assumptions and differences in definitions of land-use categories.

Undeveloped land, including woodland, agricultural land, open land, conservation and recreation land, and wetland, covered 82 percent of the State in 1960 (fig. 4) (Rhode Island Statewide Planning Program, 1975, table 33, p. 133). Undeveloped land accounted for 62 percent of the State's land in the mid-1980's, and it is projected to decrease to 55 percent of the total land area by the year 2010 (fig. 4) (Rhode Island Department of Administration, 1989, p. 5.29). The undeveloped-land category includes some low-density development, primarily residential areas with house lots of 5 acres of more (Grace Beiser, Rhode Island Department of Administration, oral commun., 1989).

Residential land use has increased dramatically, growing from 8 percent of the State's land area in 1960 to 15 percent in 1975 (fig. 4). A large amount of additional development, particularly in rural communities, has taken place since 1975, but accurate acreage figures are unavailable for the mid-1980's (fig. 4) (Rhode Island Department of Administration, 1989, p. 5.5). Residential land is projected to encompass approximately 30 percent of the State in 2010 (fig. 4).

As more of the State's rural and forested land is developed, ground-water quality will probably change and the potential for contamination will increase in these areas. Desirable locations for residential, commercial, industrial, or agricultural development commonly overlie sources of abundant ground water.

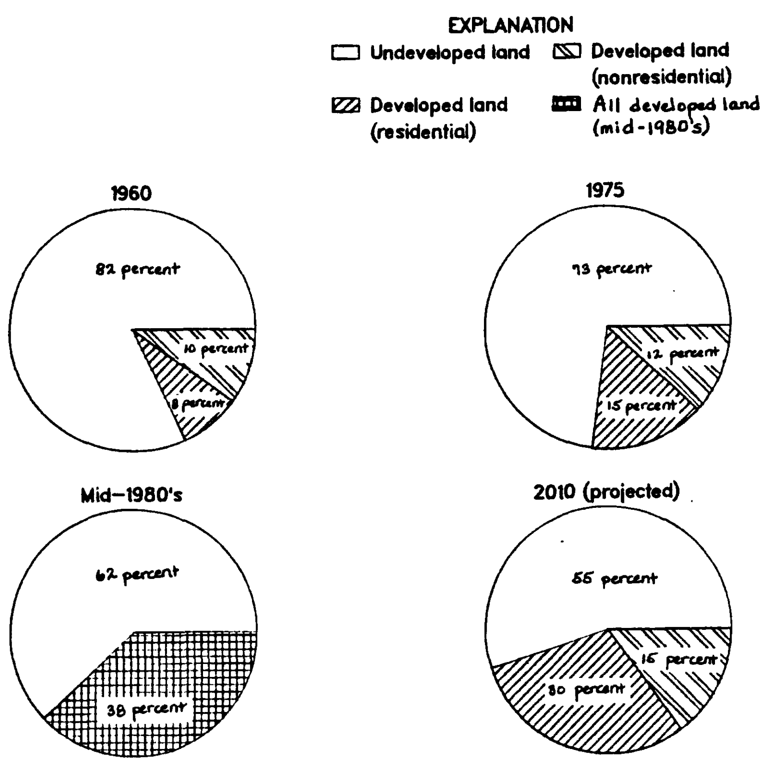


Figure 4.--Generalized land use and projected changes in Rhode Island for the period 1960-2010. (Sources: Data from Rhode Island Statewide Planning Program, 1975, table 33, p. 133; and Rhode Island Department of Administration, 1989, table 121-5 (12), p. 5.21; table 121-5 (13), p. 5.22; p. 5.29. Compiled by E.C.T. Trench and R.W. Bell, U.S. Geological Survey.)

THE OCCURRENCE OF GROUND WATER IN ROCKS AND SEDIMENTS

Ground water fills the pore spaces, fractures, and cavities in the sediments and rocks of the Earth's crust. Ground water is present below the land surface everywhere in Rhode Island, although the quantity available for use differs considerably from place to place.

Vertical Distribution of Underground Water

Underground water occurs in the unsaturated zone and the saturated zone (fig. 5). The land surface is the upper boundary of the unsaturated zone, which in Rhode Island generally ranges in thickness from a few inches to as much as 40 feet. Within the unsaturated zone, pore spaces and fractures in the earth materials contain variable amounts of air and water, and the fluid pressure in any water present is less than atmospheric pressure.

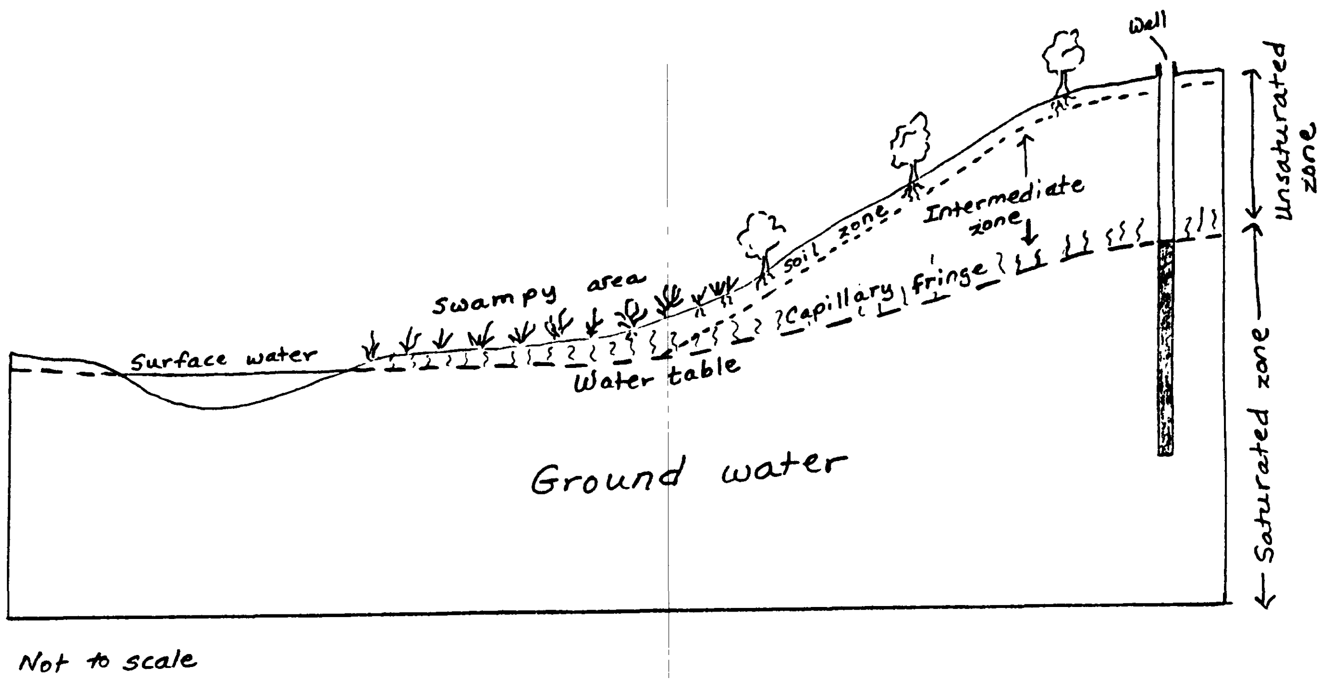


Figure 5.--Zones in which subsurface water is found in Rhode Island. (Source: Modified from Heath, 1983, p. 4.)

The unsaturated zone includes the soil zone and the intermediate zone (fig. 5). The soil zone contains organic matter and supports plant life. The intermediate zone, formed of unconsolidated materials or rock, is less biologically active than soil and does not commonly contain organic matter.

In the saturated zone, located beneath the unsaturated zone (fig. 5), all pore spaces and fractures are filled--or saturated--with water, and the fluid pressure is greater than atmospheric pressure. The water within the saturated zone is referred to as ground water. The irregular upper surface of the saturated zone is called the water table (fig. 5). The position of the water table is indicated by the level at which water stands in unused shallow wells (fig. 5). The water table is within 20 feet of the land surface in most parts of Rhode Island, but may be as deep as 40 feet. The water table is generally deeper on hilltops and closer to the land surface in valleys (fig. 5). In some low-lying areas, the water table may be at or very near the land surface during all or most of the year, in which case the unsaturated zone is thin or absent and the land surface is swampy.

The transition from the unsaturated zone to the saturated zone is not always sharply defined. Capillarity, the tendency for a liquid to cling to the surface of a solid material, draws water up from the saturated zone into the unsaturated zone and forms a capillary fringe (fig. 5) (Leopold and Langbein, 1960, p. 6; Heath, 1983, p. 16). The capillary fringe and the soil zone may overlap where the water table is near the land surface (fig. 5).

Water is held in the capillary fringe by surface tension. In fine-grained materials such as silt, pore spaces are very small, surface-tension forces predominate, and the capillary fringe may be several feet thick. In coarse-grained materials such as sand and gravel, pore spaces are large, the force of gravity predominates, and the capillary fringe may be only a few inches thick or may be absent.

Earth Materials and their Water-Bearing Characteristics

Local geology determines the availability of ground water in Rhode Island. Earth materials differ widely in their capacity to store, transmit, and yield water. Water-bearing characteristics are governed by the nature of the pore spaces or fractures within the material and by the extent and thickness of the material. Thus, knowledge of earth materials is necessary to locate, develop, and protect ground-water supplies. An understanding of ground water in Rhode Island requires information on the characteristics and distribution of the earth materials that underlie the State.

Major Types of Earth Materials

Water-bearing earth materials include sediments and consolidated rocks. Sediments are unconsolidated materials composed mostly of particles and fragments derived from the disintegration of consolidated rocks. Particles that form sediments may range in size from clay to boulders (fig. 6A). Unconsolidated materials are always underlain at some depth by consolidated rocks, which form the Earth's crust. Consolidated rocks consist of minerals or rock fragments of various sizes and shapes that have been solidified by relatively high temperatures and pressures or by chemical reactions. Consolidated rocks, referred to as "bedrock" in ground-water reports, are called ledge in the New England vernacular.

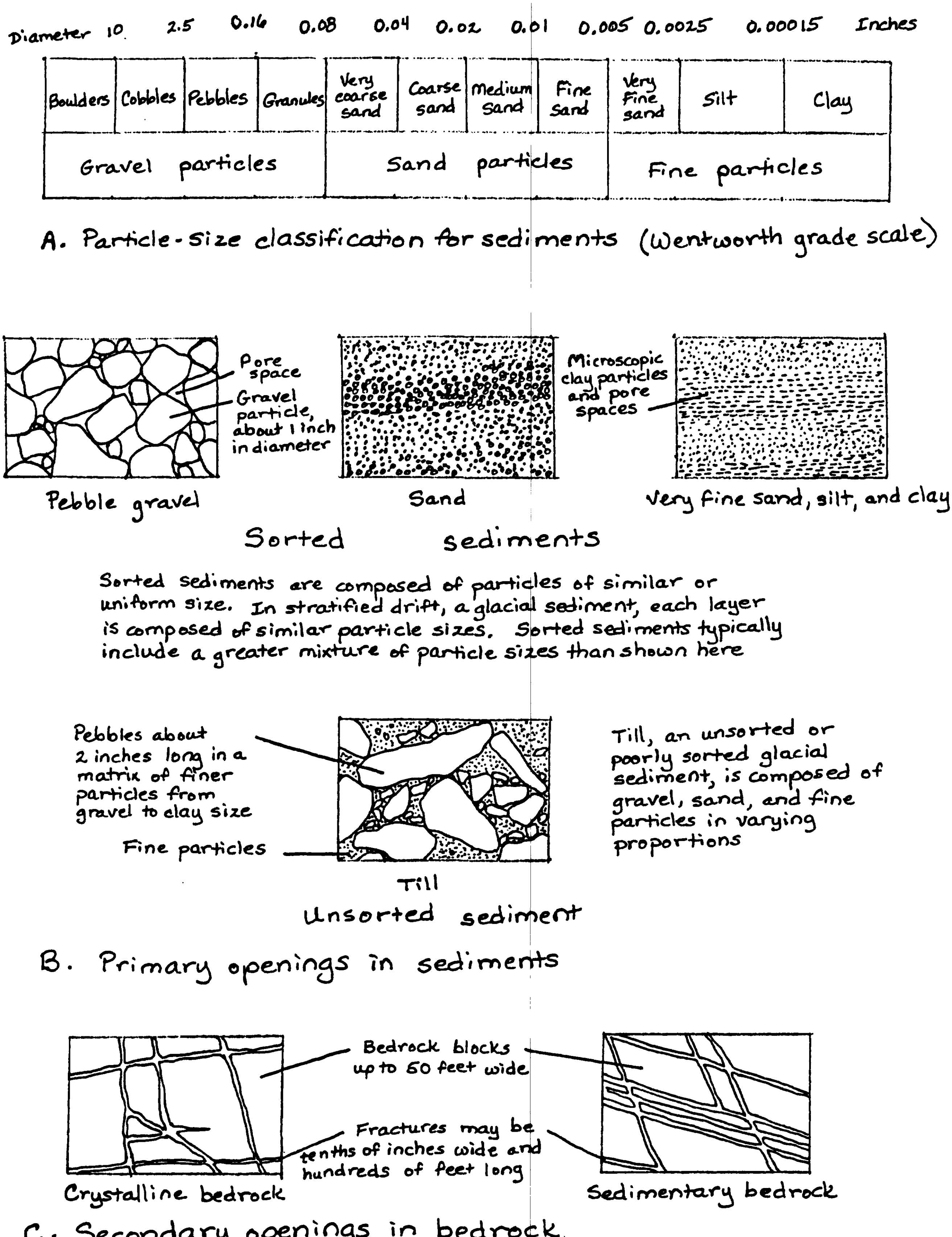


Figure 6.--Particle sizes and water-bearing openings in Rhode Island's principal earth materials. Scale of individual drawings varies. (Source: A and B modified from Stone and others, 1979, sheet 3, figs. 2 and 3.)

Consolidated rocks can be divided into three major groups--igneous, sedimentary, and metamorphic--on the basis of their origin. Igneous rocks form when molten or partially molten material cools and solidifies. Intrusive igneous rocks, such as granite, solidify at great depths below the land surface. Extrusive igneous rocks form from lava or volcanic ash ejected onto the land surface. Most sedimentary rocks form from sediment transported and deposited by water, ice, or air. These sediments may gradually become consolidated rocks if they are subjected to deep burial and compression or chemical changes. Metamorphic rocks are rocks whose structure and mineral composition have been changed as a result of great heat and pressure deep beneath the Earth's surface. Metamorphic rocks and intrusive igneous rocks have many similar characteristics, and they are often collectively termed "crystalline" rocks.

Granite is the most common igneous rock in the State. Common sedimentary rocks include conglomerate, sandstone, and shale. Gneiss and schist are common metamorphic rocks. Most unconsolidated materials in Rhode Island, as in the rest of New England, are glacial sediments.

Storage Properties

An earth material's capacity to store water is determined by its porosity. Most sediments and consolidated rocks near the Earth's surface contain pore spaces or fractures. A material's porosity is the ratio of openings (pores) to the total volume of the rock or sediment. The more porous the material, the greater its ability to store water. Earth materials differ widely in the size and arrangement of their water-bearing openings and, consequently, in the amount of water they can store. Typical arrangements of water-bearing openings in Rhode Island's major rocks and sediments are shown in figure 6.

Primary openings are the pore spaces that form at the time the rock or sediment forms, such as the pores between the grains in sand, gravel, or other sediments (fig. 6B). Sediments usually have a large volume of primary openings. Consolidation, compaction, and chemical changes tend to reduce the size and number of the primary pore openings in older rocks. Crystalline rocks, formed at depth under great pressures, do not have many primary openings.

Secondary openings, such as the fractures in granite, form after the rock becomes solid. Most ground water in Rhode Island bedrock occurs in fractures that are secondary openings (fig. 6C).

If all pore spaces and fractures in a sediment or rock are filled with water, the material is said to be saturated. Porosity indicates the maximum amount of water that a unit volume of material can contain when it is saturated; however, only some of this water is available to supply a well. When water drains from a rock or sediment, surface tension causes some water to be retained as a film on rock surfaces and in very small openings. Specific yield refers to the proportion of water that drains from the material under the influence of gravity.

Different materials have characteristic values of porosity and specific yield (Heath, 1983, p. 9). For example, sand, gravel, and clay are all very porous. Water drains easily from coarse sand and gravel, which have somewhat rounded grains with large pore spaces between grains. These materials have a high specific yield and thus yield water readily to wells.

Clay, on the other hand, has very fine grains. In the microscopic pore spaces between clay particles, surface-tension forces that retain water predominate over the influence of gravity. In spite of its high porosity, clay has a low specific yield. Gardeners can recognize this principle in the way that sandy soil drains quickly after rain, whereas clayey soil retains water.

The amount of water stored in a geologic formation is determined by the porosity of the material and the volume of the formation below the water table. A formation is an identifiable unit of the Earth's crust, such as a particular type of bedrock or a deposit of sand and gravel. Saturated thickness is the thickness of the formation below the water table (fig. 7). The greater the saturated thickness, the greater the volume of water in storage and the greater the potential value of the formation as a source of water. The variable saturated thickness of a sand and gravel deposit is shown in figure 7. Saturated thickness typically ranges from 40 to 100 feet in major sand and gravel deposits of Rhode Island.

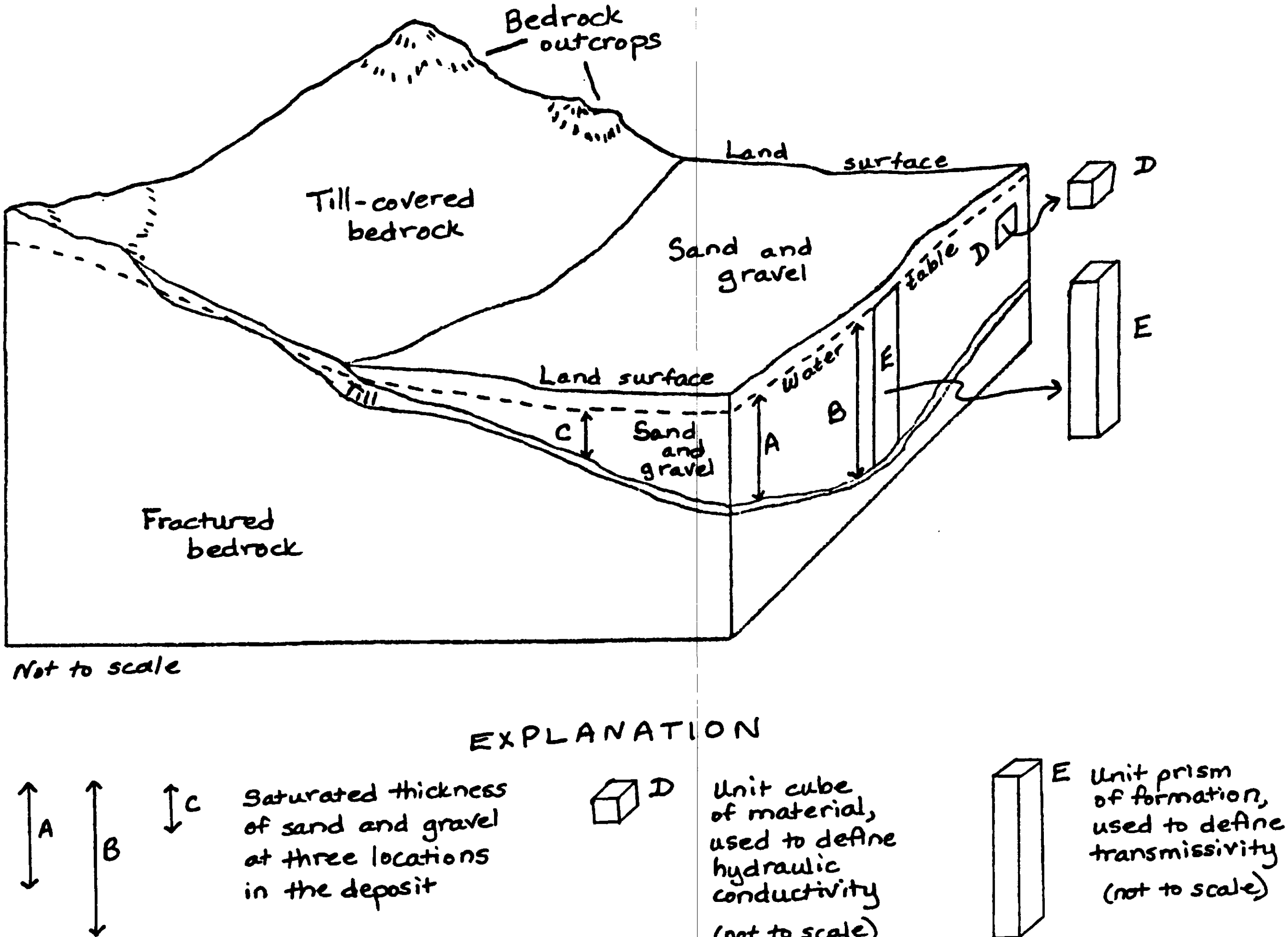


Figure 7.--Generalized dimensions used to calculate saturated thickness, hydraulic conductivity, and transmissivity in a sand and gravel deposit. If the material is identical, transmissivity is greater at B than at A or C, because the saturated thickness is greater at B.

Transmitting Properties

Ground water flows through some materials more easily than through others. Hydraulic conductivity is a precisely defined, quantitative measure of the capacity of a unit volume of material to transmit water under a standard set of conditions (fig. 7). Hydraulic conductivity is determined by the size and arrangement of pores or fractures and by the characteristics of the water. Measurement of hydraulic conductivity enables comparison of the water-transmitting properties of different earth materials from different places. A numerical value of hydraulic conductivity does not represent the actual rate at which water moves through the material in nature, although it can be used in conjunction with other measurements to calculate that rate.

In qualitative terms, it is common to refer to a sediment or rock as "permeable" if it has a high hydraulic conductivity and "impermeable" if it has a very low hydraulic conductivity. Coarse-grained materials such as sand and gravel are highly permeable, whereas fine-grained materials such as silt and clay and unfractured crystalline bedrock are nearly impermeable.

Earth materials are not typically uniform and homogeneous. Consequently, hydraulic conductivity differs from place to place within the same material. The hydraulic conductivity of an earth material may also differ in different directions. Sediments are often more permeable in the horizontal direction than in the vertical direction. In this report, hydraulic conductivity refers to horizontal hydraulic conductivity unless otherwise specified.

The following values of hydraulic conductivity have been estimated or measured for sediments from selected locations in Rhode Island (Allen and others, 1963, p. 8-10; Rosenshein and others, 1968, p. 10).

Material	Hydraulic conductivity (feet per day)
Gravel	470
Sand and gravel	200
Sand	110
Fine sand	55
Clay and silt	0.4
Till	1.2

Hydraulic conductivity is expressed here in units of feet per day, a shorthand form for cubic feet of water per day per 1-square-foot cross-section of material.

Transmissivity is the capacity of a unit width of a formation to transmit water (fig. 7). It is equal to the hydraulic conductivity of the material, as measured in the horizontal direction, multiplied by the saturated thickness of the formation. For example, a sand and gravel deposit with a saturated thickness of 70 feet and an average hydraulic conductivity of 200 feet per day would have a transmissivity of 14,000 feet squared per day. Because the saturated thickness and the hydraulic conductivity of a formation may differ from place to place, transmissivity may differ considerably within a small geographic area.

Transmissivities ranging from 5,000 to 39,000 feet squared per day have been calculated for two major sand and gravel deposits in the Pawcatuck River basin (Dickerman and Ozbilgin, 1985, p. 32-33; Johnston and Dickerman, 1985, p. 36). Methods used to calculate the transmissivity of sand and gravel deposits at various locations in Rhode Island are discussed by Dickerman (1984) and Lang and others (1960).

Aquifers, Semiconfining Units, and Confining Units

Earth materials in Rhode Island can be classified as aquifers, semiconfining units, or confining units based on their water-bearing characteristics. A formation or group of formations of either rock or sediments that will yield water in a usable quantity to a well or spring is known as an aquifer. An aquifer has economic value as a source of water supply. In contrast to aquifers, confining units are nearly impermeable. A confining unit restricts the movement of ground water either into or out of adjacent aquifers. Semiconfining units are typically materials of intermediate permeability. Semiconfining units slow down the movement of ground water but do not prevent movement. Such units are sometimes referred to as "leaky", and they are much more common than true confining units in Rhode Island.

Thick, saturated deposits of sand and gravel have high specific yields, hydraulic conductivities, and transmissivities. These sediments yield water readily to wells and are the most productive aquifers in Rhode Island. Layers of very fine sand, silt, or clay are much less permeable; they form semiconfining or confining units within unconsolidated materials at some locations in the State. A sand and gravel aquifer with lenses and layers of silt and very fine sand is shown in figure 8.

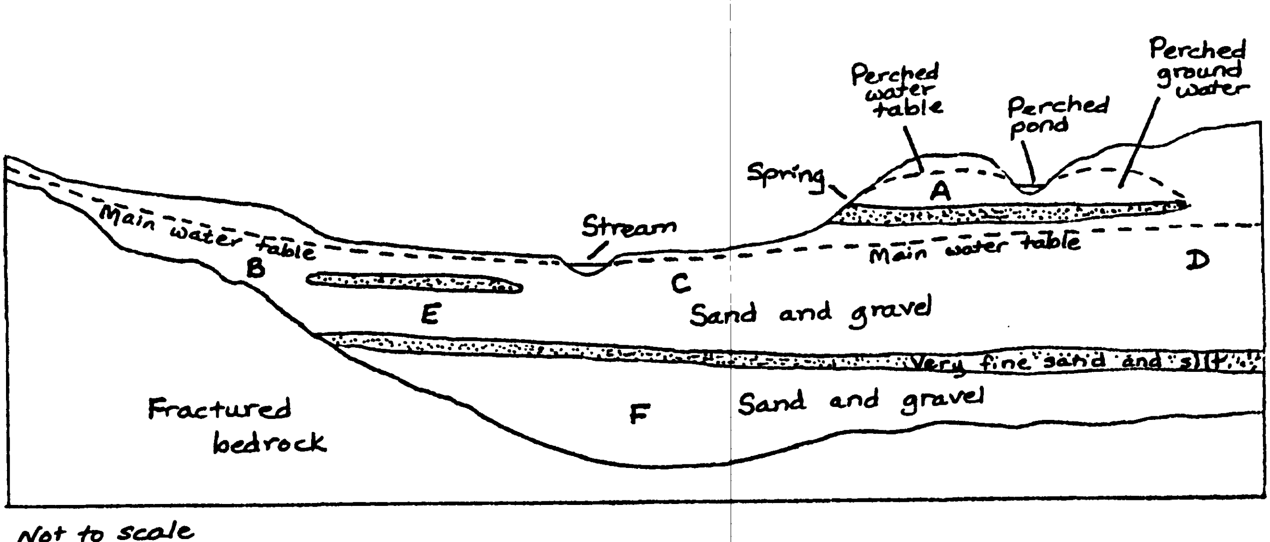


Figure 8.--Unconfined, semiconfined, and confined conditions in a sand and gravel aquifer with lenses and layers of very fine sand and silt. Perched ground water is shown above the main zone of saturation. Locations A through F are discussed in text.

Whether a rock or sediment is considered an aquifer, a semiconfining unit, or a confining unit may depend on the abundance or scarcity of other sources of water supply. Fractured bedrock might be considered an unproductive source in an area of abundant sand and gravel deposits; however, bedrock is an important aquifer in many rural areas of Rhode Island where no other sources of water supply are available.

The water-bearing properties and distribution of earth materials determine whether ground water is unconfined, confined, or semiconfined. Most ground water in Rhode Island is unconfined. In an unconfined aquifer, also called a water-table aquifer, water only partly fills the aquifer, and the water table is free to rise and fall with changes in recharge and discharge. Unconfined conditions are shown at locations A, B, C, and D in figure 8.

Ground water is confined where water completely fills an aquifer that is overlain by a confining unit, such as at location F in figure 8. The confined ground water in the aquifer is under pressure that is substantially greater than atmospheric pressure. Such an aquifer is termed a "confined aquifer" or "artesian aquifer." Wells tapping a confined aquifer are sometimes termed "artesian wells." Water in an artesian well rises to a level above the top of the aquifer, but not necessarily above the land surface. If the water in a well does rise above the land surface, the well is referred to as a flowing well. True confined conditions are uncommon in Rhode Island.

Semiconfined conditions, represented by location E in figure 8, are moderately common in the unconsolidated materials of Rhode Island. Typically, the semiconfining units are thin, small in area, or composed of somewhat permeable materials.

In some places, confining units prevent downward percolation of water. The result is a thin, local saturated zone separated from the main zone of saturation. This situation, referred to as perched ground water, is shown at location A in figure 8. Perched ground water is common on Block Island.

Aquifers in Rhode Island

Rhode Island is part of the Northeast and Superior Uplands ground-water region, which includes most of New England and parts of other northeastern States (Heath, 1984, p. 48). In this region, unconsolidated glacial deposits overlie fractured bedrock (fig. 9).

The geologic history of Rhode Island's bedrock is complex and includes episodes of sedimentary deposition, volcanic activity, intrusion of molten rock, metamorphism, folding, faulting, uplift, and erosion (Quinn, 1976; Boothroyd and Hermes, 1981). Bedrock in Rhode Island ranges from approximately 200 million years old to more than 500 million years old (Quinn, 1971, p. 51-52).

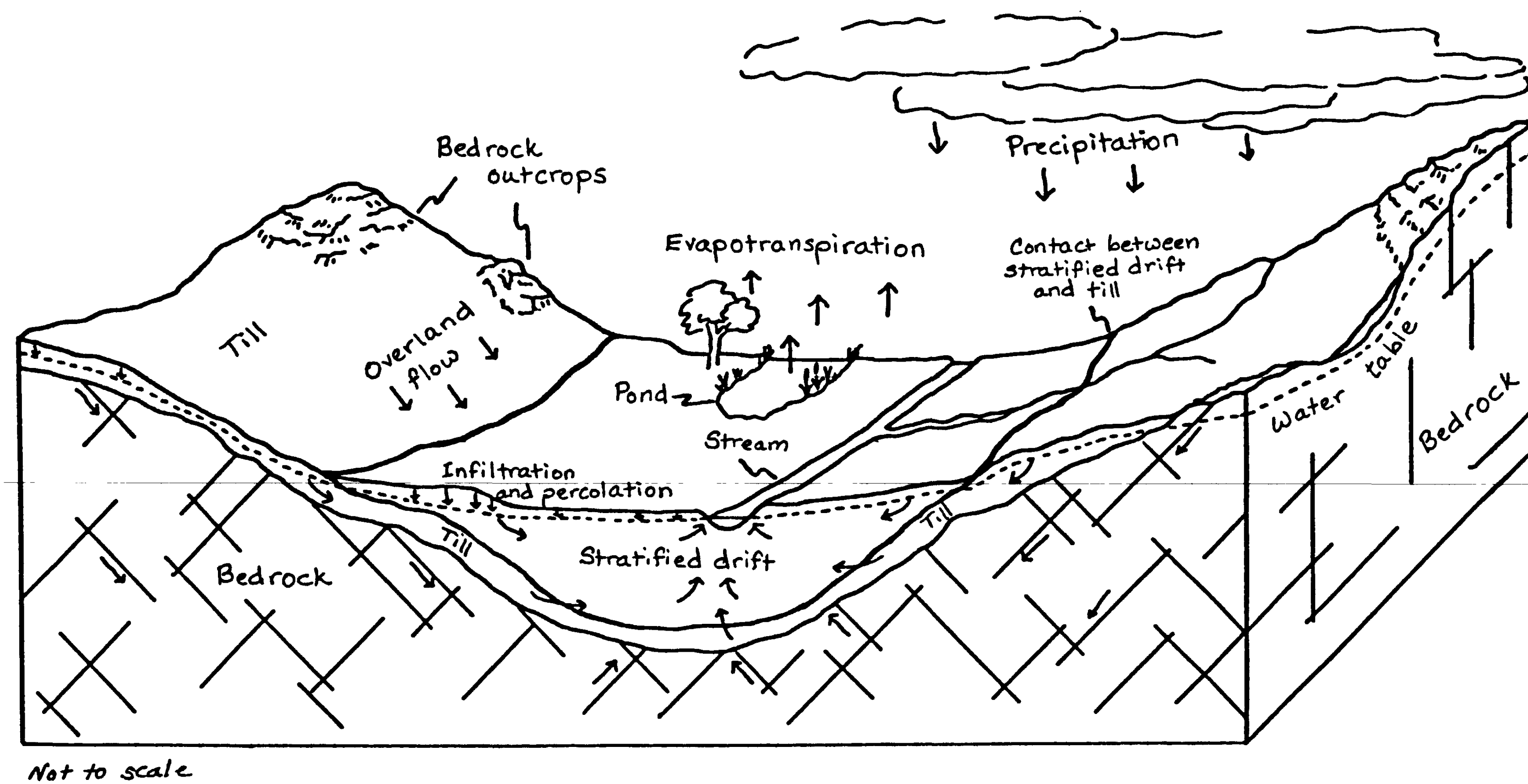


Figure 9.--Typical hydrogeologic setting in glaciated terrain. Unconsolidated glacial deposits overlie fractured bedrock. Till blankets the bedrock surface and is exposed at the land surface in upland areas. Till generally underlies the stratified drift that fills bedrock valleys. Arrows indicate directions of flow or movement of water and water vapor. (Source: Modified from Trench and Morrissey, 1985, p. 4, fig. 1.)

During the Pleistocene Epoch, or Great Ice Age, continental glaciers intermittently covered much of northern North America. From about 22,000 to 12,000 years ago, the most recent continental glacier spread out from eastern Canada, covered New England, and then melted northward (Stone and Borns, 1986, chart 1). When the ice sheet reached its maximum size, ice over much of Rhode Island was probably about 4,000 to 5,000 feet thick (B. D. Stone, U.S. Geological Survey, oral commun., 1989). This ice sheet eroded the bedrock surface and deposited sediments, forming many of the familiar features of today's landscape. Glacial deposits in Rhode Island are approximately 16,000 to 21,000 years old (Stone and Borns, 1986, chart 1).

The two major types of deposits left by the glacier are till and stratified drift. Sediments deposited since the melting of the ice sheet, such as sand dunes, beaches, and swamp deposits, are relatively minor.

Glacial deposits and the underlying bedrock form an interconnected aquifer system (fig. 9). The generalized distribution of major aquifers in Rhode Island is shown in figure 10. At least small quantities of ground water are available virtually everywhere in the State, and ground water is withdrawn from all of the major water-bearing units (fig. 11).

Stratified Drift

Stratified drift is a sorted sediment laid down by meltwater streams from a glacier or deposited in glacial lakes. It includes gravel, sand, silt, and clay deposited in layers of similar or mixed grain size (fig. 6B).

Running water tends to "sort" sediments according to grain size because different stream velocities are capable of carrying different sizes of particles in suspension. Rapidly flowing streams transport and deposit the largest pebbles and cobbles. In streams of moderate velocity, sand and gravel may be deposited. In lakes, fine silt and clay particles gradually settle to the bottom.

Glacial streams are dynamic sedimentary environments. Wide variations in stream velocity may be caused by the alternate melting and freezing of glacial ice resulting from seasonal or even daily temperature fluctuations. Thus, the area and thickness of layers and the extent of sorting in a stratified-drift deposit commonly are variable. Generally, sediments deposited near the glacier are coarser in texture and less well sorted than the sediments, referred to as outwash, that are deposited farther downstream from the glacier's margin (fig. 12). Some sediments are deposited on the ice, within tunnels in the ice, or around stagnant blocks of ice. When the ice melts, these ice-contact deposits collapse, further complicating the sedimentary picture (fig. 12).

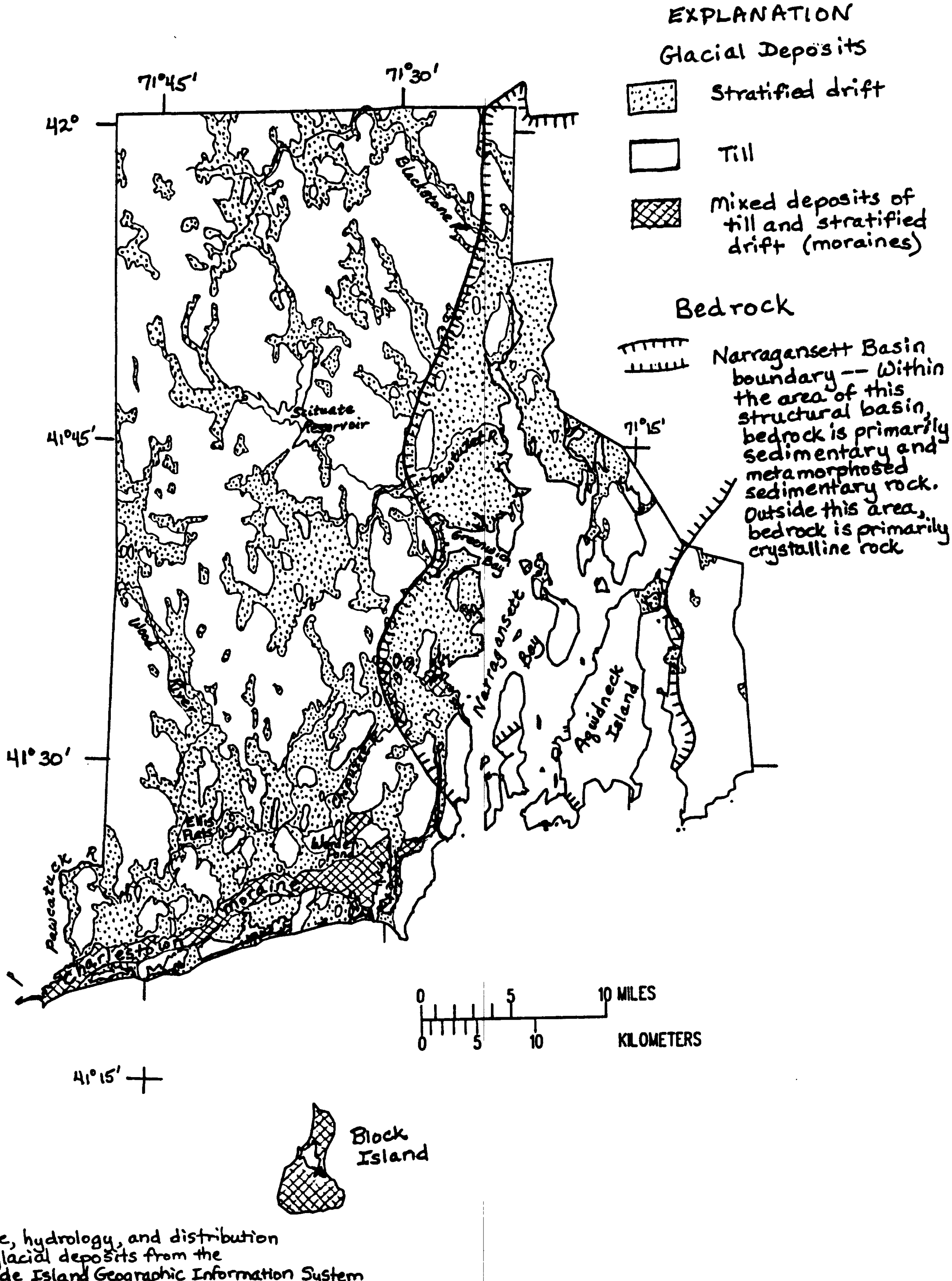


Figure 10.--Generalized distribution of major aquifers in Rhode Island. Bedrock underlies the entire State, and is an aquifer everywhere except on Block Island, where it is 1,000 feet below sea level. Crystalline bedrock underlies most areas outside the Narragansett Basin. (Sources: Narragansett Basin boundary from Frimpter and Maevsky, 1979, p. 3, fig. 2. Distribution of glacial deposits compiled by the University of Rhode Island Environmental Data Center from State reports published in cooperation with the U.S. Geological Survey.)

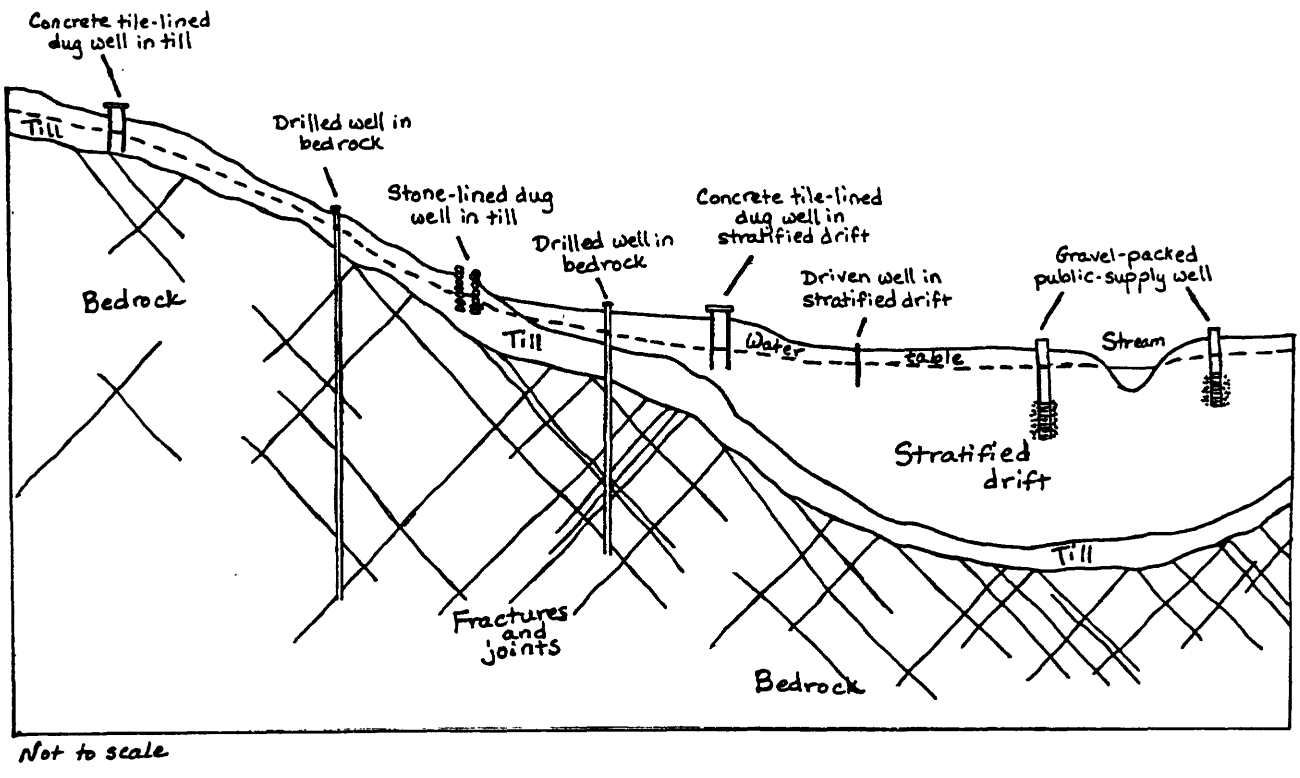
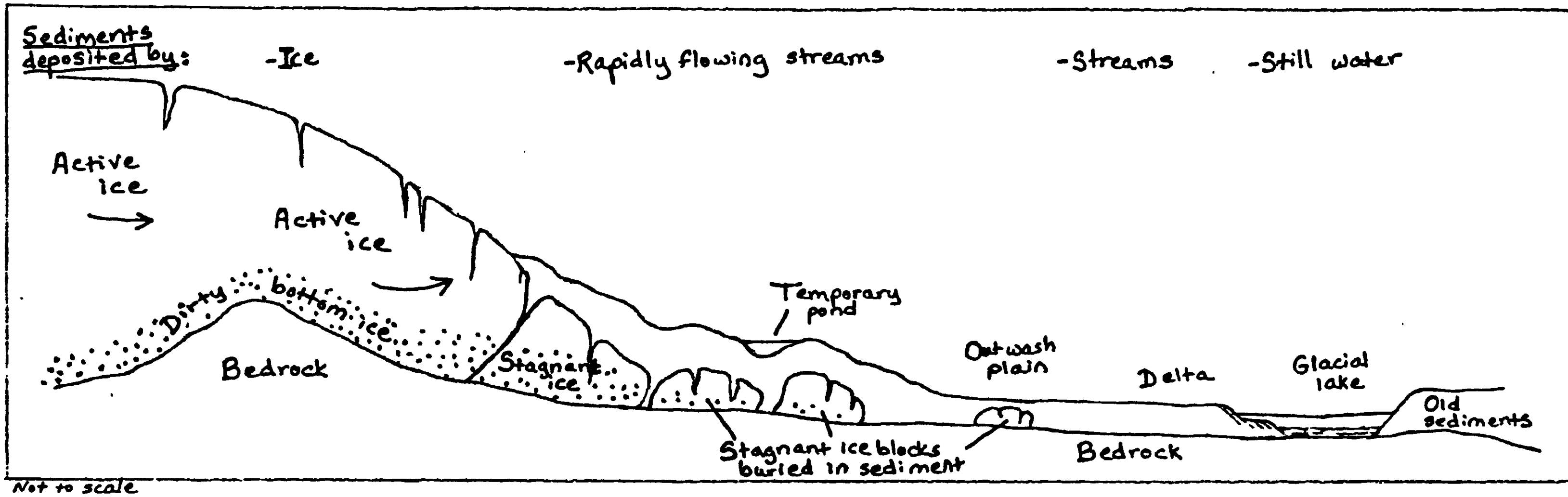
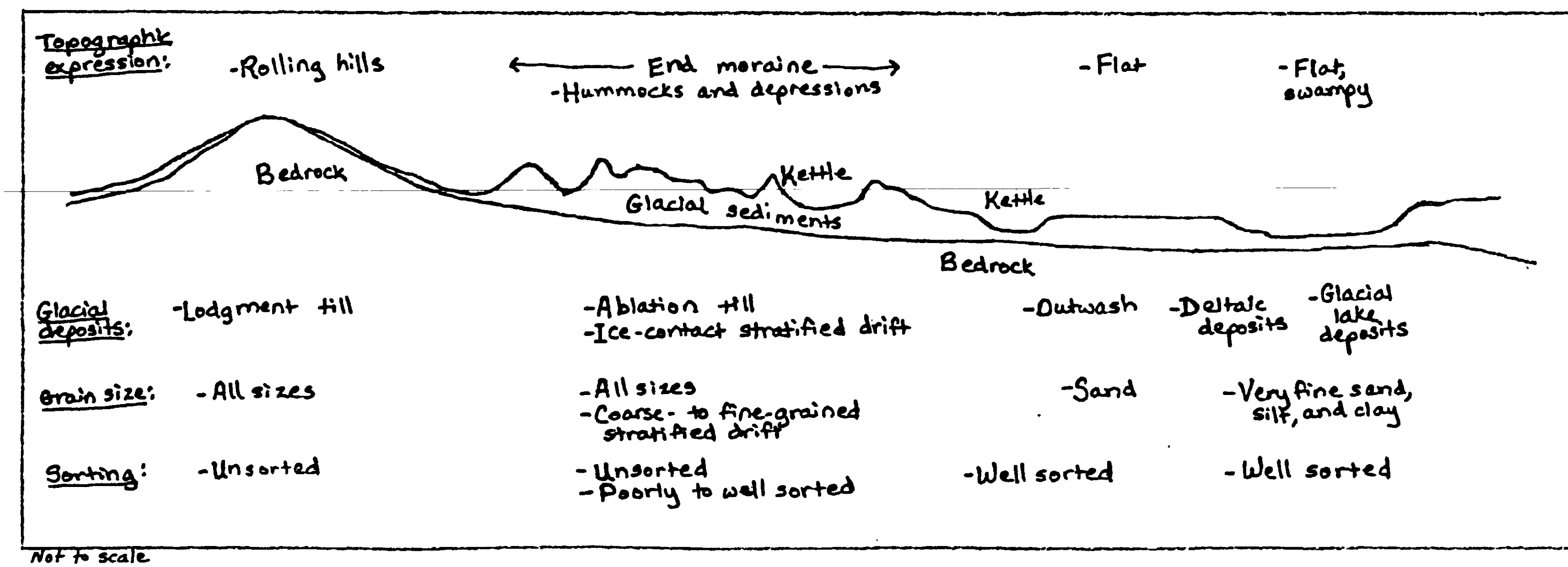


Figure 11.--Types of wells used in Rhode Island, in their common hydrogeologic settings. Nonpumping conditions shown. Typical depths for hypothetical wells shown: dug and driven wells, 15-30 feet; gravel-packed wells, 50-60 feet; drilled wells, 150-250 feet.



A. Depositional conditions during deglaciation (if rate of ice melting balances forward movement for a long enough time, an end moraine forms along the margin of the glacier)



B. Present-day sediments and topography

Figure 12.--Formation of glacial deposits and resulting topographic expression and texture of glacial sediments. Thickness of sediments is exaggerated. The horizontal distance pictured here could be in the range of 1 to 10 miles.

Stratified-drift deposits in Rhode Island, as in the rest of southern New England, were laid down primarily as the glacier retreated northward by melting. Stratified drift fills most major stream valleys (figs. 9, 10), as well as many tributary stream valleys. Extensive outwash plains form sandy lowlands bordering upper Narragansett Bay and Block Island Sound (fig. 10). In most places, the stratified drift overlies a layer of till (fig. 9) but elsewhere lies directly on the bedrock surface.

A cap of wind-blown silt and sand 3 to 5 feet thick, deposited after the glacier melted, covers stratified-drift deposits in many areas of southeastern New England (Schafer and Hartshorn, 1965, p. 124). Soils developed in this silt cap are the region's most productive agricultural soils (A.J. Gold, University of Rhode Island, oral commun., 1989).

Altogether, stratified-drift deposits cover about one-third of the State's land surface (fig. 10). Because of the flat terrain and easily excavated material, land underlain by stratified drift is often considered desirable for the construction of housing developments, industrial parks, and highways.

Stratified drift typically ranges in thickness from a few feet in small deposits or along the edges of large deposits to 100 feet or more in several large stream valleys. The maximum known thickness in the State is in the Ellis Flats area between the Wood and Pawcatuck Rivers, where more than 300 feet of stratified drift blankets the bedrock.

Thick deposits of coarse-grained stratified drift form the State's most important aquifers. The Rhode Island Water Resources Board (RIWRB) has identified 21 stratified-drift aquifers that have the best potential of all aquifers in the State for yielding large amounts of water (fig. 13). These high-yield aquifers, termed "ground-water reservoirs" by the State, are stratified-drift deposits with transmissivities equal to or greater than 4,000 feet squared per day and saturated thicknesses equal to or greater than 40 feet (W.B. Allen, Rhode Island Water Resources Board, written commun., 1978). Some ground-water reservoirs have been investigated more intensively than others, and the acquisition of new data could alter the boundaries of ground-water reservoirs shown in figure 13. The ground-water reservoirs represent a small part of the total area underlain by stratified drift (fig. 10).

Major public-supply wells tap many of the ground-water reservoirs. Yields of wells range from 100 to 700 gallons per minute in the thick, permeable parts of the stratified drift, and may exceed 1,500 gallons per minute in the thickest, most permeable areas (Johnston, 1985, p. 374). A yield of 700 gallons per minute, or approximately 1 million gallons per day, is typical of public-supply wells in Rhode Island.

Rhode Island's stratified-drift deposits also include layers of clay, silt, and silty sand deposited in lakes that formed during the melting of the glacial ice (fig. 12). These fine-grained sediments have low hydraulic conductivities and do not form productive aquifers. In some places, such as the southern end of the Chipuxet River valley (fig. 10), silt and clay form a confining layer over sand and gravel deposits.

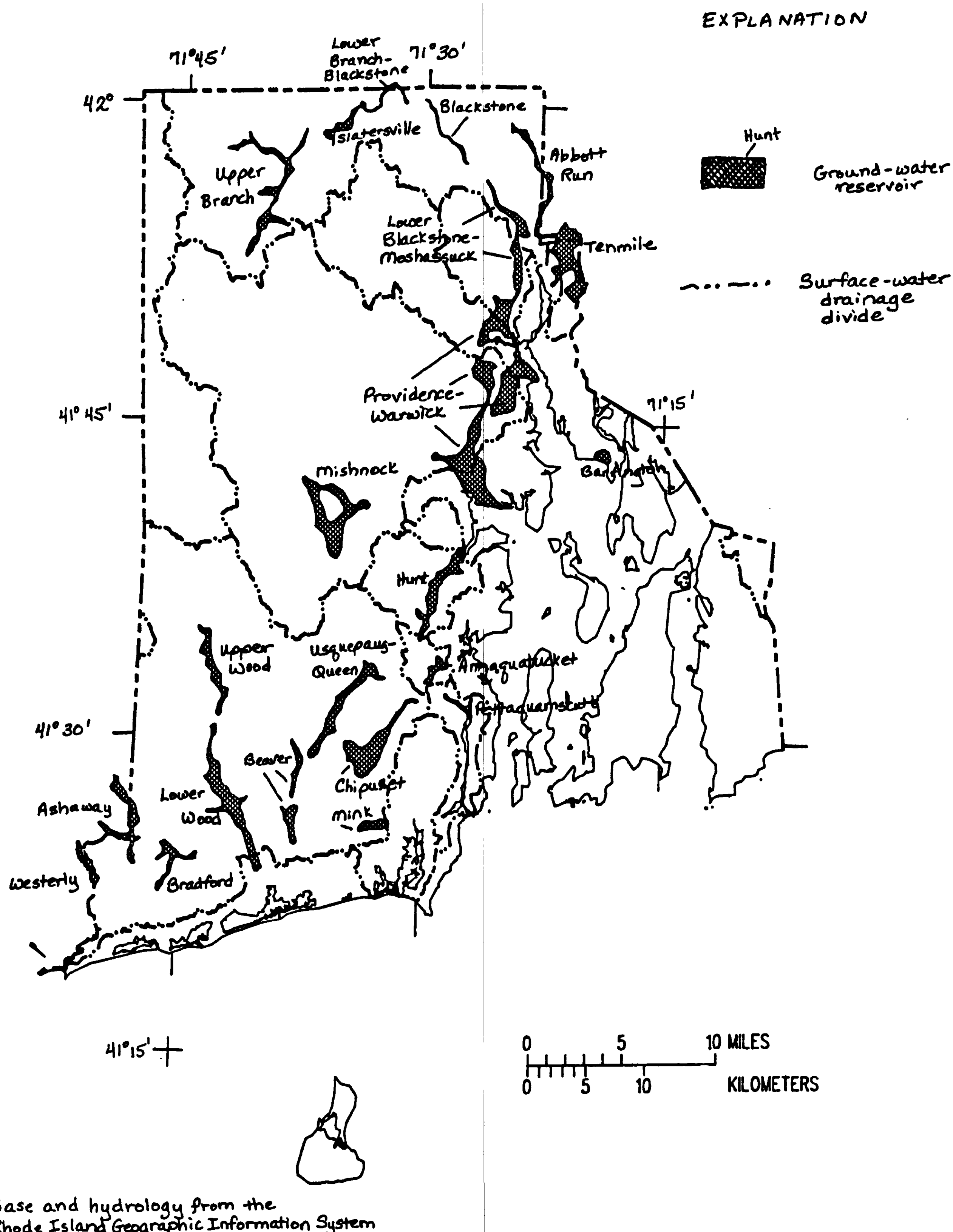


Figure 13.--Distribution of ground-water reservoirs in Rhode Island. (Source for boundaries of ground-water reservoirs: W.B. Allen, Rhode Island Water Resources Board, written commun., 1978; modified by Rhode Island Department of Environmental Management, 1988.)

Till

Till is a sediment deposited directly by a glacier (fig. 12). It is composed of boulders, gravel, sand, silt, and clay mixed in various proportions, and lacks the layering and sorting typical of water-laid deposits (fig. 6B). Till, locally called "hardpan," is usually compact, stony, and difficult to dig. Lodgment till, deposited directly beneath the base of the slowly moving ice, is generally harder and more compact than ablation till, formed as the ice sheet melted and particles within the ice were gradually let down to the ground or deposited along the margin of the glacier (fig. 12).

Till is the most extensive glacial deposit in Rhode Island (fig. 10), as in the rest of the glaciated northeastern United States. It was laid down by the ice as a nearly continuous blanket in the valleys and on uplands (Heath, 1984, p. 48-49). In most valleys and lowlands, till is covered by stratified drift, whereas on most hills and hillsides, till forms a thin, discontinuous veneer on the bedrock (fig. 9). The till surface in Rhode Island is generally bouldery (J.R. Stone, U.S. Geological Survey, oral commun., 1989). The thickness of the till is variable, but averages about 20 feet.

Till is a minor aquifer in Rhode Island because of its generally low permeability and limited saturated thickness. Yields of large-diameter dug wells in till are commonly less than 2 gallons per minute (Johnston, 1985, p. 376). Some shallow dug wells in till are still used for household water supplies in rural parts of Rhode Island; however, many dug wells have been replaced by wells drilled into the underlying bedrock. Shallow wells in till are easily contaminated and often yield insufficient amounts of water for modern household demands. During droughts, such wells may go dry. Till functions primarily as a storage reservoir that supplies recharge by gravity drainage to the underlying bedrock aquifers and to downgradient stratified-drift aquifers.

Mixed Glacial Deposits

An end moraine is a ridge-like accumulation of deposits that forms along the margin of a glacier if the forward movement of the ice front is balanced by the melting (ablation) of the ice for a long period of time (fig. 12). The Block Island and Charlestown moraines in Rhode Island each accumulated during a period of a few hundred years (Stone and Borns, 1986, chart 1).

The environment of a glacier's margin includes meltwater streams underneath and on the glacier, temporary ponds in depressions on the surface, stagnant isolated ice blocks buried in sediment, and deep ice fractures that accumulate sediment (fig. 12a). The surface of the ice becomes increasingly irregular as it melts, and sediments accumulating on the ice collapse or slide onto other sediments in depressions. The resulting deposits have irregular, hummocky topography and are composed of distorted layers of ablation till, ice-contact stratified drift, and well-sorted outwash (fig. 12b) (Kaye, 1960, p. 351-358).

End moraines in Rhode Island are fragments of long moraines deposited along the margin of the glacier across several northeastern States during the retreat of the most recent continental ice sheet (fig. 14). Block Island is a small fragment of the end moraine that marks the maximum southward position of the last ice sheet (fig. 14) (Larson, 1982, p. 101-102). The island is composed of a complicated series of layers of till and stratified drift. The Charlestown moraine in southern Rhode Island marks a major position of the ice front during its northward retreat (fig. 14). The moraine includes some lenses of stratified sand and gravel in a thick deposit of till. The hummocky belt of ridges and mounds is 0.5 to 2 miles wide (figs. 10 and 14) and extends from Westerly to South Kingstown.

Private wells tap moraine deposits in some rural areas. Yield depends on whether the well taps the predominant till, a lens of fine-grained stratified drift, or a lens of coarse-grained stratified drift. The ablation till in moraines is generally less compact, more sandy, and more permeable than the lodgment till in upland areas. Lenses of fine-grained stratified drift may form local confining units.

Bedrock

Rhode Island's land surface is underlain by numerous bedrock types (Quinn, 1971). Most of these rocks belong to one of two major groups. Sedimentary rocks and metamorphosed sedimentary rocks form a major structural feature, known as the Narragansett Basin, in the eastern part of the State (fig. 10). Rocks of the Narragansett Basin underlie Narragansett Bay, the Bay islands, and mainland areas bordering the Bay, as well as neighboring parts of Massachusetts. Bedrock in the Narragansett Basin includes conglomerate, sandstone, shale, some coal, graphite, and slate. Crystalline rocks, primarily granites, gneisses, and related igneous and metamorphic rocks, underlie most of the central and western part of the State and other areas outside the Narragansett Basin (fig. 10). Bedrock outcrops are visible on many hilltops and hillsides, along parts of the shoreline of Narragansett Bay and its islands, and in highway roadcuts and quarries.

Ground water in bedrock is stored and transmitted through networks of narrow, widely spaced fractures and joints (fig. 11). These openings generally decrease in size and number with increasing depth below land surface because the weight of the overlying rock compresses the openings. Most fractures are present at depths of less than 300 feet in crystalline rocks and at depths of less than 500 feet in metamorphosed sedimentary rocks (Cushman and others, 1953).

Rhode Island's bedrock is the most extensive aquifer in the State, and the most common source of water in rural areas not served by public water supplies. The yield of a bedrock well depends on the number, size, and degree of interconnection of fractures in the saturated zone that are intercepted by the well (fig. 11). Most wells that tap bedrock yield enough water for domestic use; yields commonly range from 1 to 20 gallons per minute (Johnston, 1985, p. 374). The yield of a bedrock well is likely to be greater if the bedrock is overlain by stratified sand and gravel than if the overlying material is till (Allen, 1953, p. 28), because coarse-grained stratified drift is more effective than till as a reservoir and conduit for transmitting water to the underlying bedrock.

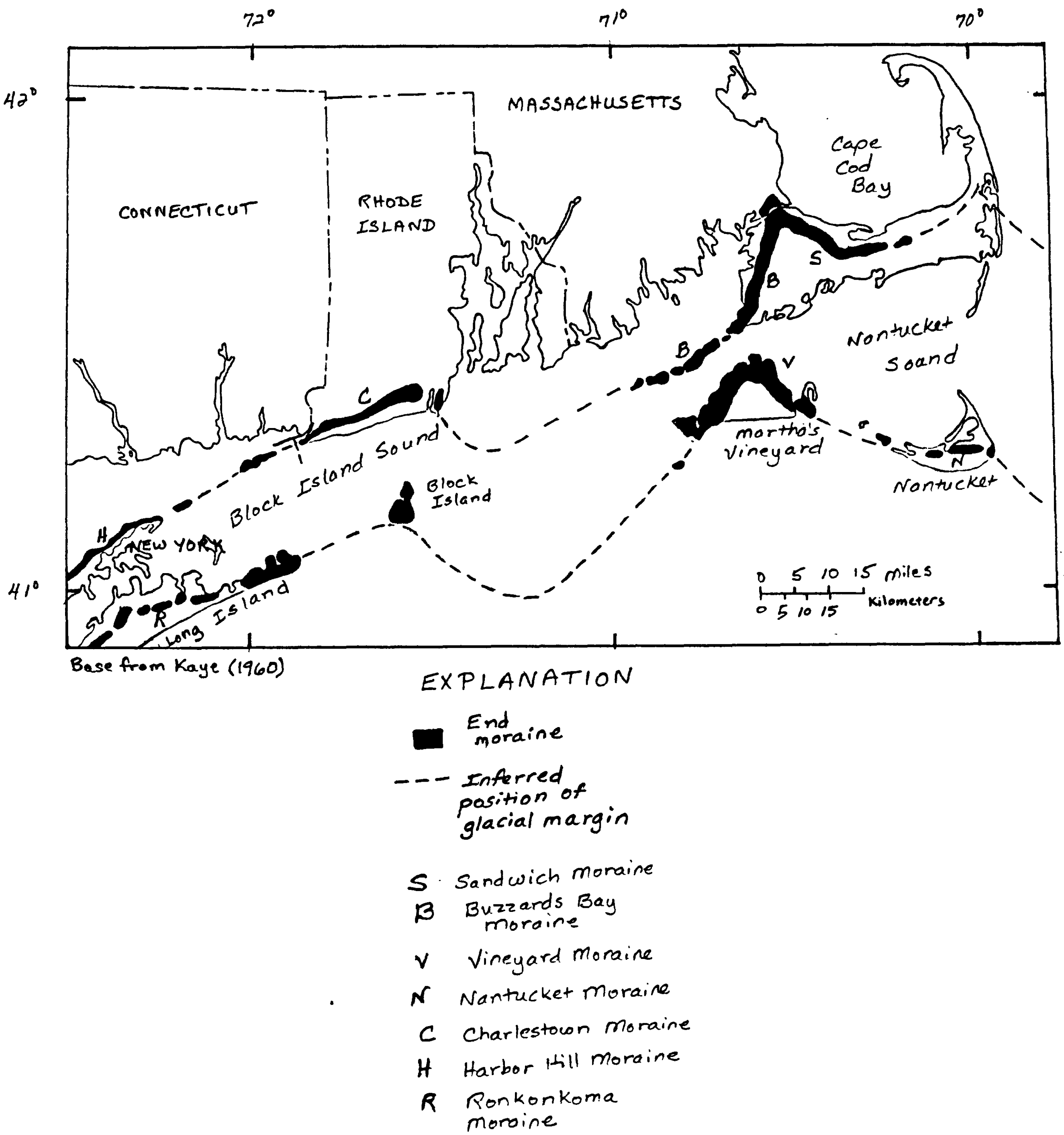


Figure 14.--Major end moraines and maximum extent of glaciation in southeastern New England. Moraine deposits and the dashed lines connecting them mark major positions of the margin of the continental ice sheet. The continental shelf south of the ice sheet, now submerged beneath the ocean, was exposed land. Numerous small moraines to the north, formed during retreat of the glacier, are not shown. (Sources: Modified from Kaye, 1960, fig. 46; U.S. Geological Survey, 1976, fig. 3; Larson and Stone, 1982, p. 102, fig. 1.)

GROUND-WATER FLOW

Ground-water flow is part of the planetary circulation of water known as the hydrologic cycle (fig. 15). The volume of ground water within the Earth remains approximately the same, but "new" water is constantly added to the saturated zone and "old" water constantly leaves the saturated zone. The new water added is termed "recharge", and the old water that leaves is termed "discharge."

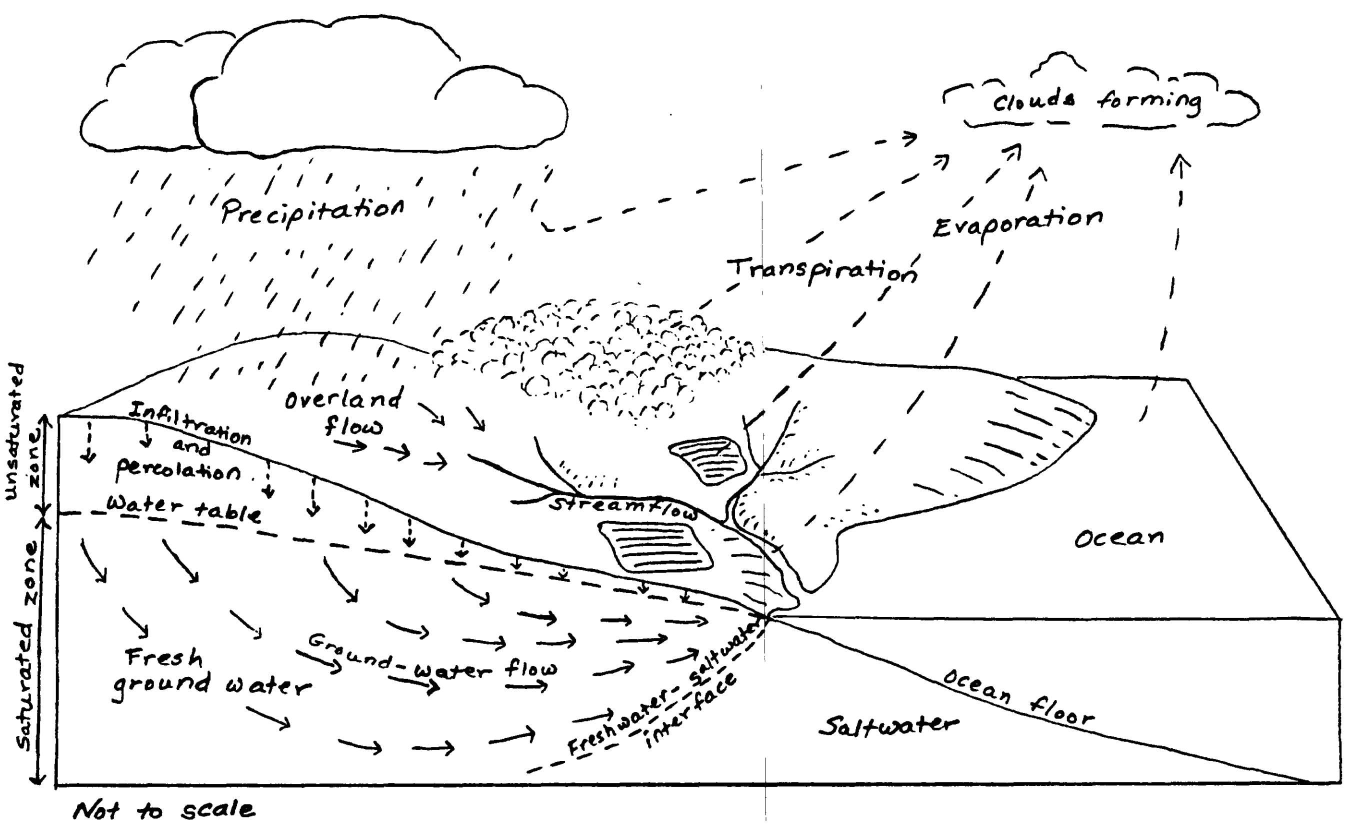


Figure 15.--The generalized hydrologic cycle. Arrows show movement of water and water vapor. (Source: Modified from Heath, 1983, p. 5.)

Contrary to a popular misconception, ground water in Rhode Island does not occur in distinct subterranean streams flowing from distant, pristine sources. Ground water flows slowly through the small pore spaces in unconsolidated materials and the joints and fractures in bedrock. The general direction of ground-water flow is from highlands toward nearby stream valleys (fig. 9).

Ground water flows slowly compared to surface water, and its movement is not visible at the land surface. Ground water contaminated at one place may flow hundreds or thousands of feet and may impair the quality of drinking water over a large area. Accurate knowledge of where ground water comes from, how it moves, and where it goes is essential for protecting this resource.

Recharge

Precipitation is the ultimate source of all ground water in Rhode Island. Under natural conditions, most recharge comes directly from precipitation that falls on the land surface, infiltrates the soil, and percolates downward through the unsaturated zone to reach the water table (fig. 15). Some recharge, however, comes from infiltration of streamwater and from artificial sources. The term "recharge" is used in two ways. It refers to the actual quantity of water that enters the saturated zone at the water table, and it refers to the process by which the water is added.

Infiltration of Precipitation

Intermittent rain and snow may not give the impression of producing a large volume of water; however, 1 inch of rain delivers 17.4 million gallons of water to 1 square mile of land. In a typical year, most parts of Rhode Island receive at least 40 inches of rain (fig. 16A)--696 million gallons per square mile.

About half of the annual precipitation evaporates or is transpired by plants. The remainder either flows downhill to stream channels or infiltrates the land surface and percolates downward through the unsaturated zone to recharge the ground-water system.

Infiltration rates, which vary widely, depend on land-surface and soil conditions and the intensity and duration of precipitation (fig. 17). Water that infiltrates the land surface percolates downward through the unsaturated zone under the forces of gravity and capillarity. Where the pore spaces between grains are large, water percolates downward easily under the influence of gravity. Where the pore spaces are small, water moves downward by capillarity, the gradual wetting of small particles.

The water that percolates downward far enough to reach the capillary fringe above the water table (fig. 5) is the water that recharges the ground-water system. Land-surface and climatic conditions control recharge rates by controlling rates of infiltration, precipitation, and evapotranspiration.

Land-surface conditions that affect recharge rates include slope, soil type, land use, soil moisture, and the type of earth materials that make up the unsaturated zone (fig. 17). Natural land-surface conditions can remain fairly constant for decades or even hundreds of years. However, land development that results in extensive paved and roofed areas may cause a substantial increase in surface runoff to streams and storm drains, and consequently, a substantial decrease in the annual rate of ground-water recharge.

Areas that have gentle slopes underlain by coarse-grained stratified drift generally have much higher recharge rates than steep slopes underlain by till. Long-term average recharge rates in parts of the Pawcatuck River basin are estimated to be about 25 inches of water per year in areas underlain by stratified drift and 9 inches per year in areas underlain by till (Dickerman and Ozbilgin, 1985, p. 22; Johnston and Dickerman, 1985, p. 45). A recharge rate of 9 inches per year means that, throughout the whole area, the equivalent of a blanket of water 9 inches deep soaks into the ground and reaches the water table over the course of 1 year.

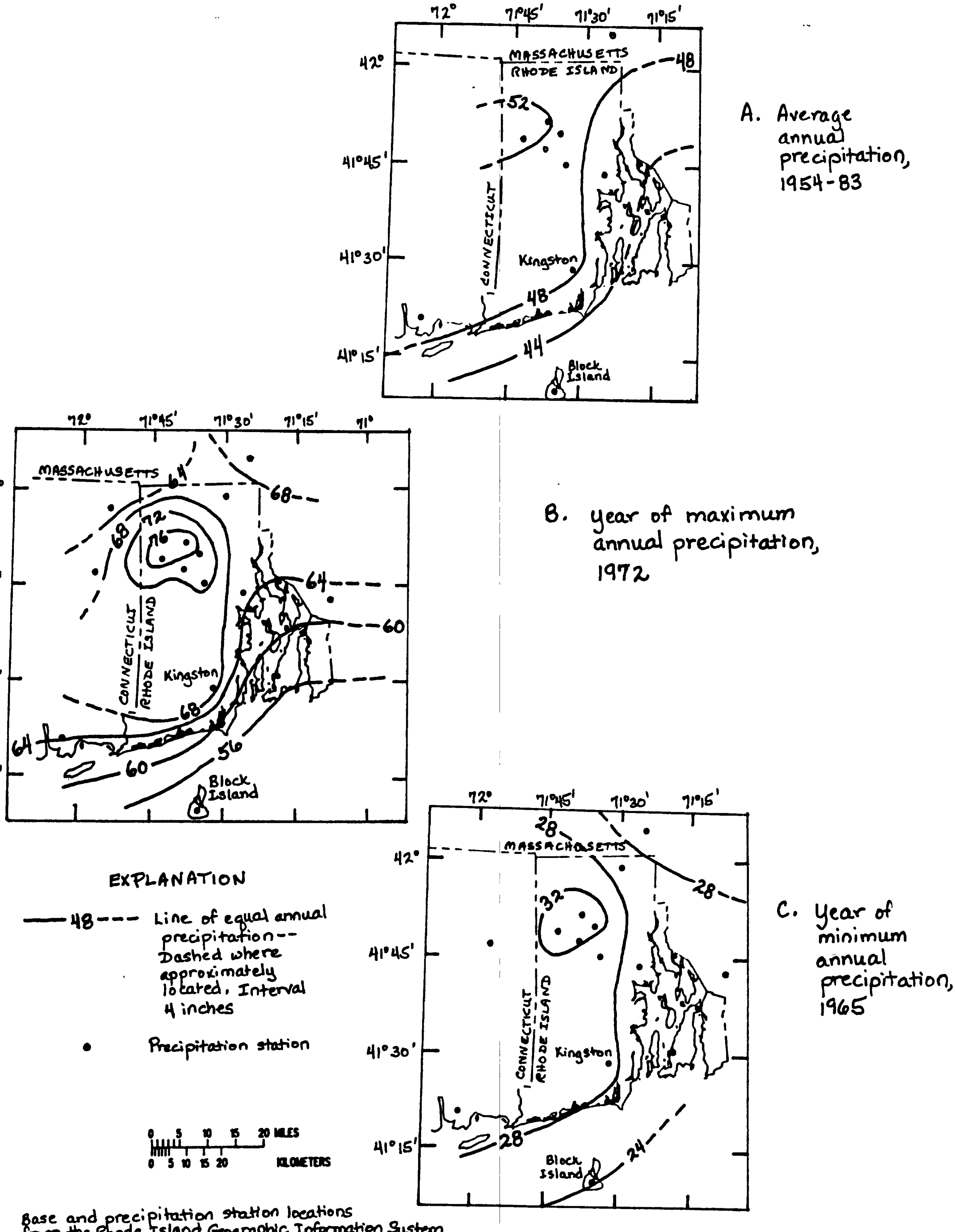


Figure 16.--Average, maximum, and minimum annual precipitation in Rhode Island for calendar years 1954-83. (Source: Data from National Oceanic and Atmospheric Administration, 1954-83, and Providence Water Supply Board, 1955-84. Compiled by R.W. Bell and E.C.T. Trench, U.S. Geological Survey.)

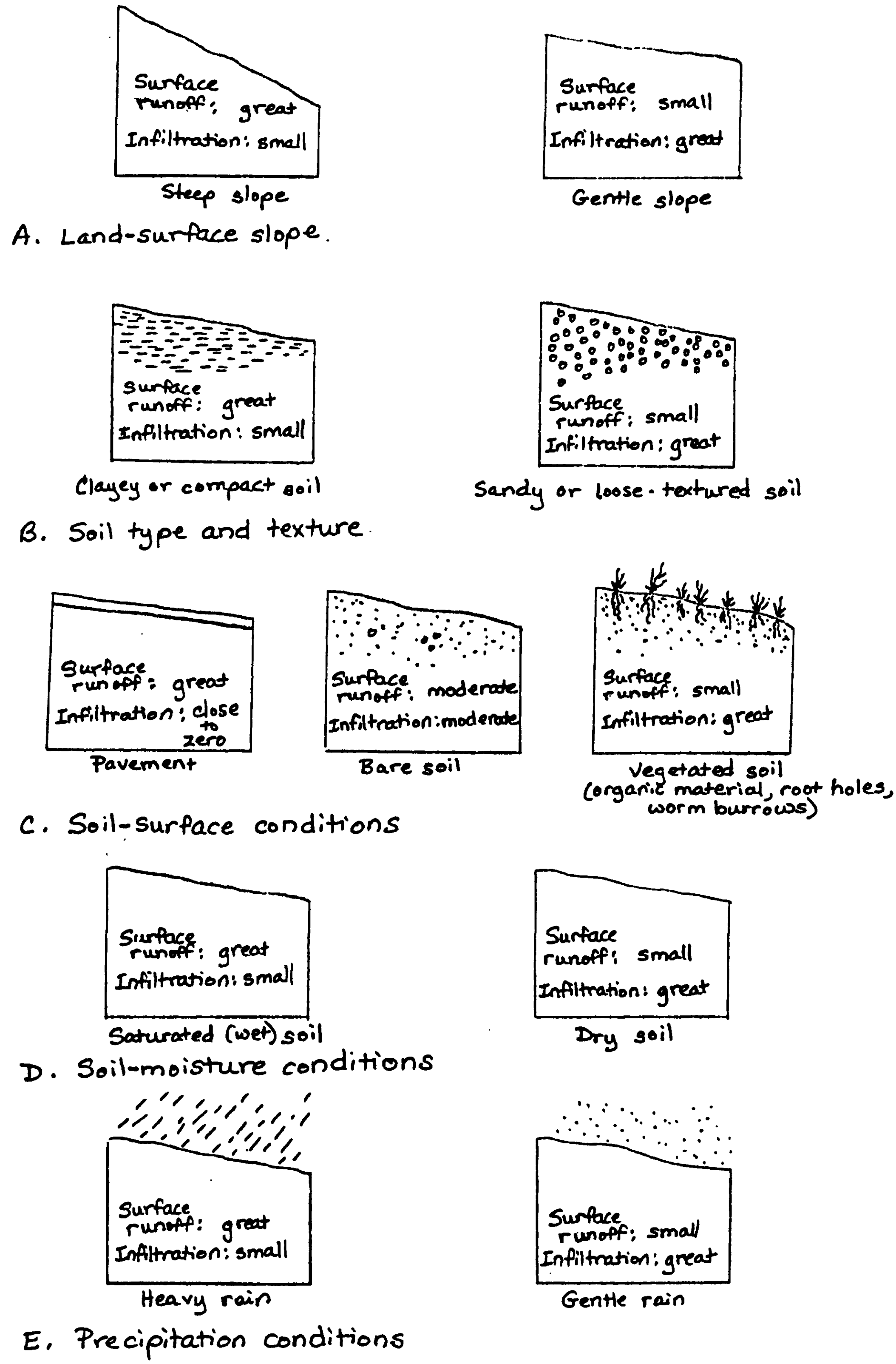


Figure 17.--Factors affecting the relative rates of infiltration and surface runoff. (Source: Modified from Leopold and Langbein, 1960, p. 28.)

Precipitation and temperature are the climatic factors that affect recharge rates. Precipitation may vary in amount, intensity (fig. 17E), duration, form (rain or snow), and frequency (fig. 17D). Temperature affects evapotranspiration rates and the presence or absence of frozen ground, which acts temporarily as a barrier to recharge.

Infiltration from Streams

Streams, ponds, and swamps generally are areas where ground water moves upward and discharges at the Earth's surface (fig. 9). This pattern is reversed under some circumstances, and water from a surface-water body may move downward and recharge the ground water.

Infiltration from a stream occurs where the altitude of the stream flowing across a stratified-drift aquifer is higher than the altitude of the water table (fig. 18B and 18D). Water within the stream percolates downward through the permeable materials between the streambed and the water table. Such a stream is called a losing stream, because some of its water is "lost" into the aquifer. Naturally losing streams are moderately common in the glaciated northeastern United States where streams from steep, till-covered bedrock hillsides flow onto permeable stratified-drift deposits in the valleys (fig. 18). Losing stream reaches are found in parts of the Chickasheen Brook and Chipuxet River basins (Johnston and Dickerman, 1985, p. 44) and in other areas of Rhode Island.

Recharge may be induced from a surface-water body into an underlying aquifer where ground-water withdrawals from wells lower the water table below the altitude of the stream or lake. The surface water percolates downward to recharge the ground water and eventually becomes part of the water that is pumped from the well.

Artificial Sources of Recharge

Artificial recharge takes place where water is transported, applied, or discarded near the land surface in such a way that some of it reaches the saturated zone. This artificial recharge may also transport contaminants to the ground-water system. The most common source of artificial recharge in Rhode Island is the household septic system, which disposes of domestic wastewater by allowing it to percolate into the ground. Excessive irrigation and water leaking from underground water-supply pipelines, sewer lines, and storm drains may also supply a small amount of recharge.

Discharge

Discharge refers to the processes by which ground water emerges from underground and returns to the atmosphere, land surface, or ocean. Evaporation and transpiration from the saturated zone are natural forms of discharge. Most ground water in Rhode Island discharges to swamps, springs, streams, lakes, and ponds. In coastal areas, ground water discharges directly to the ocean. Withdrawal of ground-water from wells is the major form of artificial discharge.

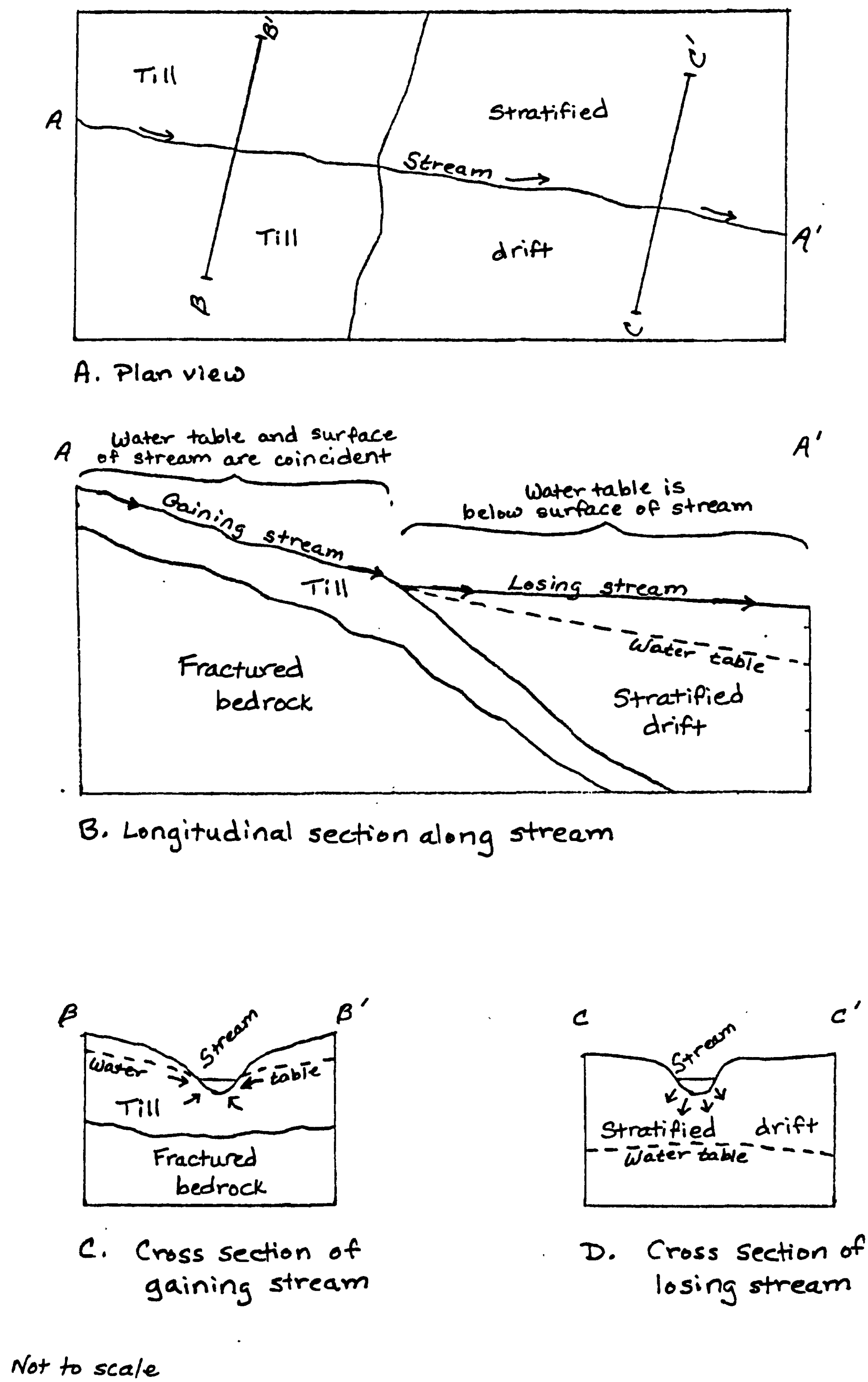


Figure 18.--Relation of water table to gaining and losing reaches of a stream. Arrows show flow direction of water. (Source: Modified from Meinzer, 1923, p. 56.)

Ground-Water Evapotranspiration

Ground water discharges into the atmosphere by evaporation and transpiration. Where the water table is close to the land surface (fig. 5), ground water drawn upward by capillarity may evaporate. Plant roots may withdraw ground water directly from the saturated zone or from the capillary fringe. Roots within 1 or 2 feet of the capillary fringe can draw water upward by a wicking action (A.J. Gold, University of Rhode Island, oral commun., 1989). The water is then discharged from the plants to the atmosphere by transpiration. These processes are collectively termed "ground-water evapotranspiration" to distinguish them from the evaporation and transpiration of moisture that occur within the unsaturated zone.

The amount of water that discharges from the saturated zone by ground-water evapotranspiration depends on air temperature, humidity, season, soil moisture, type of vegetation, depth of the root zone, and depth to water table. The root zone in Rhode Island is commonly 1 foot deep in lawns, 2 to 3 feet deep in agricultural areas, 2 feet deep in forest soils that overlie compact till, and 4 to 5 feet deep in forest soils that overlie permeable material (A.J. Gold, University of Rhode Island, oral commun., 1989). In swamps and marshes, the water table is at or near the land surface and the root zone (fig. 5). Despite their popular reputation as recharge areas, swamps and marshes discharge large volumes of water through their lush vegetation during the growing season. Ground-water evapotranspiration also takes place where the water table is within a few feet of the land surface and soils are permeable. Where the water table is at greater depths and the root zone is shallow, there may be no ground-water evapotranspiration.

Springs

A spring is a place where ground water discharges naturally to the land surface or into a body of surface water. The two main types of springs in Rhode Island are depression springs and contact springs (fig. 19).

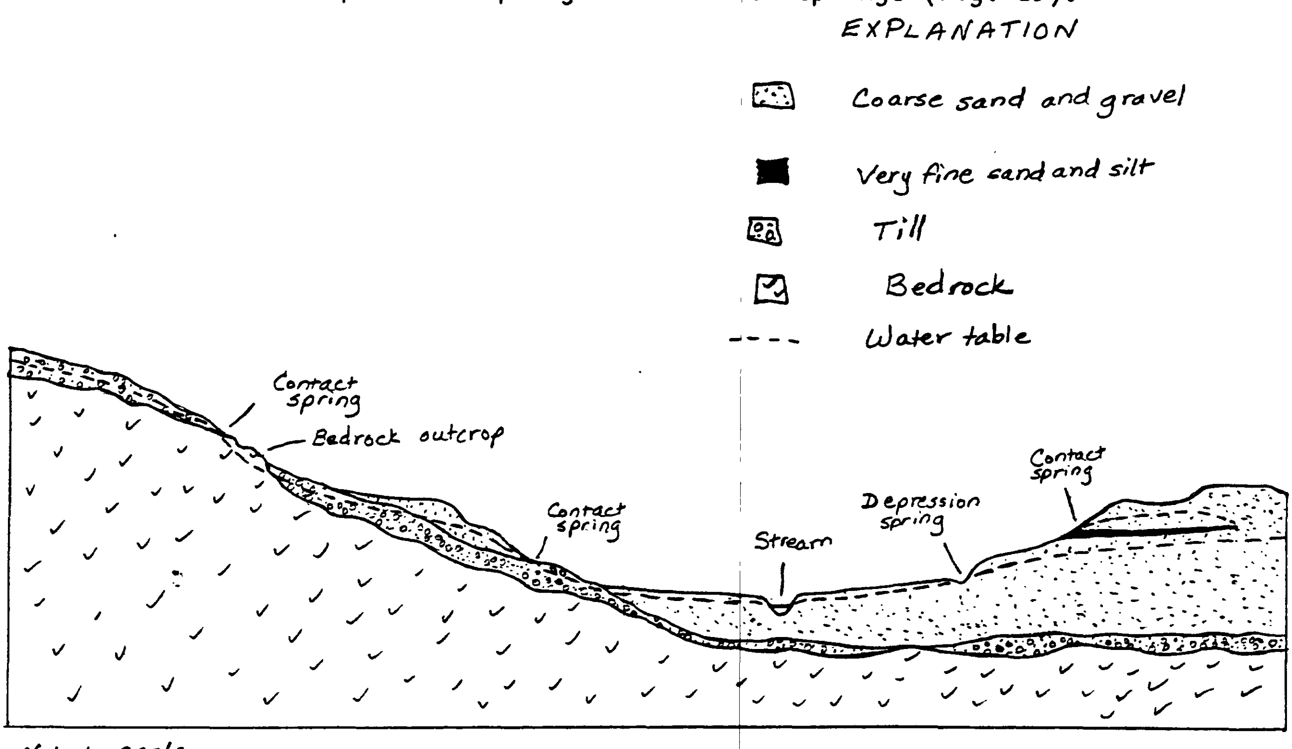


Figure 19.--Typical hydrogeologic settings of springs in Rhode Island.

In a depression spring, ground water flows to the land surface from numerous small openings in a permeable material because the bottom of the depression is lower than the water table (fig. 19). Springs of this type are found along streambeds, in ponds, and in small, isolated depressions. Depression springs are common in the towns of South Kingstown, Charlestown, and Westerly (Allen, 1953, p. 39).

A contact spring forms where ground water discharges from a permeable material over the outcrop of a less permeable underlying material (fig. 19). The less permeable material slows or prevents downward percolation of ground water, which flows through the permeable material toward the land surface (Meinzer, 1923, p. 51). The spring is located at the place, known as the contact, where the permeable material meets the less permeable material. Springs of this type occur throughout Rhode Island, especially along valley walls in upland areas (Allen, 1953, p. 39). Contact springs may form where till overlies bedrock or where stratified drift overlies till (fig. 19). Contact springs are present around the periphery of Block Island where layers of sand and gravel are underlain by beds of silt and clay or compact till (Hansen and Schiner, 1964, p. 14).

Although springs are often thought of as having mysterious and distant sources, the ground water that discharges from springs in Rhode Island ultimately has the same source as the rest of the ground-water system: precipitation. Discharge from springs fluctuates in response to variations in recharge and ground-water evapotranspiration. Springs may dry up in late summer if the water table falls beneath the land surface.

Streams

Streams flow through the lowest parts of the local landscape (fig. 9). Streamflow is derived from surface runoff and ground-water runoff. Surface runoff is derived from rainwater or melting snow that flows over the land surface and through leaf litter and shallow soil layers to the nearest stream channel. Ground-water runoff is water that discharges from the saturated zone into the stream.

Ground water discharges to perennial streams from many small and widely distributed springs or from general seepage along the main stream channel and its tributary channels (Meinzer, 1942, p. 432). In other words, streams form, in part, because the stream channel intersects the water table (fig. 9). The water discharged to the channel then flows downstream because the channel slopes. What was previously ground water becomes surface water.

Surface runoff and ground-water runoff both contribute to streamflow, but their relative proportions vary considerably. Surface runoff takes place during and shortly after rainfall and snowmelt, causing flood peaks on streams and contributing most of the water flowing in the streams during high flows. Fluctuations of surface runoff are often large and sudden, in response to short-term changes in overland flow on hillsides adjacent to stream channels.

Ground-water runoff may contribute some water to streams during storms, but its significant role is in maintaining streamflow during dry periods between rainfall or snowmelt. "Base flow" is the term used for streamflow during extended periods of dry weather. Base flow is derived almost entirely from ground-water discharge, except where there are large artificial diversions or discharges, such as discharge from a wastewater treatment plant.

Fluctuations of ground-water runoff are smaller and much more gradual than those of surface runoff. The base flow delivered to a stream by ground-water discharge represents a slow response to changes in recharge throughout the regional ground-water flow system (Freeze and Cherry, 1979, p. 225). An increase in ground-water discharge to streams may continue for many days after the recharge event caused by rain or melting snow.

Perennial streams in Rhode Island are in discharge areas, and the upper surface of the stream is generally lower than the water table (fig. 18C). Such a stream is called a gaining stream because it receives a net increase in water from the saturated zone, although reaches of some streams locally lose water to underlying aquifers (fig. 18D).

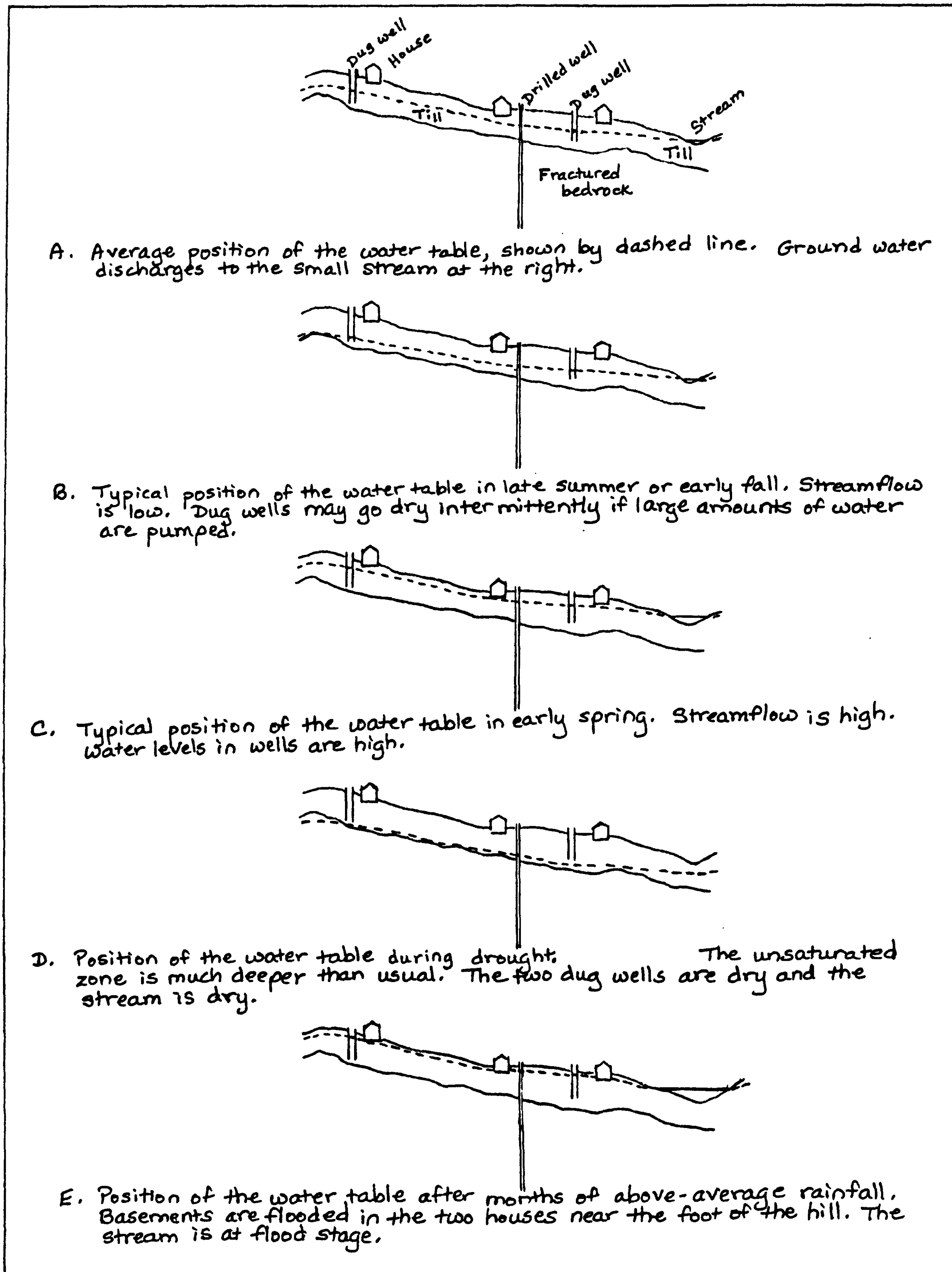
Lakes and Ponds

Lakes are bodies of water that occupy depressions in the Earth's surface. Permanent lakes in Rhode Island are almost always sites where ground water discharges from springs or by general seepage through the lake bottom. The surface of such a lake is at or below the water table of the surrounding area, and ground water constitutes a substantial part of the water that flows into the lake.

Lakes and ponds can lose water to underlying aquifers if the altitude of the lake or pond surface is higher than the water table, although losing lakes and ponds are uncommon in Rhode Island. Meadow Brook Pond in Richmond is an example of a pond from which water infiltrates downward into the underlying aquifer. Whether a lake or pond gains or loses water can change with changing climatic conditions, and, in some cases, part of a lake or pond may be gaining while the rest is losing water (Winter, 1983).

Variations in Recharge and Discharge

Variations in natural recharge and discharge affect the position of the water table and, therefore, also affect the amount of ground water stored in aquifers and the flow of streams. Aquifers in almost all of Rhode Island are unconfined, and the water table is free to rise or fall in response to changes in recharge and discharge. If recharge and discharge are exactly in balance throughout the ground-water-flow system, the amount of ground water stored in the saturated zone does not change, and the position of the water table remains constant. Recharge varies seasonally, however, and it may also vary over shorter or longer periods of time. The resulting water-table fluctuations, changes in ground-water storage, and changes in streamflow are shown in figure 20 for a hypothetical setting typical of rural Rhode Island.



Not to scale

Figure 20.--Fluctuations in the altitude of the water table under different climatic conditions. Dug wells in till are about 25 feet deep. Drilled well in bedrock is about 100 feet deep. Dashed line shows natural position of the water table; wells are not being pumped.

Seasonal Variations

The position of the water table varies annually in a fairly predictable way. During the growing season, most precipitation evaporates or is transpired by plants before percolating deep enough into the ground to reach the saturated zone. At the same time, ground water continues to discharge to streams, removing water from the saturated zone. The amount of ground water in storage decreases and the altitude of the water table declines. In late summer or early fall, the water table is usually at its lowest position, water levels in wells are low, and streamflow is low (fig. 20B). Minor tributary streams may dry up.

After the end of the growing season, precipitation that infiltrates the land surface is likely to percolate to the water table. Recharge exceeds discharge, the water table gradually rises, the thickness of the saturated zone increases, and the amount of ground water in storage increases. This simply means that more pore spaces and fractures beneath the land surface have been completely filled with water. The water table is usually at its highest position in early spring, after snowmelt and before plant growth starts (fig. 20C). Stream stages also commonly peak at this time because of increased surface runoff and ground-water discharge.

Long-Term Variations

If seasonal fluctuations are averaged, the water table tends to maintain a similar position over a period of years (fig. 20A). However, extended periods of drought or heavy rainfall may cause significant departures from this average position.

Recharge rates are likely to be lower than average in a year of below-average precipitation, and the water table in the spring may not rise as high as the maximum altitude of the previous spring. If abnormally low rainfall persists during the growing season, the water table falls to a lower-than-usual position in the late summer and early fall. If drought continues, the amount of ground water in storage continues to decrease, as reflected in continued water-table declines (fig. 20D). The amount of water added to the saturated zone by natural recharge is insufficient to replenish the water lost through evapotranspiration, discharge to streams, and artificial discharge to wells. During a prolonged drought, swampy areas become dry, the flow of major streams is abnormally low, and small perennial streams and shallow wells may be periodically dry (fig. 20D).

The northeastern United States experienced an unusually long and severe drought in the 1960's. All or parts of 14 states were affected. In Rhode Island, the drought began in 1963 and continued through 1966. In 1965, total precipitation at Kingston was less than 31 inches, only 63 percent of the long-term annual average of about 49 inches (figs. 16C and 16A) (National Oceanic and Atmospheric Administration, 1954-1983). The position of the water table was affected accordingly. For example, the median ground-water level for the month of December at an observation well in southern Rhode Island was 12.05 feet below the land surface for the period 1955-88. In December of 1965, however, the ground-water level reached a record low of 15.26 feet below land surface (H.E. Johnston, U.S. Geological Survey, written commun., 1989). Thus, the water table was more than 3 feet lower than its typical position at that time of the year.

During a prolonged period of above-average precipitation, recharge exceeds discharge throughout most of the year, the water table maintains a higher position than usual, and the amount of ground water in storage increases (fig. 20E). In areas where the water table is usually a few feet below the land surface, normally dry land becomes wet, basements are flooded, and water levels in wells are unusually high.

Record amounts of precipitation fell in most parts of Rhode Island in 1972, and annual totals ranged from 53 to almost 78 inches (fig. 16B) (National Oceanic and Atmospheric Administration, 1972). Record amounts at some locations in 1983 resulted in local flooding, high ground-water levels, and waterlogged agricultural fields. Total precipitation at Kingston in 1983 was about 70 inches, 43 percent higher than the long-term annual average of 49 inches (fig. 16A). In both April and November 1983, 13 inches of rain fell at this site (National Oceanic and Atmospheric Administration, 1983).

Flow from Recharge Areas to Discharge Areas

The general direction of ground-water flow in Rhode Island is from upland recharge areas to valley discharge areas (fig. 21). Most of the land surface in Rhode Island, as in the rest of New England, is a recharge area where rain and melting snow percolate downward through the unsaturated zone and reach the saturated zone (fig. 21). Discharge areas are very small by comparison. Most human activities take place in recharge areas.

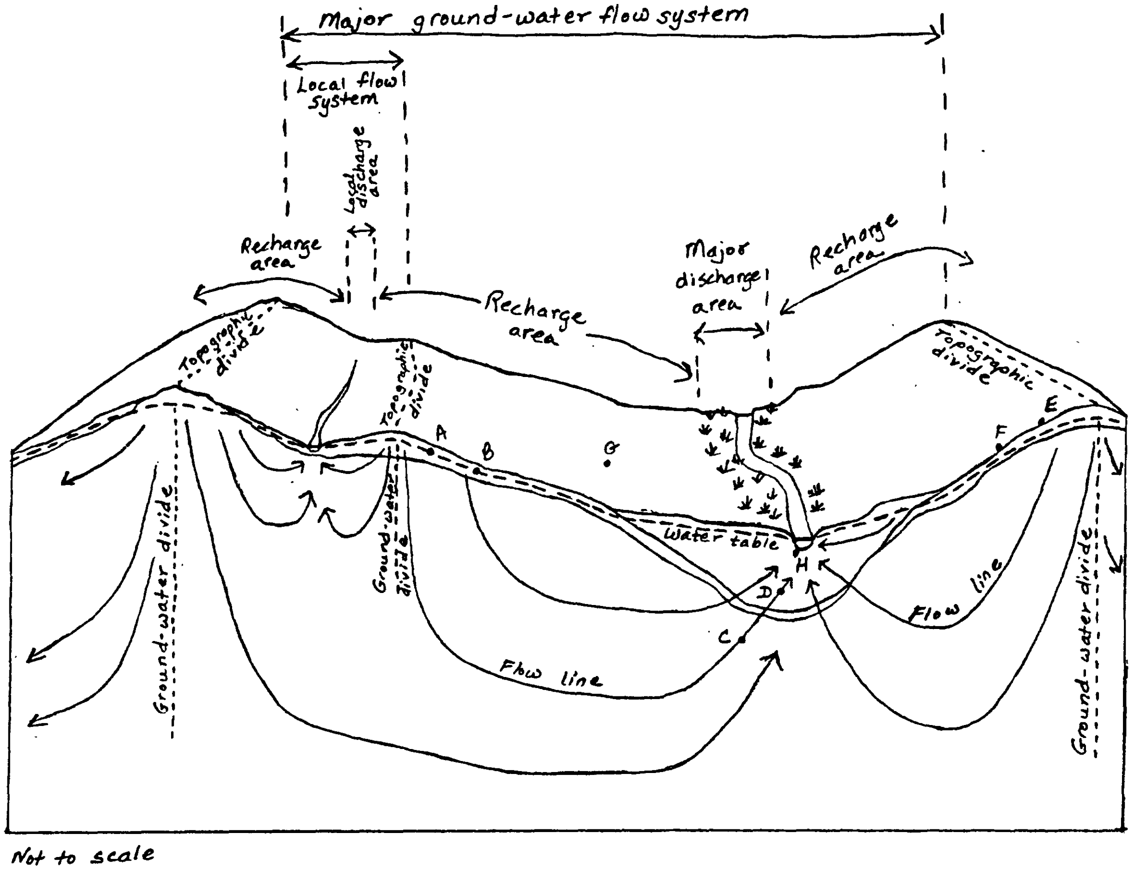


Figure 21.--Ground-water flow from recharge areas to discharge areas. Typical distribution of till, stratified drift, and bedrock is as shown in figure 9. A few representative flow lines show generalized directions of ground-water flow. Actual flow paths through bedrock fractures and unconsolidated glacial deposits are more complex. Lettered points A through H are discussed in text.

Large streams such as the Blackstone, Pawtuxet, and Pawcatuck Rivers are major discharge areas that receive ground-water runoff from local and distant parts of the ground-water-flow system (fig. 21). Streams of intermediate size such as the Hunt River can be considered major discharge areas if they receive the entire ground-water runoff of their drainage basins and are not simply part of a deep regional flow system. A small tributary stream is a local discharge area. It receives ground-water runoff from its drainage basin, but deeper flow paths may bypass this local discharge area and convey some ground water to the larger river into which the tributary flows (fig. 21).

Large permanent lakes and ponds are usually in discharge areas of major ground-water-flow systems, whereas small permanent lakes in uplands are usually discharge areas for local flow systems. Artificial impoundments such as the Scituate Reservoir also receive ground-water discharge from the surrounding flow system.

Some Rhode Island ponds, particularly on Block Island, are part of a perched water table, separated from the main zone of saturation by an underlying impermeable layer, such as silt or clay. Such ponds may function as discharge areas for the small ground-water-flow systems in the perched zones (fig. 8, location A).

The Cause of Ground-Water Flow

Gravity is the force that causes ground water and surface water to flow. The water table in Rhode Island usually has an irregular surface (fig. 21). Ground water naturally moves downgradient until it discharges at a spring, swamp, stream channel, estuary, or coastline. If recharge ceased permanently, ground water would continue to discharge at low points in the land surface until the water table became virtually flat. Ground water flows because the surface of the saturated zone, like the surface of a lake, has a natural tendency to become flat under the influence of gravity, and because new water is constantly entering the ground-water-flow system.

The concept of head, as used in fluid mechanics, is helpful in understanding directions and rates of ground-water flow. The idea that head provides energy to move something is expressed in the colloquial phrase, "building up a head of steam." Mills used to be built near waterfalls or rapids where mechanical energy was provided by water falling from a higher altitude, or head, to a lower altitude, or head, over a short distance. Ground water moves less dramatically than the streams in this example, but it likewise always moves from an area of higher head to an area of lower head.

Head at any point in the saturated zone is a combination of elevation head and pressure head. Elevation head is the altitude of the point of measurement. In figure 21, the elevation head at point A is greater than the elevation head at point B. These points are both on the water table, and therefore are at atmospheric pressure.

Beneath the water table, all ground water is under a pressure greater than atmospheric pressure because of the weight of the overlying water. In figure 21, the pressure head at point C is greater than the pressure head at point D. Pressure head is what causes water to rise in wells. A familiar example of differences in pressure head is the picnic cooler with a spigot at the bottom. The lemonade flows out more forcefully when the cooler is full (maximum pressure head) than when the cooler is almost empty (minimum pressure head).

Pressure head is often incorrectly thought of as artesian pressure, but the term "artesian pressure" only applies to ground water in confined aquifers, in which the pressure is significantly greater than in unconfined (water-table) aquifers. Most ground water in Rhode Island is unconfined, but pressure head may cause water in a deep well to rise to a level near or even above the land surface.

Directions of Ground-Water Flow

The head difference between upland recharge areas and valley discharge areas provides the energy that keeps ground water moving. This head difference creates a hydraulic gradient that determines the direction of ground-water flow. Ground water flows in the direction of the steepest hydraulic gradient, just as surface water flows downhill in the direction of the steepest slope (from point E to point F in fig. 21).

Along the water table, such as between point A and point B in figure 21, ground water is at atmospheric pressure, total head equals elevation head, and the hydraulic gradient is equivalent to the slope of the water table. Beneath the water table, the difference in head between recharge area and discharge area is distributed along each curved three-dimensional ground-water flow path. In the ground-water system shown in figure 21, total head at point C is greater than total head at point D. Ground water flows from point C to point D and discharges to the stream. Point D is hydraulically downgradient from point C, even though its altitude is above that of point C.

Ridges in the saturated zone form ground-water drainage divides in upland areas (fig. 21). A ground-water drainage divide is analogous to a topographic divide between two surface-water drainage basins on the land surface. Ground water flows away from a ground-water drainage divide, in opposite directions on opposite sides of the divide. The divide is an imaginary vertical plane across which no flow takes place (fig. 21).

In recharge areas, ground water moves downward into the earth, away from the water table, and laterally toward discharge areas (fig. 21). In discharge areas, ground water flows upward, toward the water table and the land surface (fig. 21). In the three-dimensional ground-water-flow system, the flow path followed by a water particle is seldom a straight horizontal line. The curved flow lines shown in figure 21 are idealized paths. Only a few representative flow lines are shown. The ground-water system is composed of a multitude of curved or angular flow lines. Figure 21 shows flow lines in the two-dimensional plane of the drawing, but the flow lines are actually three dimensional. Recharge entering the saturated zone at point G may discharge slightly downstream at point H (fig. 21).

Differences in permeability affect the shape and direction of flow lines. Flow lines bend where they cross the boundary between a high-permeability material and a low-permeability material (fig. 22). For example, in Rhode Island's deposits of stratified drift, ground water tends to move vertically through layers of very fine sand and silt (low permeability) and horizontally through layers of coarse sand and gravel (high permeability). Large fractures or highly permeable layers of sediment may function as preferential pathways for the relatively rapid movement of ground water and any contaminants it may contain.

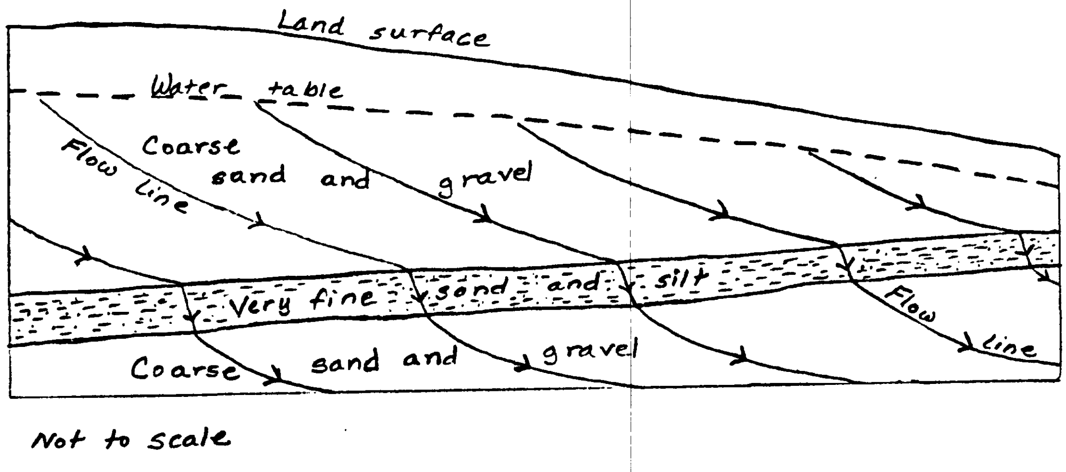


Figure 22.--Directions of ground-water flow in materials of different permeability. Ground water flows horizontally through highly permeable layers of coarse sand and gravel and vertically through poorly permeable layers of very fine sand and silt. (Source: Modified from Heath, 1983, p. 24.)

Rates of Ground-Water Flow

Water in the saturated zone moves very slowly in comparison to surface water. The velocity of water flowing in a river is measured in feet per second, whereas ground-water movement is usually measured in feet per day or feet per year (Baldwin and McGuinness, 1963, p. 7).

Ground water moves by laminar flow, also called streamline flow. In each microscopic flow line or streamline, an endless stream of particles of water moves from recharge area to discharge area. Turbulent flow, in contrast to laminar flow, occurs at velocities that are typical of surface streams. In turbulent flow, eddies occur and water particles move in irregular, circuitous paths. Turbulent flow seldom occurs in Rhode Island ground water, except under unusual conditions where openings in the rock are exceptionally large, such as large bedrock fractures or the pore spaces in cobble gravel.

The local hydraulic gradient and the hydraulic conductivity of the earth material determine the rate of ground-water flow in a particular place. Ground-water velocities, which vary widely because of the large natural variability in these two factors, generally range from about 5 feet per day to about 5 feet per year (Meinzer, 1942, p. 449).

Ground water moves rapidly in highly permeable materials such as sand and gravel, and slowly in less permeable materials such as till, silt, and clay. Velocities are higher under a steep hydraulic gradient than under a gentle hydraulic gradient.

Velocities of ground-water flow can be estimated if values for hydraulic conductivity, porosity, and hydraulic gradient are known. Information available for the Chipuxet River basin and other parts of the Pawcatuck River basin (Johnston and Dickerman, 1985) indicates that the average rate of ground-water flow in till is a few inches per day, and the average flow rate in stratified drift is 1 to 2 feet per day. Velocities could be higher or lower in individual layers or lenses.

The time required for a water particle to move through the ground-water system from a recharge area to a discharge area may be relatively brief, or it may be many years or even centuries. In shallow flow paths adjacent to discharge areas, it may take only a few weeks for water to enter the ground-water system, flow through it, and discharge to a stream. The estimated residence time of ground water in two stratified-drift aquifers in southwestern Connecticut ranges from about 1 to 45 years (Grady and Weaver, 1988, p. 13-14). Along deep flow paths that originate in distant recharge areas, it may take centuries for ground water to move through the system.

EFFECTS OF WELLS ON THE GROUND-WATER SYSTEM

Discharge of water from a well can cause major or minor changes in the ground-water-flow system, depending on the well's pumping rate and location. Principal types of wells used in Rhode Island are shown in their common hydrogeologic settings in figure 11.

Removal of Ground Water from Storage

Any shallow well that extends below the water table will fill with water up to the level of the water table (fig. 5). If the well is pumped dry, it will eventually fill up again. As the pump removes water from the well, the water level in the well is quickly lowered below the level of the water table in the surrounding aquifer. This means that the head is lower in the well than in the aquifer. Because ground water flows downgradient, water begins to flow into the well. As pumping continues, the withdrawal, or discharge, is supplied from ground water stored near the well. In figure 23A, ground water from a stratified-drift aquifer discharges to a stream under natural conditions. In figure 23B, a well has been constructed and pumping has recently begun. At this time, the well discharge is supplied by removal of ground water from storage in the aquifer near the well.

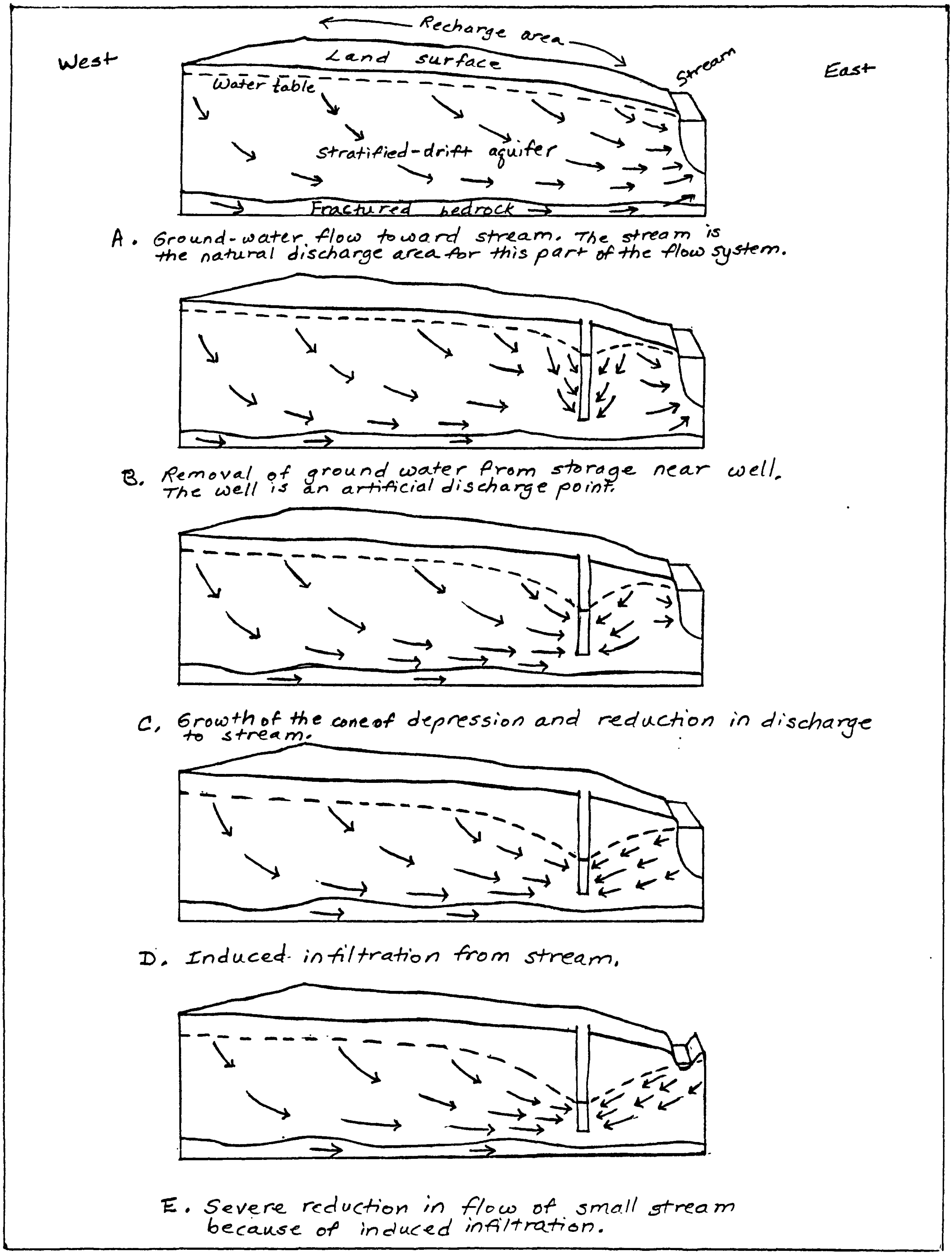
Changes in Water-Table Altitude and Configuration

Water drains downgradient toward the well from the pores of the aquifer materials surrounding the well. This lowers the water table near the well (fig. 23C). Water from pores still farther from the well flows toward the expanding low spot in the water table (Leopold and Langbein, 1960, p. 12). This occurs on all sides of the well, and so ground water converges on the well from all directions.

The lowered surface of the saturated zone around a pumped well is termed the "cone of depression" (Leopold and Langbein, 1960, p. 12). As withdrawal of water from the well continues, the cone of depression expands gradually in all directions (fig. 23B-D).

The slope of the water table near a well becomes steeper during pumping (fig. 23A and 23D). This increased hydraulic gradient means that the rate of ground-water flow near the well increases during pumping. Thus, if contaminant sources are nearby, withdrawal of water from a well could accelerate the movement of contaminated ground water toward the well.

The area of influence of a well is the land that overlies the area where the water table is lowered a discernible amount as a result of pumping the well (fig. 24B). In other words, the area of influence is the land above the cone of depression (shown in sectional view in fig. 24D). The size and shape of the area of influence depend on several factors, including the pumping rate of the well and the earth material in which it is located. The area of influence tends to be larger in permeable coarse-grained deposits than in less permeable fine-grained or poorly sorted deposits. The area of influence of a high-yield well in a stratified-drift aquifer may be several square miles. In the hypothetical setting shown in figure 24B, the area of influence includes most of the stratified-drift aquifer west of the river, and part of the stratified-drift aquifer east of the river, but probably does not extend into the till-covered bedrock uplands.



Not to scale

Figure 23.--Effects of a well on the ground-water-flow system. (Source: Modified from Heath, 1983, p. 33).

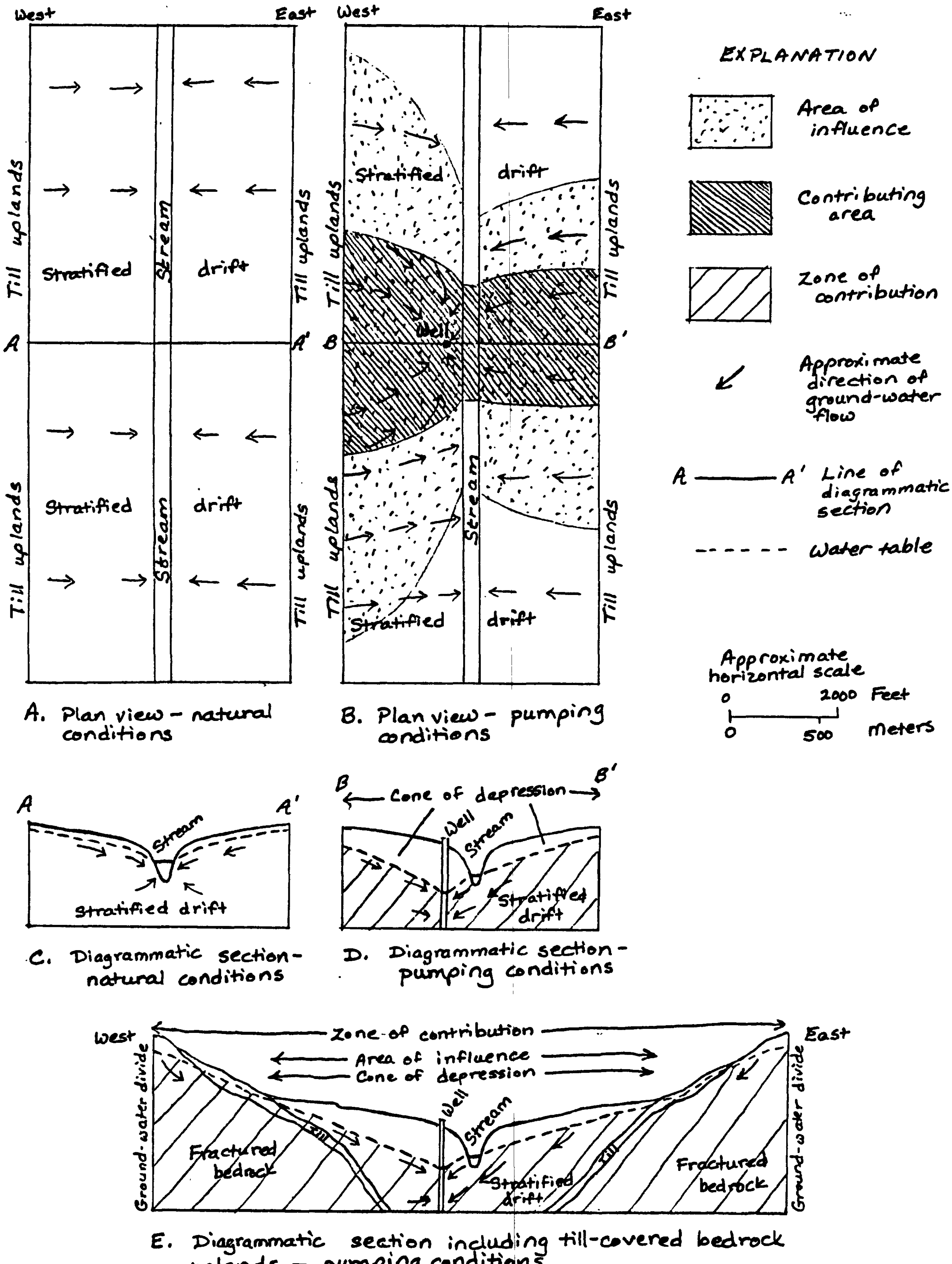


Figure 24.--The area of influence, cone of depression, contributing area, and zone of contribution for a high-yield well in a hypothetical stratified-drift aquifer. Till-covered bedrock uplands (not shown in A, B, C, and D) border the eastern and western sides of the aquifer. Vertical scale in C, D, and E is exaggerated. Size of well and stream is greatly exaggerated in all views. (Source: Modified from Morrissey, 1989, fig. 9, p. 10; fig. 17, p. 20.)

Not all the ground water beneath the area of influence flows into the well. On the contrary, it is possible for the water table to be drawn down measurably without appreciably changing the natural direction of ground-water flow. In figure 23C, for example, the entire area between the well and the stream is within the area of influence, because the water table is lowered slightly throughout this part of the aquifer. However, ground water adjacent to the stream is discharging to the stream rather than flowing into the well. Likewise, the water table in the aquifer may be influenced by the well for a considerable distance along the river upstream and downstream from the well, without substantially changing the general direction of ground-water flow before pumping (fig. 24A and fig. 24B).

Changes in Base Flow to Streams

As the cone of depression expands outward from a pumped well, it may reach an area where ground water is discharging from the aquifer to a stream. The magnitude of the original hydraulic gradient toward the natural discharge area is reduced by the changes in water-table configuration (fig. 23A-C). The rate of natural discharge to the stream decreases because the rate of flow is proportional to the hydraulic gradient. Some of the ground water that would have flowed into the stream under natural conditions has been intercepted by the cone of depression and now flows into the well (fig. 23C).

If the well water is not returned to the ground-water system in some way, such as through discharge to residential septic systems, then the ground-water runoff to the stream will be reduced, and the base flow of the stream during dry periods will also be reduced. The larger the pumping rate relative to the flow of the stream, the greater will be the reduction in base flow.

Induced Infiltration from Streams

Large ground-water withdrawals near streams can completely reverse the natural hydraulic gradient from the aquifer toward the stream, and can cause surface water to infiltrate through the streambed into the aquifer (fig. 23D). This process is called induced infiltration, and the water entering the aquifer by this process is termed induced recharge. Induced recharge can constitute a significant percentage of the water that is pumped from a well.

The process of induced infiltration changes a natural discharge area (the stream channel) into a recharge area. This is an important consideration if streamwater is contaminated or if a minimum amount of streamflow is required for other purposes, such as dilution of waste discharges.

Several factors affect the extent to which water is induced into an aquifer from a stream, including the pumping rate of the well, the distance between the well and the stream, and the permeability of the streambed materials. If a well close to a stream is pumped at a high rate and the streambed is very permeable, then most of the water pumped from the well may be induced recharge. In contrast, a private well on a hilltop does not receive any of its water from induced recharge.

The pumping rate of the well, its proximity to the stream, the permeability of the streambed, and the size of the stream determine the magnitude of the effect that induced infiltration has on streamflow. A well may obtain a substantial percentage of its water from induced infiltration without any discernible effect on the flow of a large stream (fig. 23D). The base flow of a major stream is composed of ground-water runoff to many tributaries throughout a large drainage basin that receives recharge at different times and places. The same pumping rate, on the other hand, may severely reduce the base flow of a small stream (fig. 23E). When the pumping rate of the well or the combined pumping rate of several wells equals the flow of a nearby stream, then the entire flow may be induced into the aquifer, and the stream may be dry for days or even weeks. This condition is most likely in late summer and early fall, when natural streamflow is generally lowest of the year.

Induced infiltration is common in Rhode Island because many public-supply wells in stratified-drift aquifers are near surface-water bodies. Large streams such as the Blackstone River downstream from Woonsocket or the Pawcatuck River near Westerly are virtually unaffected by large ground-water withdrawals. On the other hand, the flow of a small stream such as the Hunt River is affected by wells that supply water to North Kingstown and the Kent County Water Authority. Small tributaries such as the Beaver River, Pasquiset Brook, and the Chipuxet River, all within the Pawcatuck basin, could be severely affected by large ground-water withdrawals. Studies of ground-water development in these stream valleys have estimated withdrawal rates and well locations that could cause periods of no streamflow (Dickerman and Ozbilgin, 1985; Johnston and Dickerman, 1985).

Changes in the Direction of Ground-Water Flow

When water is withdrawn from a well, the hydraulic gradient near the well is changed, and the direction of ground-water flow can also be changed. The change may be slight, or the direction of ground-water flow may be completely reversed. In figure 23A, the natural direction of ground-water flow is from west to east, and ground water discharges to the stream at the east. In figure 23B through 23D, withdrawal of water from the well has changed the direction of the water-table slope east of the well. Ground water in a gradually expanding area is now flowing west toward the well instead of east toward the stream.

The Zone of Contribution

Ground-water withdrawals cause changes in flow directions and create within the aquifer a zone in which ground water flows toward a well or group of wells. This "zone of contribution" is a three-dimensional volume of earth below the water table. Within the zone of contribution, all flow lines converge on the well. All ground water within the zone of contribution of a well will eventually flow into the well, even if it takes years to get there.

The size and shape of the zone of contribution are determined by

* the nature and distribution of the aquifer materials,
* the distance to materials of low permeability such as till and bedrock,
* the presence of confining layers,
* the proximity of the well to a source of induced infiltration, such as a stream or pond,
* the size of the stream,
* the permeability of the streambed,
* the rate of natural recharge to the aquifer,
* the depth of the well relative to the saturated thickness of the aquifer,
* the pumping rate of the well, and
* the duration of pumping

(Morrissey, 1989, table 1, p. 9; p. 39).

Wells in all types of aquifers have zones of contribution. The size and shape of the zone of contribution for a high-yield well in stratified drift are of particular interest because this is the common setting for public-supply wells in New England.

The zone of contribution of a well tapping a hypothetical stratified-drift aquifer near a stream is shown in sectional view in figure 24D. Natural (nonpumping) ground-water-flow conditions are shown in figure 24A and 24C. The setting illustrated is highly simplified; only the generalized stratified-drift aquifer is shown in figure 24A through 24D. However, adjacent till-covered bedrock uplands are commonly part of the zone of contribution for a well tapping a typical stratified-drift aquifer in New England (fig. 24E) (Morrissey, 1989, p. 39).

The zone of contribution for a well can extend beneath and beyond a river that is a source of infiltration and can include stratified drift and adjacent upland areas on the opposite side of the river (fig. 24E) (Morrissey, 1989, p. 21). This condition is likely in Rhode Island, as well as in the rest of New England, because streams are shallow relative to the saturated thickness of stratified-drift aquifers, and streambed deposits are semipermeable (Morrissey, 1989, p. 15).

The zone of contribution for the well pictured in figure 24E extends from the ground-water drainage divide west of the river to the divide east of the river. The valley illustrated in figure 24E is about 2 miles wide, a distance fairly typical of many Rhode Island valleys, although the details of actual hydrogeologic settings differ considerably. The stratified-drift aquifer shown is a little more than 1 mile wide.

The zone of contribution may extend to the base of the stratified-drift aquifer, particularly if the saturated thickness is 100 feet or less (Morrissey, 1989, p. 1). The amount of flow into the aquifer from the underlying till and bedrock may be minimal because the permeability of till is so low relative to that of the stratified drift, but some inflow from till and bedrock does take place (Morrissey, 1989, p. 14).

The Contributing Area

The size and shape of the three-dimensional zone of contribution determine the configuration of the contributing area, a two-dimensional feature that can be mapped on the land surface. The contributing area of a well is the land that overlies and supplies recharge to the zone of contribution (Morrissey, 1989, p. 8). A map of the contributing area of a well shows the land beneath which ground water is flowing toward the well. The contributing area is identical to the recharge area of the well. Theoretical analyses indicate that the size of the contributing area may range from about 1 to 2 square miles for a well pumped at a rate of 1 million gallons per day in a stratified-drift aquifer typical of New England (Morrissey, 1989, table 5, p. 34). Such a contributing area includes upland areas underlain by till as well as the stratified-drift aquifer itself.

The contributing area for a well is determined by fixed and variable characteristics of the local hydrogeologic setting and the well. Aquifer materials and well location are essentially constant factors at a particular site. If all other factors are equal, a well located near a stream will have a smaller contributing area than a well far from a stream, because a large percentage of the discharge from the well near the stream is likely to be supplied from induced infiltration.

Natural recharge rates, pumping rates, and stream characteristics are variable. The contributing area for a particular well will be larger in dry years, when recharge is minimal and streamflow is low, than in wet years, when recharge and streamflow are high. A larger volume of aquifer is required to supply the well discharge in dry years than in wet years because less water is added to the aquifer by natural recharge and induced infiltration in dry years. Likewise, the size of the contributing area increases or decreases if the pumping rate of the well increases or decreases. The contributing area is constantly changing in response to changing hydrologic conditions (Morrissey, 1989, p. 39).

GROUND-WATER DRAINAGE BASINS

The occurrence and flow of ground water are organized within units of the Earth's crust known as ground-water drainage basins. Much of the science of hydrology has to do with determining the boundaries of ground-water drainage basins and the directions of ground-water flow within these basins. The fact that patterns of ground-water flow are organized and understandable, though complex, makes it possible to estimate amounts of ground water available for use and to evaluate potential threats to ground-water quality.

A ground-water drainage basin and the overlying surface-water drainage basin are usually considered to form a single interconnected hydrologic unit in Rhode Island's hydrogeologic setting (fig. 25). A surface-water drainage basin is composed of a network of streams and the land area that contributes surface runoff to those streams. Lakes, ponds, and swamps where the water table intersects the land surface are also important features of a surface-water drainage basin. The surface water and underlying ground water are connected by the movement of water through the permeable surface of the Earth. Within a drainage basin, the use and quality of ground water and surface water affect each other.

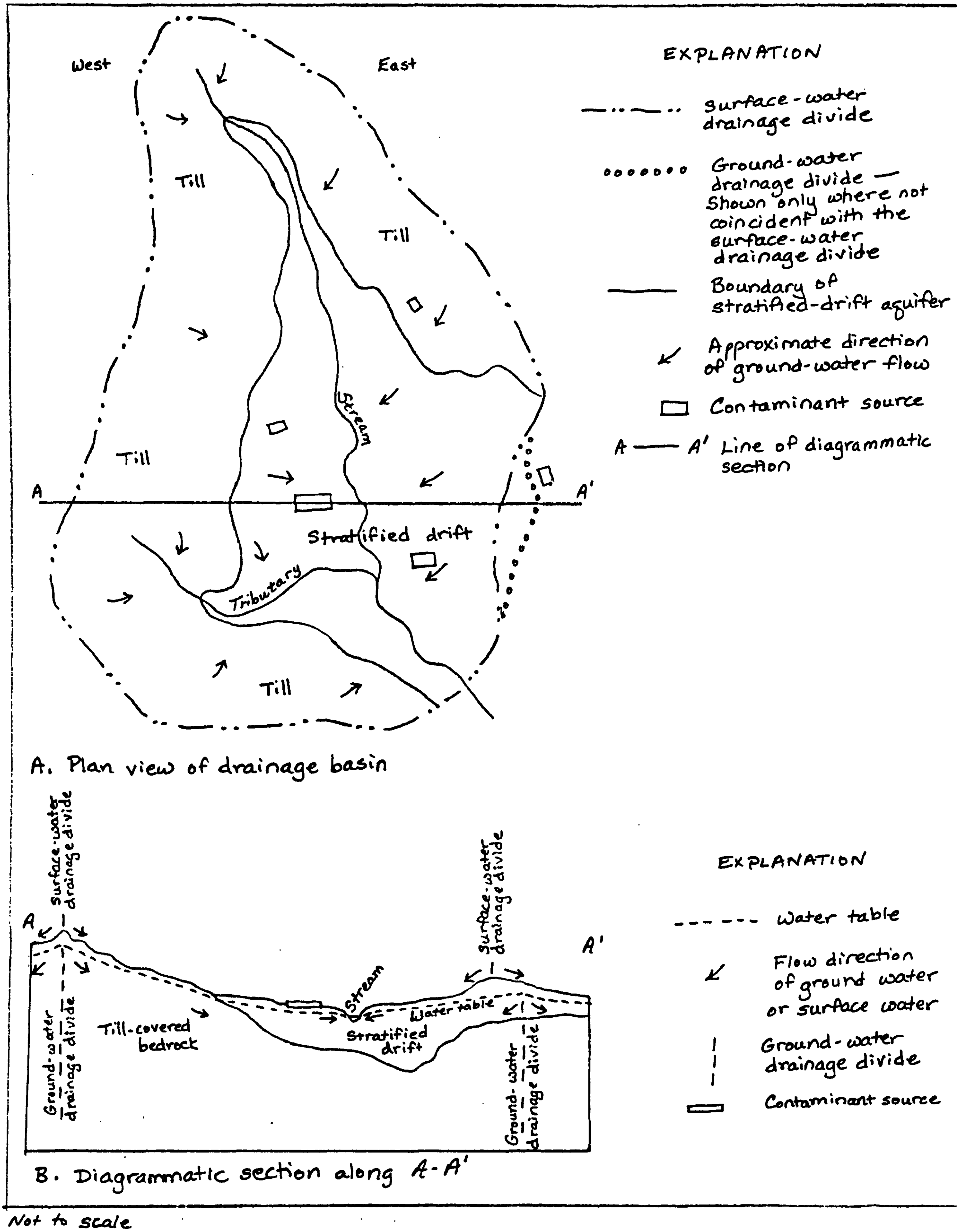


Figure 25.--Natural hydrologic conditions in a hypothetical small drainage basin. Width of the drainage basin from A to A' is about 2 miles. Depth of the stratified-drift aquifer averages about 70 feet.

Basin Geometry and Boundaries

A ground-water drainage basin is a volume of the Earth's crust, much wider than it is deep, within which ground water flows in an organized manner along innumerable flow paths from recharge areas to discharge areas. The water table, often described as a subdued replica of the land surface, forms the upper boundary of a ground-water drainage basin. The position of this boundary fluctuates in response to changes in recharge and discharge. The lower boundary, where the permeability of the bedrock becomes negligible, is irregular but approximately horizontal in most places. Most ground-water circulation in southern New England takes place in the upper part of the saturated zone, within 300 to 400 feet of the land surface (Melvin, 1986, p. 7). Vertical ground-water drainage divides form the irregular lateral boundaries of a ground-water drainage basin.

The hypothetical small drainage basin shown in figure 25 is a few square miles in size and is drained by a river system that is hydraulically connected to a stratified-drift aquifer in the central and eastern parts of the basin. Ground water is unconfined, and no well discharges alter the natural directions and rates of ground-water flow. The shape of the water table along section A-A' is shown in figure 25B; dashed vertical lines show the position of the ground-water drainage divides.

A surface-water drainage divide is formed by a ridge or other topographic high point on the land surface. It forms the boundary between two surface-water drainage basins. A ground-water drainage divide is also marked by a ridge or high point on the surface of the saturated zone, and it forms the boundary between two ground-water drainage basins. A ground-water drainage divide is an imaginary plane that extends vertically downward through the saturated zone and marks a change in the direction of ground-water flow (fig. 25B).

Ground-water drainage divides and surface-water drainage divides may not coincide when plotted on a map. Thus the area of a ground-water drainage basin may not be identical to the area of the overlying surface-water drainage basin. In figure 25A, the ground-water and surface-water drainage divides coincide along most of the perimeter of the drainage basin, except for a short distance along the eastern boundary of the basin, where the drainage divides cross the stratified-drift aquifer.

The conditions shown in figure 25 are typical of Rhode Island. In till-covered bedrock uplands throughout much of the State, the shape of the water table is similar to that of the land surface, although smoother, as shown at the western end of section A-A' in figure 25B. Ground-water drainage divides in these areas coincide approximately with surface-water drainage divides, and their locations can be estimated from topographic maps. In areas covered by stratified drift, however, the water table may be almost flat, and its shape may be unrelated to the topography of the overlying land, as shown at the eastern end of section A-A' in figure 25B. Measurements of the water-table altitude are necessary to determine the location of a ground-water drainage divide where a surface-water drainage divide crosses a stratified-drift aquifer. Areas where major surface-water and ground-water drainage divides do not coincide are relatively uncommon in Rhode Island and are usually small. Such areas are shown on hydrologic maps if the information is available.

A surface-water drainage divide is usually considered a permanent feature of the landscape, whereas the position of a ground-water drainage divide may change in response to changes in the rates of recharge or discharge on either side of the divide. Withdrawal of ground water from nearby wells can shift the position of a ground-water drainage divide. Changes in the location of a ground-water drainage divide are most likely where the divide is located in coarse-grained stratified drift, a well is located nearby, and the pumping rate is high. In such cases, the sediments are highly permeable, the natural slope of the water table is rather flat, and the divide is formed only by a gentle rise in the water table. In contrast, significant changes are unlikely in upland areas of till-covered bedrock where only small-capacity private wells are in use.

In figure 26, for example, a high-yield well has been added to the hypothetical small drainage basin shown in figure 25. Withdrawal of ground water has changed the water-table configuration in the stratified drift (fig. 26B). The ground-water drainage divide along the eastern boundary of the basin has moved farther east, as shown in figure 26A and 26B, as a result of the withdrawal.

A change in the location of a ground-water drainage divide represents a change in the direction of ground-water flow in part of the aquifer. This change in flow direction could cause contaminated ground water to move into areas that were previously uncontaminated. For example, the contaminant source near the eastern end of section A-A' in figure 25A is outside the ground-water drainage basin mapped under natural (nonpumping) conditions. Any ground water contaminated by this source flows east, away from the drainage basin pictured here. In figure 26A, however, this contaminant source is within the contributing area of the well because the ground-water drainage divide has moved farther east in response to ground-water withdrawals. Ground water contaminated by this source now flows west toward the well.

Recharge Areas and Discharge Areas

A ground-water drainage basin is composed of recharge areas and discharge areas. In figure 25A, most of the land surface is a recharge area for the underlying ground-water basin. The outer boundary of the recharge area is formed by the ground-water drainage divide. Discharge areas are confined to the stream valleys and swampy areas bordering the streams. The general direction of ground-water flow in figure 25 is from the hills along the perimeter of the basin toward the stream valleys in the center of the basin.

Changing conditions can cause a recharge area to become a discharge area, or can cause a discharge area to become a recharge area. In figure 26, a high-yield well has been constructed east of the river. When the well is being pumped, it creates an artificial discharge area in a place that was formerly a recharge area. If the well discharge is large enough to induce recharge from the adjacent stream into the aquifer, then the stream reach where induced infiltration occurs will change from a discharge area to a recharge area. The streambed from B to B' in figure 26A is a recharge area.

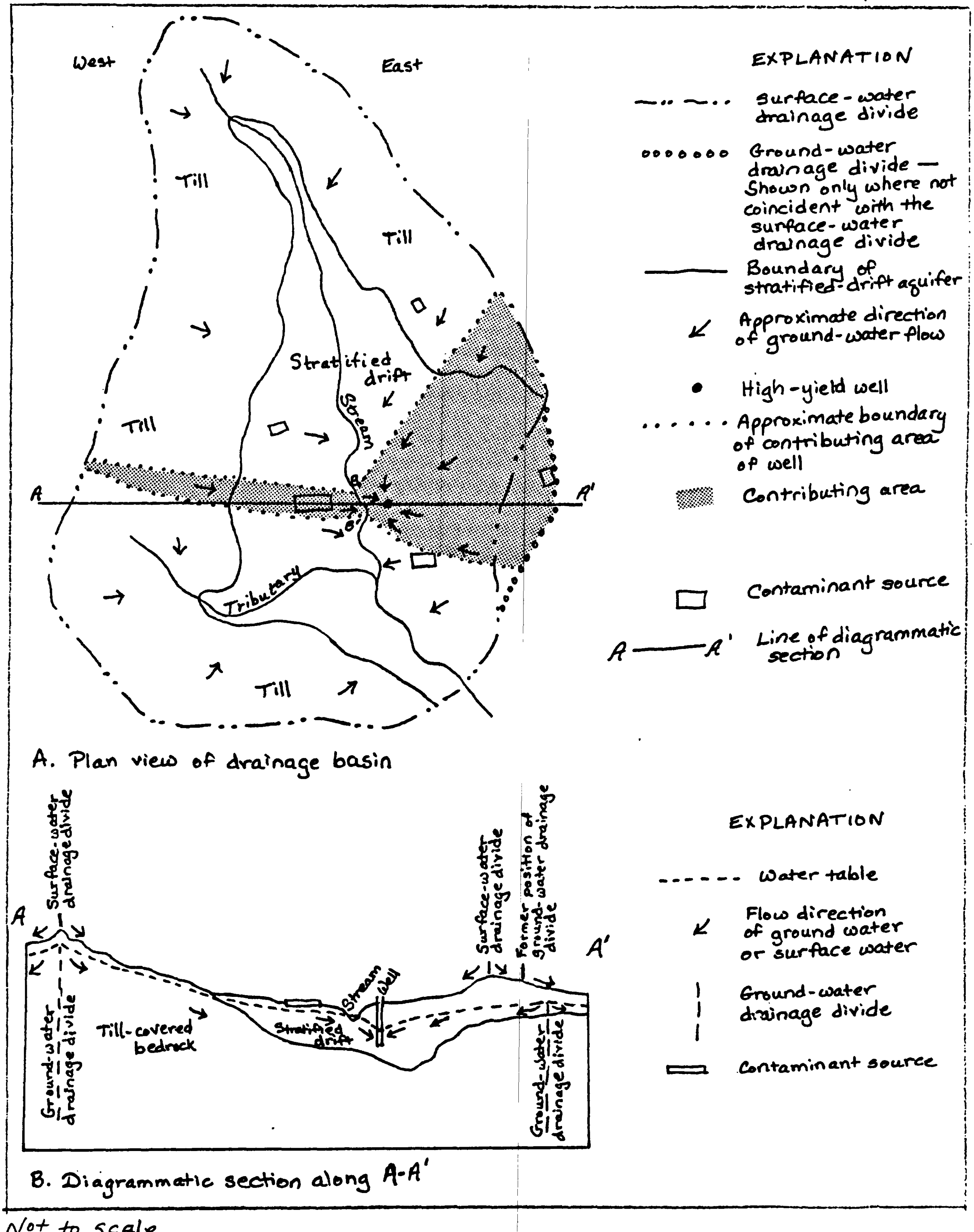


Figure 26.--Effects of ground-water withdrawal from a large-capacity well in the hypothetical small drainage basin shown in figure 25. Surface water infiltrates the aquifer along the stream reach from B to B'.

Equilibrium and Change in the Ground-Water-Flow System

The flow system of a ground-water drainage basin is dynamic. Precipitation brings new water into the system and old water discharges from the system. If recharge balances discharge throughout the ground-water drainage basin, the system is said to be in equilibrium. This is seldom the case in the short term because of changing stresses on the system. Over a period of many years, however, the system may be approximately in equilibrium, with average recharge equal to average discharge.

A stress is a natural or artificial condition that causes a response in the ground-water system, such as a change in the quantity or location of recharge or discharge. A difference between the rate of recharge and the rate of discharge is accounted for by a change in the amount of ground water stored in the flow system. The ground-water system adjusts gradually when a change occurs, and it eventually achieves a new equilibrium.

Variations in recharge, caused by natural variability in the frequency and distribution of precipitation, constitute the major natural stress in a ground-water drainage basin. If recharge exceeds discharge, the water table rises, increasing the hydraulic gradient between recharge area and discharge area, and thereby increasing the rates of ground-water flow and discharge. The increased discharge compensates for the increased recharge, and the water table gradually falls to its average position. Conversely, ground-water storage decreases and the water table falls when discharge exceeds recharge. With a decreased hydraulic gradient between recharge area and discharge area, the rates of ground-water flow and ground-water discharge decrease.

Withdrawal of water from wells is the major artificial stress in a ground-water drainage basin (fig. 26). Wells merely alter the distribution of discharge if the water they withdraw is returned to the ground-water system or to streams within the basin. The system can approach a new state of equilibrium as long as the total well discharge does not exceed natural recharge rates.

Some of the water withdrawn from wells may be exported from a drainage basin or discharged from wastewater-treatment plants downstream from the basin. For example, much of the water withdrawn from the Chipuxet ground-water reservoir in the Pawcatuck River basin (fig. 13) is discharged to Narragansett Bay through a regional sewer system (Johnston and Dickerman, 1985, p. 8). In these cases, the natural discharge of the basin is permanently reduced. Consequently, streamflow and ground-water evapotranspiration are reduced by an amount equal to the water exported from the basin.

The relation among inflow, outflow, and storage forms the basis for developing a water budget for a drainage basin. A water budget is useful in evaluating the amount of ground water or surface water available for human use. Generalized water budgets are included in hydrologic studies for several drainage basins in Rhode Island (Dickerman and Ozbilgin, 1985; Gonthier and others, 1974; Rosenshein and others, 1968; Allen and others, 1966).

The rate at which water can be withdrawn from a ground-water drainage basin is referred to as the basin's yield. Safe yield refers to the amount of water that can be withdrawn without producing an undesired effect (U.S. Geological Survey, 1984, p. 241). Undesired effects could include, for example, excessive lowering of stream and pond levels, increased costs of withdrawing water, or saltwater intrusion.

Simplified mathematical ground-water-flow models are sometimes used to estimate the yield of aquifers in a ground-water basin and to predict the effects of stresses on the ground-water system. Such predictions are inherently approximate. Computer models may expedite and improve the evaluation of ground-water resources; however, as with other mathematical models, the accuracy of their predictions depends entirely on the accuracy of the information used in the models, and on the extent to which the models represent actual hydrologic conditions. Ground-water drainage basins are always more complicated than the models used to evaluate them.

GROUND-WATER QUALITY

Natural or Background Quality

A water molecule consists of two atoms of hydrogen and one atom of oxygen. This simple molecule has diverse properties that make it an integral and essential part of many biological, chemical, and physical processes. Water can dissolve at least small quantities of almost any substance with which it comes in contact, and for this reason it is often called the universal solvent (Heath, 1983, p. 64). This characteristic means that natural water is virtually never pure.

The quality of natural ground water is highly variable. It is determined by climate, the chemistry of precipitation, biologic processes, the physical structure and chemical composition of soil and aquifer materials, and ground-water-flow patterns (Handman and others, 1979). The quality of ground water is measured by its biological, physical, and chemical properties and constituents.

The quality of ground water in most parts of Rhode Island is suitable for drinking and other uses with little or no treatment (Johnston and Barlow, 1988, p. 443). The major sources and the significance of common natural constituents and properties of ground water in Rhode Island are listed in table 1.

Virtually all ground water in Rhode Island has been affected by human activities to some extent. In this report, "natural ground water" refers to ground water in undeveloped or sparsely developed areas where the effects of human activities are believed to be minimal.

The quality of ground water in the undeveloped upper Wood River basin is probably most representative of natural ground water in Rhode Island (Johnston and Barlow, 1988, p. 443). The chemical and physical quality of ground water and surface water near the Upper Wood ground-water reservoir (fig. 13) is summarized in table 2. The ranges shown for most constituents and properties of ground water in this area, with the exception of nitrate and ammonia nitrogen, are fairly typical of uncontaminated ground water in areas of Rhode Island where stratified-drift aquifers are underlain by crystalline bedrock. Values outside the ranges listed, however, may be found in ground water that is not contaminated as a result of human activities.

Table 1.--Source and significance of common constituents and properties of ground water in Rhode Island

[Constituents and properties shown are reported in milligrams per liter (mg/L) unless otherwise specified. µS/cm, microsiemens per centimeter at 25 degrees Celsius; °F, degrees Fahrenheit. Sources: Handman and others, 1979, p. 14-16; Johnston and Dickerman, 1985, p. 54-55]

Constituent or property	Principal natural and artificial sources	Significance
	CHEMICAL CONSTITUENTS	
Silica (SiO_2)	Dissolved from practically all rocks and soils.	High concentrations precipitate as hard scale in boilers, water heaters, and pipes. Inhibits deterioration of zeolite-type water softeners and corrosion of iron pipes.
Iron (Fe)	Dissolved from minerals that contain oxides, sulfides, and carbonates of iron. Decaying vegetation, iron objects that are in contact with water, sewage, and industrial waste are also major sources.	On exposure to air, iron in ground water oxidizes to a reddish-brown precipitate. More than about 0.3 mg/L stains laundry and utensils, causes unpleasant odors, and favors growth of iron bacteria. Iron in water is objectionable for food and textile processing. Most iron-bearing waters, when treated by aeration and filtration, are satisfactory for domestic use.
Manganese (Mn)	Dissolved from many rocks and soils. Commonly associated with iron but less common.	More than 0.05 mg/L oxidizes to a black precipitate on exposure to air. Manganese has the same undesirable characteristics as iron but is more difficult to remove.
Calcium (Ca)	Dissolved from rocks and soils, especially those containing calcium silicates, and carbonate and clay minerals.	Hardness and scale-forming properties of water are caused principally by dissolved bicarbonates and sulfates of calcium and magnesium. (See hardness.) Hard water is objectionable for electroplating, tanning, dyeing, and textile processing. It also causes scale formation in steam boilers, water heaters, and pipes.
Magnesium (Mg)	Dissolved from rocks and soils, especially those containing magnesium silicates, and carbonate and clay minerals.	See Calcium.
Sodium (Na) Potassium (K)	Dissolved from practically all rocks and soils. Sewage, industrial wastes, road salt, and seawater are also major sources. Most home water softeners increase the amount of sodium in water by exchanging it for calcium and magnesium.	Quantities found in fresh ground water in Rhode Island have little effect upon the usefulness of water for most purposes; however, more than 50 mg/L may cause foaming in steam boilers. For people on a very restricted sodium diet, a maximum sodium concentration of 20 mg/L in drinking water has been recommended by many health agencies.
Hydrogen ion (pH) (standard units)	Water, acids, and acid-generating salts. Hydrogen ions are produced by various types of chemical reactions in natural water.	Values of pH range from 1 to 14. A pH of 7.0 indicates a neutral solution. Values greater than 7.0 denote alkaline conditions; values less than 7.0 indicate acidic conditions. Acidic waters and very alkaline waters corrode metals. The pH of most natural waters ranges from 6 to 8.

Table 1.--Source and significance of common constituents and properties of ground water in Rhode Island--Continued

Constituent or property	Principal natural and artificial sources	Significance
	CHEMICAL CONSTITUENTS (continued)	
Carbonate (CO_3) Bicarbonate (HCO_3)	Dissolved from carbonate and calcium silicate minerals by reaction with carbon dioxide in water. Decaying vegetation, sewage, and industrial wastes are also important sources.	Carbonates of calcium and magnesium cause hardness, form scale in boilers and pipes, and release corrosive carbon dioxide. (See hardness.) Water of low mineral concentration and low bicarbonate concentration in proportion to carbon dioxide is acidic and corrosive.
Sulfate (SO_4)	Dissolved from rocks and soils containing sulfur compounds, especially iron sulfide; also from sulfur compounds dissolved in precipitation, and from sewage and industrial wastes.	Sulfates of calcium and magnesium cause permanent hardness and form hard scale in boilers and hot-water pipes.
Chloride (Cl)	Dissolved from rocks and soils in small amounts. Other sources are animal wastes, sewage, road salt, industrial wastes, and seawater.	Large amounts in combination with calcium will result in a corrosive solution, and, in combination with sodium, will give water a salty taste.
Fluoride (F)	Dissolved from various minerals of widespread occurrence. Added to public water supplies by fluoridation.	About 1.0 mg/L reportedly reduces the incidence of tooth decay in young children; larger amounts may cause mottling of tooth enamel, depending on average water intake and climate.
Nitrate (NO_3; expressed as N)	Sewage, industrial wastes, fertilizers, and decaying vegetation are major sources. Lesser amounts are derived from precipitation and solution processes.	Values higher than the local average may indicate contamination. Water containing more than 10 mg/L (as N) reportedly causes methemoglobinemia, which can be fatal to infants (U.S. Environmental Protection Agency, 1976, p. 81).
Dissolved oxygen (O_2)	Derived from the atmosphere and from photosynthesis by aquatic vegetation. Amount varies with temperature and pressure, and decreases during decomposition of wastes and organic matter.	Its presence or absence affects many biological and chemical reactions in ground water. It causes precipitation of iron and manganese in well water and can cause corrosion of metals.
	CHEMICALLY-RELATED PROPERTIES	
Dissolved solids	Includes all dissolved mineral constituents derived from solution of rocks and soils; locally augmented by mineral matter in sewage and industrial wastes.	Water containing more than 500 mg/L is undesirable for public and private supplies and many industrial purposes.

Table 1.--Source and significance of common constituents and properties of ground water in Rhode Island--Continued

Constituent or property	Principal natural and artificial sources	Significance
	CHEMICALLY-RELATED PROPERTIES (continued)	
Hardness (as $CaCO_3$)	Primarily due to calcium and magnesium and to a lesser extent to iron, manganese, aluminum, barium, and strontium.	Hard water requires a considerable amount of soap to form a lather and it deposits soap curds on bathtubs. Hardness forms scale in boilers, water heaters, radiators, and pipes, causing a decrease in rate of heat transfer and restricted flow of water. Water having a very low hardness may be corrosive. A general hardness scale is: soft, 0-60 mg/L; moderately hard, 61-120 mg/L; hard, 121-180 mg/L; very hard, more than 180 mg/L mg/L (U.S. Geological Survey, 1985, p. 461).
Acidity	Acidic precipitation caused by combustion products vented to the atmosphere, oxidized sulfide minerals, products of other oxidation processes, organic acids, industrial wastes.	The acidity of a solution is its capacity to react with hydroxyl (OH) ions. The acidity of water may provide an index of the severity of pollution (Hem, 1985, p. 109).
Alkalinity	Carbonate and bicarbonate dissolved from earth materials are important contributors to alkalinity. Alkalinity is commonly reported in terms of an equivalent amount of calcium carbonate in mg/L.	The alkalinity of a solution is the capacity for solutes it contains to react with and neutralize acid (Hem, 1985, p. 106). The alkalinity of natural water in New England is generally low compared to parts of the country where rocks formed of calcium carbonate are abundant.
	PHYSICAL PROPERTIES	
Specific conductance ($\mu S/cm$)	Constituents that dissolve to form ions in water.	Specific conductance of water provides an approximate indication of the dissolved mineral content of the water. Values significantly higher than the local average may indicate contamination.
Color (units)	May be imparted by iron and manganese compounds, algae, weeds, and humus. May also be caused by inorganic or organic wastes from industry. True color of water is considered to be only that remaining in solution after the suspended material has been removed.	Water for domestic and some industrial uses should be free of perceptible color. Color in water is objectionable in food and beverage processing and many manufacturing processes. Usually expressed in units of color (platinum-cobalt method) rather than in milligrams per liter.
Temperature	In streams and shallow aquifers, seasonal variations are caused by changes in air temperature. At depths of 30 to 60 feet, ground-water temperature remains within 4 °F or 5 °F of average annual air temperature. Increases gradually with depth. May fluctuate where affected by induced infiltration. Disposal of industrial cooling or processing water may cause local temperature anomalies.	Affects the usefulness of water for many purposes. For most uses, especially cooling, water of uniformly low temperatures is desired. Warm water carries less oxygen in solution and is more corrosive than cold water.

Table 2.--Chemical and physical quality of ground water and surface water in the Upper Wood ground-water-reservoir area

[Unit of measurement is milligrams per liter (mg/L), unless otherwise specified; °C, degrees Celsius; <, less than; μS/cm, microsiemens per centimeter; --, no data available; *, no drinking-water limit set. For location of Upper Wood ground-water reservoir, see figure 13. Source: D.C. Dickerman, U.S. Geological Survey, written commun., 1989]

Constituent or property	Maximum contaminant level for drinking water	Ground water				Surface water			
		Number of samples	Minimum value measured	Median value	Maximum value measured	Number of samples	Minimum value measured	Median value	Maximum value measured
CHEMICAL CONSTITUENTS									
Silica (SiO_2)	*	7	6	8	20	6	5.3	8.9	12
Iron (Fe)	[1] 0.3	70	0	< .05	13	15	.05	.16	.32
Manganese (Mn)	[1] .05	69	0	< .02	1.5	13	< .01	< .01	.04
Calcium (Ca)	*	27	.40	4.0	12	6	1.9	2.65	4.1
Magnesium (Mg)	*	27	.2	.97	3.4	6	.57	.7	1.5
Sodium (Na)	*	21	2.7	6.0	10	5	3.0	4.0	11
Potassium (K)	*	21	.35	.70	1.2	5	.60	1.0	1.2
pH (standard units)	[1] 6.5-8.5	20	5.5	6.1	6.9	20	5.5	6.5	6.8
Bicarbonate (HCO_3)	*	7	1.8	11.6	29.3	5	7.6	8	12
Sulfate (SO_4)	[1] 250	27	1.0	5.0	9	15	3.1	5.4	6.7
Chloride (Cl)	[1] 250	69	0	6	47	15	2.9	7.8	65
Fluoride (F)	[2] 2.0	27	0	.1	.54	4	.1	.15	.2
Nitrate (NO_3 as N)	[2,3] 10	65	0	.1	9.13	13	0	.03	.14
Ammonia Nitrogen (as N)	*	21	0	.04	.08	3	< .01	< .01	< .01
MBAS[4]	[1] .5	16	0	< .05	< .1	--	--	--	--
Dissolved oxygen (O_2)	*	5	.8	7.2	11.7	17	9.3	11.6	12.4

Table 2.--Chemical and physical quality of ground water and surface water in the Upper Wood ground-water-reservoir area--Continued

Constituent or property	Maximum contaminant level for drinking water	Ground water				Surface water			
		Number of samples	Minimum value measured	Median value	Maximum value measured	Number of samples	Minimum value measured	Median value	Maximum value measured
				CHEMICALLY-RELATED PROPERTIES					
Total solids (residue at 105°C)	[1] 500	27	27	54	102	1	41	41	41
Dissolved solids (residue at 180°C)	[1] 500	--	--	--	--	14	33	52	149
Hardness (as $CaCO_3$)	*	28	0	14	40	6	8	9	14
Alkalinity (as $CaCO_3$)	*	31	1.5	10	24	4	6.5	8.5	10
				PHYSICAL PROPERTIES					
Specific conductance (μS/cm at 25°C)	*	6	33	50	118	18	35	46	220
Color (platinum cobalt units)	[1] 15	21	0	0	10	15	20	40	70
Temperature (°C)	*	--	--	--	--	18	4.5	9.5	19

1 Secondary maximum contaminant level established for public water systems by the U.S. Environmental Protection Agency (1987d).

2 Maximum contaminant level for inorganic chemicals established for public water systems by the Rhode Island Department of Health, Division of Water Supply (1983).

3 Maximum contaminant level for inorganic chemicals established for public water-supply systems by the U.S. Environmental Protection Agency (1987b).

4 Detergents as methylene-blue-active substance (MBAS).

Biological Constituents

Biological constituents of ground water include bacteria and other microscopic organisms. Natural filtration by unconsolidated materials removes many living organisms from ground water because the organisms are large relative to the size of the pore spaces in many sediments. Some organisms, however, occur naturally in ground water.

Chemical Constituents

Chemical constituents of ground water are numerous and may be subdivided into inorganic and organic chemicals. Inorganic chemicals, which include dissolved gases and minerals, are the most common constituents of natural ground water in Rhode Island. Radionuclides, an important group of inorganic chemicals, are radioactive elements produced during nuclear fission. Natural radioactive decay of certain elements in the Earth's crust produces radionuclides that can be dissolved by ground water. Some naturally occurring radionuclides are gases and others are solids.

Gases

Common gases.--Carbon dioxide, oxygen, and nitrogen are common dissolved gases derived from the atmosphere or from organic processes in the soil. Carbon dioxide dissolved in water forms a weak acid that is influential in rock-weathering processes. Thus, carbon dioxide affects the dissolved-mineral composition of ground water. Underground biochemical processes may generate the flammable gases methane or hydrogen sulfide.

Radon.--Radon is a naturally occurring radioactive gas that is colorless, odorless, and tasteless. It is fairly soluble in water, and is found in low concentrations almost everywhere. Radon is the most common naturally occurring radionuclide in Rhode Island's ground water (Zapecza and Szabo, 1988, fig. 19, p. 53).

Radon is one of a series of radioactive-decay products resulting from the natural breakdown of uranium, which is found in granites, gneisses, and other rocks in Rhode Island. In New England, the highest levels of radon in well water have generally been found in areas underlain by granite or highly metamorphosed rock (University of Maine, 1986). Radon is dissolved in ground water that flows through rocks and sediments that contain even trace quantities of uranium.

Dissolved radon migrates upward into the unsaturated zone and becomes mixed with other soil gases. Radon is also produced directly from the rocks and sediments within the unsaturated zone.

Radon disperses quickly outdoors, but can build up to hazardous levels indoors. Breathing air containing elevated levels of radon is associated with an increased risk of developing lung cancer (U.S. Environmental Protection Agency, 1986). The exposure to radon resulting from direct consumption of well water is generally considered insignificant by comparison (University of Maine, 1986). The significance of radon in ground water is that activities such as showering or dishwashing release additional radon to the indoor air. Radon is usually not a problem in large public ground-water supplies, because the radon is likely to be dispersed in the outside air before reaching the home.

Radioactivity is commonly measured in picocuries per liter of air or water. The U.S. Environmental Protection Agency (USEPA) has recommended a limit of 4 picocuries per liter for radon in air; a limit of 10,000 picocuries per liter for radon in drinking water has been proposed by some health physicists on the basis of assumptions related to air volume and water use in the home (Zapecza and Szabo, 1988, p. 52).

RIDEM has sampled 303 private wells among 19 sites in Rhode Island for radon. The 19 sites represent large areas of the State, but probably do not represent all geologic environments because the sites were chosen to evaluate the effects of land use on ground-water quality. Provisional data for the 303 wells show a maximum concentration of 49,080 picocuries of radon per liter of water, a minimum value of 140 picocuries per liter, and a median value of 2,930 picocuries per liter (S.M. Bobiak, Rhode Island Department of Environmental Management, written commun., 1989). The concentration of radon was less than or equal to 5,840 picocuries per liter in 75 percent of the samples. Values greater than 10,000 picocuries per liter were measured in ground water from several areas of the State.

Dissolved Minerals

Minerals dissolved from the rocks of the Earth's crust are the source of the most important chemical constituents in natural ground water. As water moves through soil, sediments, and bedrock, it reacts with the minerals it contacts. For this reason, ground water generally contains more dissolved minerals than does surface water. Dissolved minerals often impart a characteristic taste to ground water.

Different minerals have different degrees of solubility in water. Some, like sodium chloride (common table salt), dissolve easily and in large amounts. Others, like silica (quartz), dissolve slowly and in small quantities. Most of the bedrock and sediments in Rhode Island are composed of quartz, feldspar, and other silicate minerals of low solubility. Consequently, natural ground water in the State contains low concentrations of dissolved minerals (table 2), and is considered to be of good aesthetic quality for drinking.

Many minerals break up into ions when they dissolve. An ion is an atom or group of atoms that carries a positive or negative electrical charge. A cation is an ion that has a positive electrical charge, and an anion is an ion that has a negative electrical charge. Common cations in Rhode Island's ground water include iron, manganese, calcium, magnesium, sodium, and potassium; common anions include carbonate, bicarbonate, sulfate, chloride, and fluoride (tables 1 and 2).

Iron and manganese are the only dissolved minerals that impair the quality of ground water in Rhode Island under natural conditions. Ground water dissolves these metals from numerous minerals in the bedrock and sediments of Rhode Island (table 1). The presence or absence of dissolved oxygen affects the solubility of iron and manganese. Water that does not contain dissolved oxygen easily dissolves some iron- and manganese-bearing minerals. In contrast, these minerals are insoluble in water that contains significant amounts of dissolved oxygen. Iron and manganese will precipitate when ground water containing these dissolved constituents is exposed to the air.

Excessive concentrations of iron and manganese in water are considered an aesthetic problem rather than a health problem (table 1). Where the concentration of iron exceeds 0.3 milligram per liter, precipitation of iron causes reddish-brown stains on plumbing fixtures, containers, and laundry. Where the concentration of manganese exceeds 0.05 milligram per liter, precipitation of manganese causes black stains and films. Concentrations of iron or manganese in ground water exceed these levels at some locations in Rhode Island (table 2), although concentrations generally are below these levels (Johnston and Barlow, 1988, p. 444, fig. 2C; p. 445).

Natural organic chemicals

Organic chemicals are made up of carbon and hydrogen atoms, with variable amounts of other elements. Plants and animals are composed of complex organic chemicals such as starches and proteins. Some organic chemicals of natural origin may be found in ground water. These are mostly derived from humus, the decomposed organic material in soil.

Properties Related to Chemical Constituents

Several important characteristics of ground water are closely related to its dissolved chemical constituents. These characteristics include dissolved solids, hardness, and pH (table 1).

Dissolved solids include all the mineral matter dissolved in water, and the dissolved-solids concentration indicates how highly mineralized the water is. Freshwater contains from 0 to 1,000 milligrams per liter of dissolved solids, and saline water contains more than 1,000 milligrams per liter of dissolved solids (U.S. Geological Survey, 1988, p. 549, 551). The dissolved-solids concentration of seawater, by comparison, is commonly in the range of 35,000 milligrams per liter. Ground water in Rhode Island is not highly mineralized, and in most areas the dissolved-solids concentration is less than 200 milligrams per liter (Johnston and Barlow, 1988, p. 443).

Hardness, caused primarily by dissolved calcium and magnesium minerals, is a property of water that is commonly recognized by the amount of soap required to form a lather. Soap lathers easily in soft water. The harder the water, the greater the amount of soap needed to form a lather. Hard water causes formation of an insoluble residue when used with soap, and it leaves scale on containers. Most ground water in Rhode Island is soft. An adverse effect of soft water is its tendency to corrode metal pipes.

The concentration of hydrogen ions in water is expressed as pH. Many physical, chemical, and biological factors affect pH. Measurement of pH gives an indication of how acidic or alkaline the water is (table 1). Carbon dioxide, released by bacterial action in the soil or dissolved from the atmosphere, affects the pH of natural water. As dissolved carbon dioxide reacts with water molecules, hydrogen ions are produced, acidity is increased, and the pH is lowered. Carbonate minerals also affect pH by consuming hydrogen ions and reducing acidity as the minerals dissolve in water. Many household antacids contain calcium carbonate and work on this same principle. Carbonate rocks such as marble, although uncommon in Rhode Island, are found locally in the northeastern part of the State. Ground water in Rhode Island is commonly slightly acidic; pH typically ranges from 5.5 to 7.0 (Johnston and Barlow, 1988, p. 443).

Physical Properties

Physical properties of ground water include temperature, color, taste, odor, turbidity, and specific electrical conductance. Temperature in shallow aquifers is primarily related to climate. In contrast to the large seasonal temperature fluctuations in surface water, the temperature of ground water is fairly constant and is close to the average annual air temperature for the region. The temperature of ground water in Rhode Island is typically near 50 degrees Fahrenheit. Color in ground water may be caused by dissolved mineral or organic matter. Tastes and odors, which are somewhat subjective qualities, may be derived from bacteria, dissolved gases, organic matter, or minerals. Turbidity is a measure of the murkiness of water and is caused by suspended clay, silt, organic matter, or microscopic organisms. Natural filtration by unconsolidated materials generally eliminates turbidity from ground water.

Specific electrical conductance is a measure of the ability of water to conduct an electrical current. Because many minerals dissolve into ions, the ability of water to conduct electricity is related to the concentration of dissolved minerals. The more dissolved minerals, the higher the specific electrical conductance. Thus, specific electrical conductance is an easily measured indirect indication of the dissolved-solids concentration.

Variations in Natural Quality

The constituents and properties that determine the quality of ground water are affected by the changing characteristics of the ground-water environment. Temperature, pressure, the presence or absence of other minerals and gases, and the rock type through which the ground water is flowing all affect the solubility of a mineral or gas. A change in the environment can increase or decrease the capacity of the water to dissolve a particular mineral. If the capacity increases, more of the mineral is dissolved; if the capacity decreases, less of the mineral is dissolved, and some dissolved constituents may precipitate out of solution. In the process of precipitation, oppositely charged ions come together in large numbers to form a solid mineral that is deposited as a crust or coating on sediment grains or fracture surfaces in the aquifer.

Contaminants and Their Sources

Water-Quality Standards

Water-quality standards are defined and established with respect to a particular intended use. Water-quality requirements for drinking water, irrigation, or industrial processes differ widely.

Standards for drinking-water quality, established to protect public health and welfare, are of greatest interest to most citizens. The USEPA has established national regulations for public drinking-water supplies. States, however, may choose to set more stringent standards. Substances and properties for which national drinking-water regulations have been set by the USEPA are listed in tables 3 and 4. Maximum Contaminant Levels (MCLs) are legally enforceable standards regulating contaminants that are hazardous to human health (table 3) (U.S. Environmental Protection Agency, 1976; 1987b; 1987c). MCLs have not been set for many potentially harmful substances. Nonenforceable guidelines for constituents that cause aesthetic problems, but are not harmful at low concentrations, are referred to as Secondary Maximum Contaminant Levels (SMCLs) (table 4) (U.S. Environmental Protection Agency, 1987d). Existing regulations are periodically reviewed and are revised, if necessary, as new information becomes available.

The Rhode Island Department of Health (RIDH) establishes water-quality standards and other regulations for public drinking water in Rhode Island and periodically monitors the quality of water from public water systems. The RIDH also conducts tests of private well water. RIDH monitoring results cited in this report refer to the RIDH monitoring year, which begins on July 1 and ends on June 30. For example, the 1987 monitoring year extends from July 1, 1986 through June 30, 1987.

Types of Contaminants

Contaminants are classified in the same general groups as the substances found in natural ground water--biological, inorganic-chemical, and organic-chemical constituents. Some substances are harmless at the low concentrations commonly found in natural ground water but are considered contaminants if present at higher concentrations. Other substances are rarely or never found in uncontaminated ground water, and are harmful even at very low concentrations. Bacteria, iron and manganese, sodium, trace metals, nitrate, radionuclides, petroleum products, and synthetic organic chemicals are the major contaminants that have been found in Rhode Island ground water (Rhode Island Department of Environmental Management, 1988).

Biological contaminants

Biological contaminants include disease-causing bacteria, viruses, and other microscopic organisms. These organisms were formerly the most serious contaminants in ground water, and they still pose significant health hazards in some situations. Advances in sanitation practices for disposal of human and animal wastes have substantially reduced, but have not eliminated, biological contaminants.

Bacteriological quality of water is indicated by the population density of coliform bacteria (table 3). The coliform group includes many species, some of them harmless. Their presence in large numbers indicates fecal pollution and the likely presence of pathogenic organisms (Hem, 1985, p. 211).

Table 3.--National Primary Drinking-Water Regulations

[Unit of measurement is milligrams per liter (mg/L) unless otherwise specified; mL, milliliters; TU, turbidity unit; pCi/L, picocurie per liter; mrem/yr, millirem (one thousandth of a rem) per year. Extracted from U.S. Environmental Protection Agency, 1976, 1987b, 1987c; standards set by the Rhode Island Department of Health are the same, except as noted]

Constituent or property	Maximum contaminant level (MCL)
INORGANIC CHEMICALS	
Arsenic	0.05
Barium	1
Cadmium	0.010
Chromium	0.05
Lead	0.05
Mercury	0.002
Nitrate (as N)	10
Selenium	0.01
Silver	0.05
Fluoride [1]	4.0
ORGANIC CHEMICALS	
Pesticides:	
Endrin	0.0002
Lindane	0.004
Methoxychlor	0.1
Toxaphene	0.005
2,4-D	0.1
2,4,5-TP Silvex	0.01
Volatile organic compounds:	
Benzene	0.005
Carbon tetrachloride	0.005
1,2-Dichloroethane	0.005
Trichloroethylene (TCE)	0.005
Para-dichlorobenzene	0.075
1,1-Dichloroethylene	0.007
1,1,1-Trichloroethane	0.20
Vinyl chloride	0.002
Total trihalomethanes [the sum of the concentrations of bromodichloromethane, dibromochloromethane, tribromomethane (bromoform), and trichloromethane (chloroform)]	0.10
PHYSICAL PROPERTIES	
Turbidity [2]	1-5 TU

Table 3.--National Primary Drinking-Water Regulations--Continued

Constituent or property	Maximum contaminant level (MCL)
MICROBIOLOGICAL CONTAMINANTS	
Coliform bacteria	1 colony per 100 mL (mean)
RADIONUCLIDES	
Radium 226 and 228 (combined)	5 pCi/L
Gross alpha particle activity	15 pCi/L
Gross beta particle activity	4 mrem/yr

1 A secondary maximum contaminant level of 2.0 mg/L also has been established. Standard for fluoride in Rhode Island is 2.0 mg/L (Rhode Island Department of Health, 1983, p. 7).

2 Applies only to surface-water sources (Rhode Island Department of Health, 1983, p. 10).

Table 4.--National Secondary Drinking-Water Regulations

[Unit of measurement is milligrams per liter (mg/L) unless otherwise specified. Extracted from U.S. Environmental Protection Agency, 1987d]

Constituent	Secondary maximum contaminant level (SMCL)
INORGANIC CHEMICALS	
Chloride	250
Fluoride	2.0
Sulfate	250
Copper	1
Iron	0.3
Manganese	0.05
Zinc	5
Total dissolved solids	500
Foaming agents	0.5
PHYSICAL PROPERTIES	
Color	15 color units
Corrosivity	Noncorrosive
Odor	3 (threshold odor number)
pH	6.5-8.5 units

Tests of private well water conducted by RIDH from 1975 to 1985 showed that concentrations of bacteria exceeded State drinking-water standards, on the average, in almost 40 percent of the samples from shallow dug wells and in about 8 percent of the samples from deeper driven and drilled wells (Johnston and Barlow, 1988, p. 447). About 1,000 wells were tested annually. These figures are probably not representative of all private wells in the State, because water from many private wells is not analyzed unless contamination is suspected.

Inorganic chemicals

Important inorganic chemical contaminants in Rhode Island's ground water include several metals, nonmetals, and radionuclides from natural sources and from various human activities. Inorganic chemicals for which USEPA Primary or Secondary Drinking-Water Regulations have been established are shown in tables 3 and 4.

Iron and manganese.--These metals are common natural constituents of ground water in Rhode Island and are also derived from land-use and waste-disposal practices (table 1). Iron concentrations exceeded the SMCL (table 4) in about 18 percent of the water samples from approximately 100 public-water-system wells tested annually by RIDH from 1982 through 1986 (Rhode Island Department of Environmental Management, 1988, p. IV-11). Manganese concentrations exceeded the SMCL (table 4) in samples from about 28 percent of the public-water-system wells sampled during this period.

Sodium.--Sodium concentrations greater than 20 milligrams per liter in drinking water may pose a health risk for people with cardiovascular problems (table 1). Concentrations exceeded this health guideline in samples from 19 to 23 percent of the 93 to 105 public-water-system wells tested annually by RIDH from 1982 through 1986 (Rhode Island Department of Environmental Management, 1988, p. IV-12).

Trace metals.--Trace constituents are substances that nearly always occur in concentrations less than 1 milligram per liter (Hem, 1985, p. 129). Trace metals that have been detected in Rhode Island's ground water include barium, cadmium, chromium, copper, lead, mercury, nickel, silver, and zinc (Rhode Island Department of Environmental Management, 1988, table 4-8a, p. IV-15). All may occur naturally in trace concentrations, but they are not known to be significant constituents of natural ground water in Rhode Island. Of these nine metals, only barium has been detected in water from the Upper Wood ground-water reservoir (fig. 13), a relatively pristine area (Dickerman and others, 1989, table 18C, p. 265). Several of these metals cause serious adverse health effects (U.S. Environmental Protection Agency, 1976). MCLs are shown in table 3. Copper in drinking water is commonly derived from corrosion of copper pipes, and causes greenish stains on plumbing. SMCLs for copper and zinc are based on taste considerations (table 4).

The RIDH sampled 109 to 135 public-water-system wells annually for trace metals from 1982 through 1986 (Rhode Island Department of Environmental Management, 1988, p. IV-10). MCLs for barium, cadmium, chromium, and silver were not exceeded in any samples during this period. The MCL for mercury was exceeded once in water from one well, and the MCL for lead was exceeded in water from no more than two wells per year. The SMCL for zinc was not exceeded, and the SMCL for copper was exceeded in water from no more than two wells per year.

Nitrate.--Natural ground water in Rhode Island contains very little nitrate. Concentrations of nitrate (as nitrogen) are likely to be less than 0.2 milligram per liter in ground water from stratified-drift aquifers in areas of Rhode Island that are relatively unaffected by human activities (Johnston and Barlow, 1988, p. 444). Concentrations higher than 10 milligrams per liter are hazardous to infants (table 1) (U.S. Environmental Protection Agency, 1976, p. 81).

The concentration of nitrate exceeded the State drinking-water standard of 10 milligrams per liter in water samples from about 2 percent of approximately 1,000 private wells tested annually by RIDH from 1975 through 1985 (Johnston and Barlow, 1988, p. 447). In public-water-system wells monitored by RIDH from 1982 through 1986, the concentration of nitrate was greater than 0.2 milligram per liter in about 80 percent of the 93 to 105 wells tested annually (Rhode Island Department of Environmental Management, 1988, p. IV-11). There were no violations of the State drinking-water standard among these public-water-system wells, and the highest concentration measured was 7.6 milligrams per liter.

Radionuclides.--Naturally occurring radon is the most widespread and significant radionuclide in Rhode Island ground water. Radionuclides from industrial waste have contaminated ground water in part of the Lower Wood ground-water reservoir (fig. 13) near the Pawcatuck River. Contaminants in ground water at this site include the beta-particle emitters strontium-90 and technetium-99. Concentrations range from 4 to 250 picocuries per liter for strontium-90 and from 75 to 1,350 picocuries per liter for technetium-99 (Ryan and Kipp, 1985, p. 29). An average annual strontium-90 concentration of 8 picocuries per liter in drinking water is assumed to produce a total body dose of 4 millirems per year (table 3), the MCL for gross beta-particle activity (U.S. Environmental Protection Agency, 1976, p. 7-8).

Petroleum products and synthetic organic chemicals

A thorough discussion of petroleum products and synthetic organic chemicals is beyond the scope of this report; however, general aspects of these compounds deserve mention for several reasons. The chemicals are widely used, a number of them have been detected in ground-water supplies, and many of them are known to be, or are suspected of being, hazardous to human health at extremely low concentrations.

Petroleum products and synthetic organic chemicals, also called hydrocarbons, are composed of carbon and hydrogen with variable amounts of other elements, as are the natural organic chemicals in plants and animals. Carbon atoms link together in chains and rings that form large, complicated molecules. Small groups of carbon atoms and other elements may be joined in a virtually infinite number of arrangements, much like a large set of children's interlocking plastic building blocks. Thousands of organic chemicals have been created in the second half of the 20th century, and hundreds of new ones are synthesized each year.

The presence of hydrocarbons constitutes one of the most serious and complex ground-water contamination problems because of the widespread use of hydrocarbons and the health risk they pose at low concentrations. National Primary Drinking-Water Regulations have been established for few of the many organic chemicals that may be found in ground water (table 3). A total of 57 organic chemicals have been detected in ground water in Rhode Island (Rhode Island Department of Environmental Management, 1988, table 4-8a, p. IV-15).

Petroleum products.--Petroleum is a natural hydrocarbon formed in the Earth from ancient deposits of animal matter over millions of years. Petroleum fuels are a group of products refined from petroleum hydrocarbons. They are composed of numerous carbon compounds that are hazardous to human health. Petroleum hydrocarbons themselves provide the raw materials for the manufacture of many synthetic organic chemicals.

A public-supply well for the town of Westerly was removed from service in 1986 because of contamination from petroleum products (Rhode Island Department of Environmental Management, 1988, table 4-2, p. IV-9). As of January 1988, about 30 homes in Rhode Island were receiving bottled water from the State because their private wells had been contaminated by gasoline or fuel oil (Rhode Island Department of Environmental Management, 1988, p. IV-12).

Trihalomethanes.--Chlorine, commonly used as a disinfectant in public water supplies, reacts with natural organic substances derived from soil humus to form trihalomethanes in water. Ground water generally contains lower concentrations of trihalomethanes than does surface water, because natural organic substances are filtered out of the water by aquifer materials. Trihalomethanes are also used in industrial processes. All the trihalomethanes listed in table 3 have been detected in ground water in Rhode Island (Rhode Island Department of Environmental Management, 1988, table 4-8a, p. IV-15).

Solvents.--Solvents are a large family of organic chemicals used in many industrial and commercial processes and some household products. Examples of solvents include trichloroethylene (TCE), benzene, tetrachloroethylene, and carbon tetrachloride. Many commonly used solvents belong to a group of chemicals called volatile organic compounds.

Volatile organic compounds.--Trihalomethanes, many solvents, and other organic chemicals belong to a group called volatile organic compounds (VOCs). VOCs evaporate readily and are generally not very soluble in water; however, many are very hazardous to health at low concentrations. VOCs for which MCLs have been established are shown in table 3.

The RIDH monitored 81 to 103 public-water-system wells annually for selected VOCs from 1984 through 1986 (Rhode Island Department of Environmental Management, 1988, p. IV-8 to IV-10). One or more VOCs were detected in water from 16 to 20 percent of the wells sampled during this period. Ten different VOCs were detected; 1,1,1-trichloroethane (a solvent, coolant, and dry-cleaning agent) and chloroform (a trihalomethane used as a fumigant and solvent) were detected most frequently.

With the exception of trihalomethanes (table 3), MCLs had not been set for any volatile organic compounds during the 1984-86 sampling period. None of the current (1989) MCLs were exceeded during the sampling period (Rhode Island Department of Environmental Management, 1988, p. IV-10); however, MCLs for some of the compounds detected have not been set as of 1989.

Contamination of ground water by VOCs has been the major cause for removal of public-supply wells from service in Rhode Island. Seven major public-supply wells and six wells serving small public-water systems were removed from service for this reason from 1979 through 1987 (Rhode Island Department of Environmental Management, 1988, table 4-2, p. IV-9). As of January 1988, about 60 homes were receiving bottled water from the State because their private wells had been contaminated by VOCs (Rhode Island Department of Environmental Management, 1988, p. IV-12).

Pesticides.--Many pesticides are synthetic organic chemicals. Some, such as the chlorinated hydrocarbons (also called organochlorines) are not very soluble in water but are hazardous at very low concentrations. The most familiar member of this group is DDT. Endrin, lindane, methoxychlor, and toxaphene are chlorinated hydrocarbon pesticides for which MCLs have been set (table 3). Another widely used group of pesticides, called carbamates, dissolve easily in water and are also very toxic. Carbamate pesticides detected in ground water in Rhode Island include aldicarb, carbofuran, and oxamyl (Rhode Island Department of Environmental Management, 1988, table 4-8a, p. IV-15).

Sources of Contaminants

Human use of the land introduces many contaminants to ground water. Contaminant sources may be categorized as either point sources or nonpoint sources. Point sources are usually a few acres or less in size and include sources such as landfills and chemical spills. Nonpoint sources introduce contaminants over a broad area and include activities such as the application of road salt or agricultural chemicals.

Studies in several States have attempted to relate land use to regional ground-water quality (Cain and others, 1989). Preliminary results indicate that effects on water quality increase with increased intensity of urbanization. The results of these and other studies also indicate that certain contaminants are likely to be associated with particular land uses (table 5).

The relation of land use to ground-water quality is complex. Many types of potential contaminants may be produced by a single source, and many different sources may contribute the same contaminant to ground water. Land uses in areas that supply recharge to public or private wells in Rhode Island are typically diverse and include both point and nonpoint sources (fig. 27).

Table 5.--Probable ground-water contaminants associated with major land uses in the northeastern United States

[X indicates that the land use is likely to produce the selected contaminants. Sources: Cain and others, 1989; Grady and Weaver, 1989; Handman and others, 1979, p. 20]

Land use	Selected contaminants							
	Sodium	Nitrate	Detergents	Bacteria and viruses	Petroleum hydrocarbons	Volatile organic compounds	Trace metals	Pesticides
Agricultural areas		X	X	X				X
Residential areas	X	X	X	X		X		X
Industrial and commercial areas	X	X	X		X	X	X	
Transportation routes and facilities	X				X		X	
Waste-disposal sites	X			X	X	X	X	
Urbanized areas with mixed land uses	X		X	X	X	X	X	

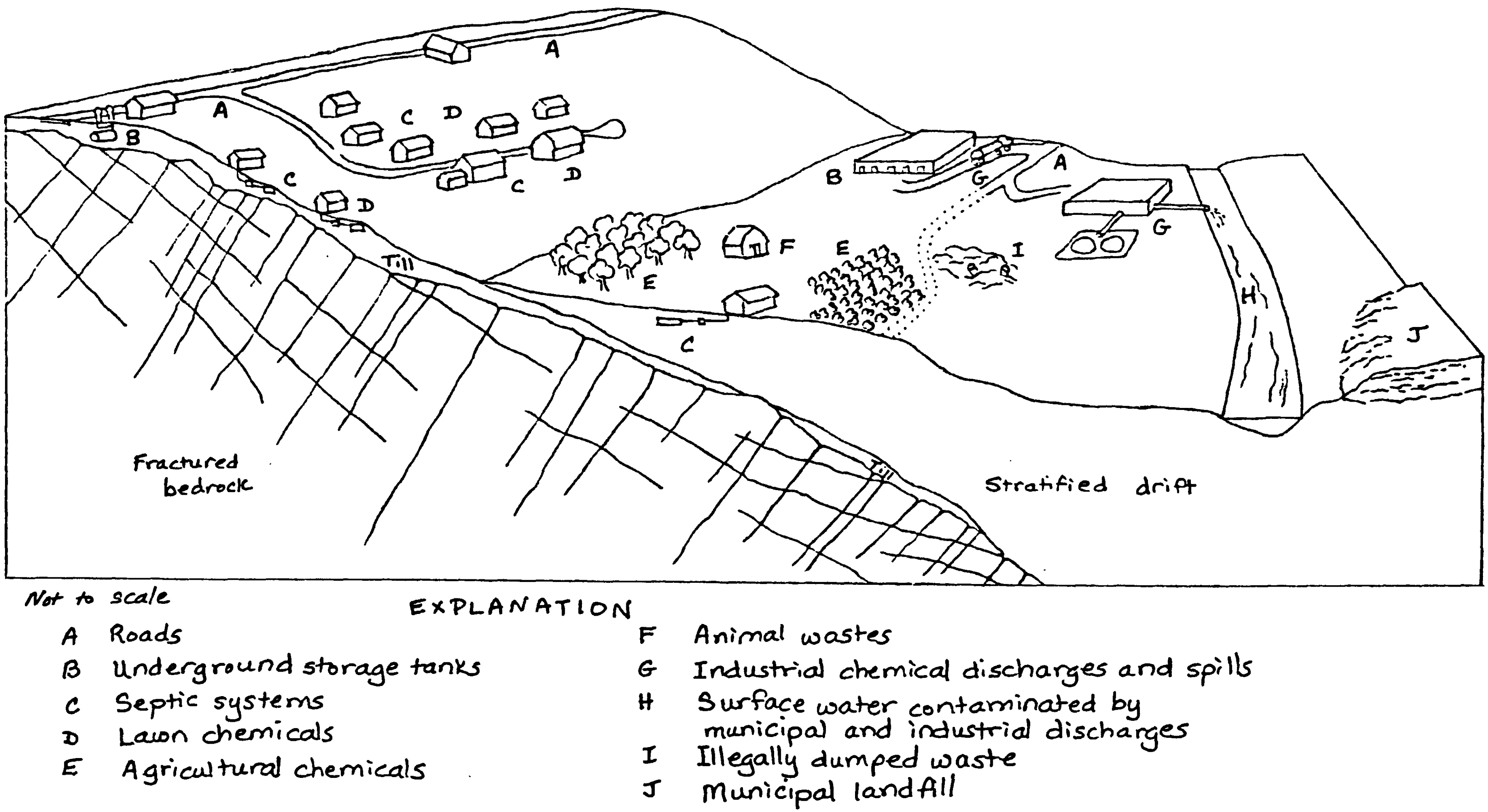


Figure 27.--Potential sources of ground-water contamination related to land use and waste disposal in Rhode Island's hydrogeologic setting. Geologic units are as shown in figure 9. Unconsolidated glacial deposits overlie fractured bedrock. A thin layer of till covers the hillside at the left side of the diagram. A thick layer of stratified drift fills the bedrock valley on the right.

The RIDEM has inventoried 121 sites where ground water has been contaminated by municipal solid-waste landfills, industrial-waste sites and discharges, leaking underground storage tanks, petroleum-storage facilities, State road-salt storage facilities, and miscellaneous sources including U.S. Department of Defense waste-disposal sites and unknown sources (Rhode Island Department of Environmental Management, 1988, fig. 4-7, p. IV-30; table 4-15, p. IV-31 to IV-35). The locations of these identified point sources are shown in figure 28. Significant nonpoint sources in Rhode Island include agricultural pesticides and fertilizers, septic systems, and road salt in highway runoff (Rhode Island Department of Environmental Management, 1988, p. IV-27, IV-36 to IV-40). Inventories of ground-water contamination sites change frequently as regulatory programs evolve and as new information becomes available.

Undeveloped areas

Airborne substances are presumably the only substantial nonpoint source of the chemical constituents of ground water in undeveloped areas. A statistical comparison of land use and ground-water quality in stratified-drift aquifers in Connecticut found that the median concentrations or detection frequencies for many common and trace constituents of ground water were significantly lower in undeveloped areas than in agricultural, residential, or industrial and commercial areas (Grady and Weaver, 1989).

Ground water may be affected by human activities even in relatively pristine areas such as the upper Wood River basin in southwestern Rhode Island (fig. 13). The presence of nitrate concentrations above presumed natural levels, as well as detectable amounts of ammonia nitrogen, indicates that ground-water quality has been affected locally by septic-system effluent (table 2).

Agricultural areas

The most common contaminants in agricultural areas of Rhode Island are nitrate and pesticides. Nitrate is derived from fertilizers and animal wastes. Most pesticides currently in use are synthetic organic chemicals, but some contain metals. Ground-water quality may be affected by the application, storage, or disposal of fertilizers and pesticides. Proper application procedures do not necessarily eliminate the possibility of ground-water contamination.

Investigations at two sites in the Chipuxet River basin indicate that shallow ground water has been degraded by nitrate derived from fertilizer applied to agricultural fields (Johnston and Dickerman, 1985, p. 65-70). Nitrate concentrations exceeded the MCL of 10 milligrams per liter in water from some of the wells sampled.

Aldicarb, a carbamate pesticide used on potato fields, has contaminated ground water in parts of southern Rhode Island. From 1984 through 1986, aldicarb was detected in water from 169 of the 980 drinking-water wells tested by RIDH (Johnston and Barlow, 1988, p. 446). Concentrations of aldicarb exceeded the USEPA Proposed Maximum Contaminant Level Goal (MCLG) of 0.009 milligram per liter (9 micrograms per liter) in samples from 42 of the wells (U.S. Environmental Protection Agency, 1985, p. 46986; Johnston and Barlow, 1988, p. 446). The MCLG is a nonenforceable health goal.

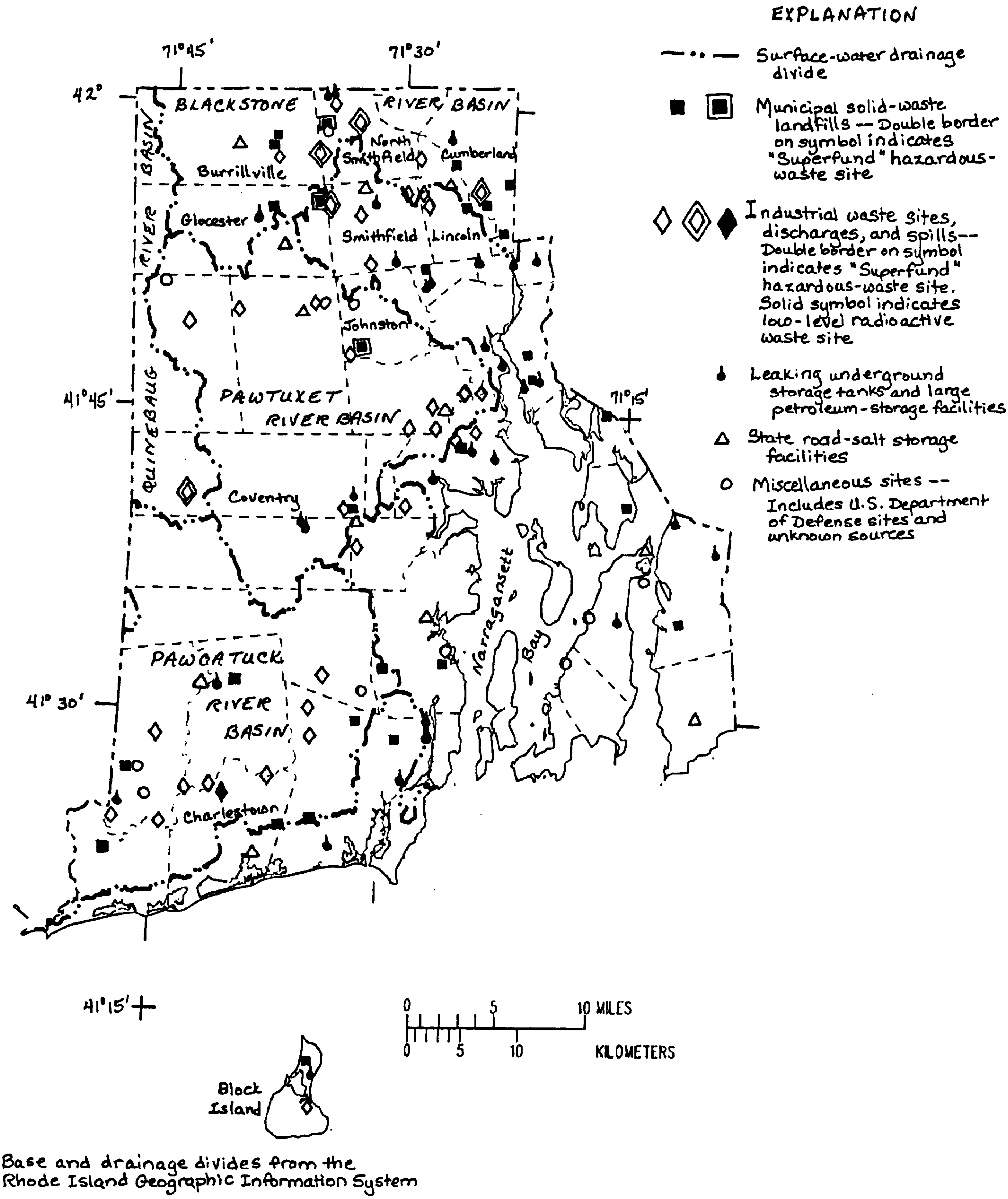


Figure 28.--Locations of known point sources of ground-water contamination. (Source: Data from Rhode Island Department of Environmental Management, 1988, table 4-9, p. IV-18 to IV-20; fig. 4-7, p. IV-30; table 4-15, p. IV-31 to IV-35.)

All of the wells yielding water contaminated by aldicarb are located in Washington and Newport Counties (fig. 1). One well yielding contaminated water was part of a public-supply system in South Kingstown, and was removed from service in 1984 (Rhode Island Department of Environmental Management, 1988, table 4-2, p. IV-9). The extent of ground-water contamination from other pesticides used in Rhode Island is not known.

Residential areas

Residential areas in Rhode Island may contribute a number of contaminants to ground water (table 5). Sources of these contaminants include individual sewage-disposal systems, underground heating-oil tanks, lawn and garden products, street runoff, and household chemical products.

Individual sewage-disposal systems.--Septic systems and cesspools serve about one-third of the State's population (Johnston and Barlow, 1988, p. 447). Septic-system effluent may add nitrate and other nutrients, bacteria, detergents, and a variety of other contaminants to ground water (table 2). Use of septic-tank degreasers is now illegal in Rhode Island because of the potential hazard to private water supplies from these solvent-based chemicals. Many areas that depend on private wells for drinking water are also dependent on individual sewage-disposal systems. Consequently, contamination of private wells by septic-system effluent is not uncommon in such areas.

Heating oil tanks.--Thousands of underground heating-oil tanks less than 1,100 gallons in volume are not regulated by RIDEM because of their small size (Rhode Island Department of Environmental Management, 1988, p. IV-26). These tanks may be local sources of contamination if they corrode and leak petroleum products into the ground.

Household chemical products.--The disposal of hazardous household chemicals can contaminate ground water in residential areas. Materials containing solvents, petroleum hydrocarbons, metals, and other toxic substances may be improperly discharged to septic systems or discarded on the land surface. A partial list of common household products that may contaminate ground water includes: cleaning solvents, disinfectants and deodorizers, oven cleaners, drain cleaners, spot removers and degreasers, other household cleaners, septic-tank degreasers; oil and gasoline, brake and transmission fluids, antifreeze, car waxes and cleaners, other fuels; paint, paint strippers, paint thinner, turpentine, wood preservatives, solvent-based glues, varnish; mothballs, baits and poisons, pesticides, fertilizers; nail polish and polish remover; metal polishes, shoe polish, furniture polish, floor wax; and art, craft, and photographic supplies (Langlois, 1984; Water Pollution Control Federation, 1986).

Industrial and commercial areas

Industrial and commercial processes use and produce many chemicals, and the possible types of contaminants from these areas are extremely varied (table 5). Contaminants may be released to the environment inadvertently during transportation, transfer, storage, use, or processing of industrial chemicals. Some contaminants are released from permitted on-site disposal of industrial wastes as well as from unregulated or illegal waste-disposal practices.

Communities are often reluctant to regulate industrial and commercial practices and to restrict the locations for certain types of businesses because of the economic costs imposed on businesses or the potential loss of revenue to the town. Consequently, the siting of many industries and businesses threatens ground-water quality, and new hazards continue to be introduced. In some cases, ground water has been contaminated by practices that were formerly legal but are now regulated.

Ground water has been contaminated by industrial wastes, discharges, and spills at 38 sites in Rhode Island (fig. 28) (Rhode Island Department of Environmental Management, 1988, p. IV-32 to IV-33). Major contaminants include solvents and other organic chemicals from industrial areas. Petroleum products from leaking underground storage tanks are major contaminants from commercial and industrial areas.

Chemical spills.--Solvents such as tetrachloroethylene are commonly used for metal degreasing, dry cleaning, and many other industrial and commercial applications. In Lincoln, three public-supply wells near the Blackstone River were removed from service in 1979 after a statewide testing program conducted by RIDH detected several volatile organic solvents in the well water (Rhode Island Department of Environmental Management, 1988, table 4-2, p. IV-9). An industry upstream from the wells on the opposite side of the river in Cumberland was identified as the most likely source of the contaminants (Goldberg-Zoino & Associates, Inc., 1982, p. 40). This industrial site is now on the USEPA National Priority List (NPL) for investigation and cleanup under the Federal "Superfund" program (fig. 28) (Rhode Island Department of Environmental Management, 1988, table 4-9, p. IV-19). A second "Superfund" site where spilled industrial solvents have contaminated ground water is in North Smithfield (fig. 28).

Leaking underground storage tanks.--Underground storage tanks are used to store a variety of chemicals and waste products, but the most common use is to store petroleum products. Leakage of chemicals from underground tanks and pipelines is a particularly serious problem because leaks may go undetected, and the stored products are often so hazardous that very small amounts may contaminate large volumes of ground water. Leakage of petroleum products from underground tanks occurs most commonly because of corrosion in old tanks.

Ground water has been contaminated by leaks from underground storage tanks at 29 sites in Rhode Island and by chronic leaks and spills at two large petroleum storage facilities (fig. 28) (Rhode Island Department of Environmental Management, 1988, table 4-15, p. IV-33 to IV-34). Water from private wells has been contaminated by petroleum products from 15 gasoline stations (Rhode Island Department of Environmental Management, 1988, p. IV-27). Leakage from underground tanks at gasoline stations in one Washington County neighborhood contaminated drinking water in private wells serving 29 homes. A new public-supply system was developed to serve the affected area, at an overall cost of more than $2 million (Rhode Island Department of Environmental Management, 1988, p. IV-27). There is potential for contamination at numerous other sites because of the age of many tanks.

RIDEM has regulated underground storage tanks with a volume of 1,100 gallons or more since 1985. There were 3,487 commercial and industrial underground storage tanks registered with RIDEM as of December 1988 (M.G.D. Bradley, Rhode Island Department of Environmental Management, oral commun., 1989). RIDEM regulations specify procedures for design and construction, leak and spill detection, reporting, recordkeeping, and abandonment of unused tanks.

Transportation routes and facilities

Highways, local roads, storage areas, rights of way, and airports may be sources of several kinds of contaminants. Street runoff may contribute sodium and chloride from winter application of road salt, nitrate from animal and plant wastes, metals, and petroleum products. Accidents may cause spills during transportation of chemicals on highways or freight trains. Herbicides are used to maintain highway, railway, and utility rights of way. Solvents are commonly used at airports to clean planes and remove grease from runways.

Sodium and chloride from road salt are common constituents in runoff from highways. Elevated concentrations of sodium and chloride in water from private and public wells near highways in Rhode Island are likely to result from use of road salt, but the extent of contamination from this source is not known.

Sodium and chloride also leach into the ground where road-salt storage piles are uncovered or are located directly on the land surface. There are 91 road-salt storage sites in Rhode Island. Ground water has been contaminated by sodium and chloride at 12 State road-salt storage facilities (fig. 28) (Rhode Island Department of Environmental Management, 1988, p. IV-27, IV-34). At eight sites, water from private wells has been affected, with chloride concentrations exceeding the SMCL of 250 milligrams per liter and sodium concentrations exceeding the health guideline of 20 milligrams per liter.

Waste-disposal sites

Waste-disposal sites may contain a wide variety of wastes and contribute many kinds of contaminants to ground water (table 5). Major contaminants derived from waste-disposal sites include synthetic organic chemicals and trace metals.

Waste-disposal sites may be classified according to the type of waste received and the method of disposal. Major types of waste include municipal refuse, liquid or solid industrial waste, bulky construction waste, and sewage sludge. Municipal solid waste and sewage sludge in Rhode Island are disposed of in landfills, where waste is compacted and buried under layers of earth. Liquid industrial wastes in Rhode Island have been discharged to surface water, to artificial ponds or lagoons, or to industrial septic systems, and have also been disposed of in some municipal landfills.

Most waste-disposal facilities in Rhode Island were in place before the promulgation during the 1980's of regulations that addressed ground-water protection (M.G.D. Bradley, Rhode Island Department of Environmental Management, oral commun., 1989). Three of the major categories of point-source ground-water contamination in Rhode Island include waste-disposal sites: municipal solid-waste landfills; industrial waste sites, discharges, and spills; and miscellaneous sites, which include waste-disposal sites on Department of Defense property (fig. 28).

Hazardous-waste sites.--The Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA), popularly known as the "Superfund" legislation, established procedures by which USEPA identifies sites containing hazardous materials that need to be cleaned up (U.S. Geological Survey, 1984, p. 58). Sites requiring immediate attention under the "Superfund" program are placed on the NPL.

The RIDEM has inventoried 221 known or potential hazardous-waste sites in Rhode Island under the auspices of this Federal program (Rhode Island Department of Environmental Management, 1988, p. IV-14). Eight of these sites are "Superfund" sites on the NPL. Two of the eight sites involve chemical spills at industrial locations, and six are waste-disposal sites (Rhode Island Department of Environmental Management, 1988, table 4-9, p. IV-18 to IV-20).

Three of the six "Superfund" waste-disposal sites are classified as municipal landfills, discussed below, and three are industrial waste-disposal sites. The three industrial sites include a private landfill and junkyard in Smithfield, a liquid-waste site at a sand and gravel pit in Burrillville, and an illegal dump in western Coventry (fig. 28). Synthetic organic chemicals are significant contaminants at all three sites.

Municipal solid-waste landfills.--Landfills are the primary means of solid-waste disposal in Rhode Island. The RIDEM has identified 45 landfills, including septage disposal areas (Rhode Island Department of Environmental Management, 1988, p. IV-21; table 4-15, p. IV-31 to IV-32). Twelve of these are active facilities. Ground water has been contaminated at 29 of the landfills, including the 12 active sites (fig. 28). Contaminants detected in ground water at several of the active facilities include VOCs, trace metals, iron, arsenic, selenium, chloride, and nitrate (Rhode Island Department of Environmental Management, 1988, table 4-11, p. IV-23 to IV-24).

The Rhode Island Central Landfill in Johnston is New England's largest municipal-waste facility. Three million gallons of hazardous waste were disposed of at the site in the late 1970's, before its use as a public landfill (Rhode Island Department of Environmental Management, 1988, p. IV-21; table 4-9, p. IV-18). Consequently, the landfill is a "Superfund" site on the NPL (fig. 28). VOCs are common contaminants in ground water at the site (Rhode Island Department of Environmental Management, 1988, table 4-11, p. IV-23).

Two other municipal solid-waste landfills are "Superfund" sites on the NPL (Rhode Island Department of Environmental Management, 1988, table 4-9, p. IV-18 to IV-19). One is a private landfill and junkyard in Glocester (fig. 28) that contains solvents and other hazardous wastes. The other is a private landfill in North Smithfield (fig. 28) that contains hazardous industrial waste as well as municipal waste.

Ground-water contamination from landfills usually encompasses small areas but may affect important ground-water resources. At least 16 landfills in the State overlie major ground-water reservoirs (fig. 13) (Rhode Island Department of Environmental Management, 1988, p. IV-25).

Underground injection sites.--Wastes are discharged to ground water at 70 facilities registered under the Underground Injection Control (UIC) Program (Rhode Island Department of Environmental Management, 1988, table 4-13, p. IV-25). UIC sites in Rhode Island include active industrial and commercial surface impoundments, shallow dry wells, commercial septic systems, and storm-drainage wells in areas not served by public sewer systems (M.G.D. Bradley, Rhode Island Department of Environmental Management, oral commun., 1989). Most of the UIC sites existed before the inception of the UIC program in 1984. Sites known to have contaminated ground water are included in the category of industrial waste sites, discharges, and spills in figure 28.

Surface impoundments.--Liquid wastes have been disposed of in ponds and lagoons, referred to as surface impoundments, at 29 active facilities and an uncertain number of inactive facilities in the State (Rhode Island Department of Environmental Management, 1988, p. IV-26). Active facilities are registered under the UIC program. Most of the surface impoundments overlie moderately to highly permeable soils, and at many sites, the waste material has been placed at or near the seasonal high water table (Rhode Island Department of Environmental Management, 1979, p. 6, 18). Investigations at three sites have detected VOCs, oil and grease, lead, copper, and chromium in ground water (Rhode Island Department of Environmental Management, 1988, p. IV-26). Ground water in part of the Lower Wood ground-water reservoir (fig. 13) has been contaminated by the radionuclides strontium-90 and technetium-99 (Ryan and Kipp, 1985). Sites known to have contaminated ground water are included in the industrial and miscellaneous categories in figure 28.

Movement of Contaminants to Ground Water

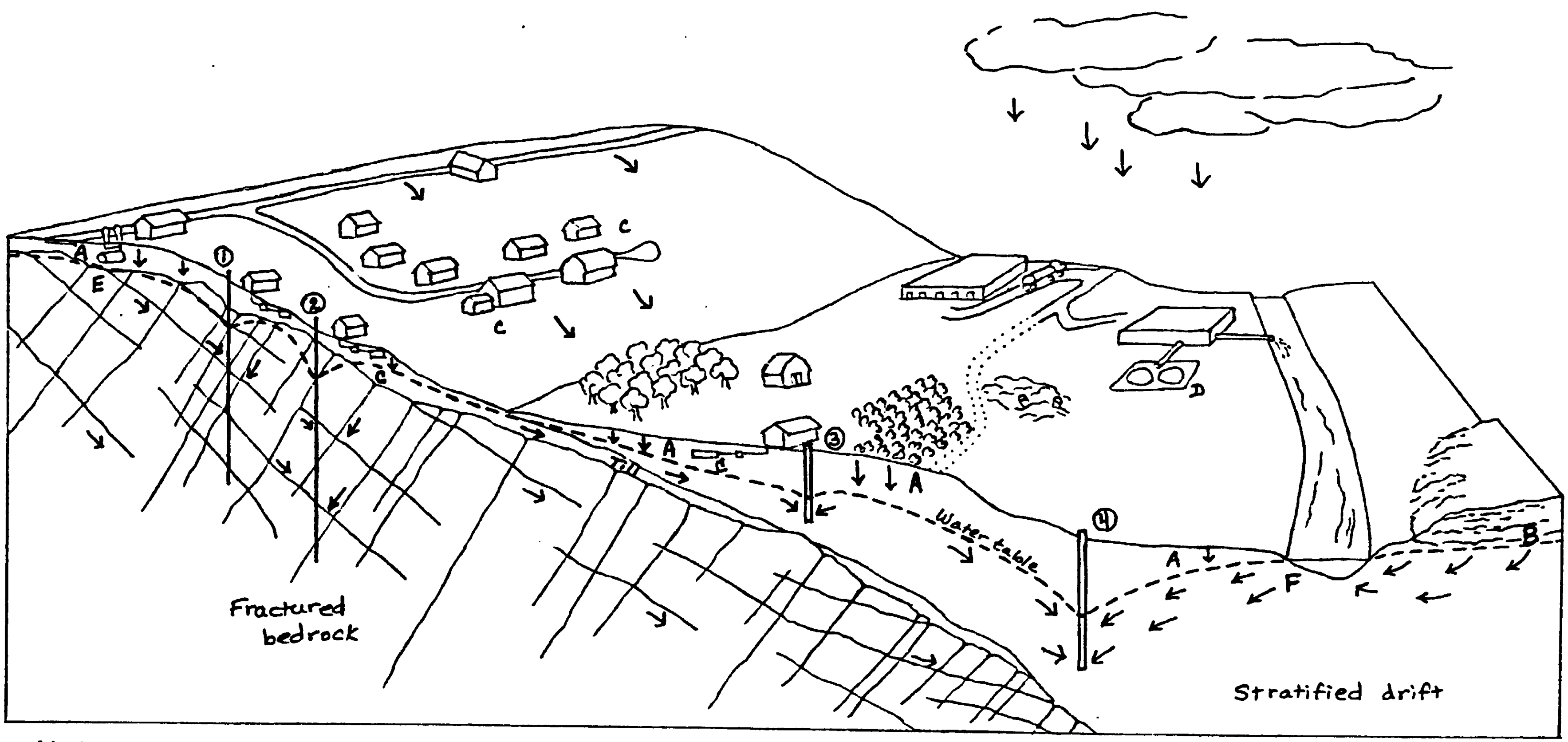
Substances that affect ground-water quality may reach the saturated zone in several ways (fig. 29). Contaminants at or near the land surface may be dissolved and transported through the unsaturated zone by natural or artificial recharge. Liquid contaminants such as gasoline migrate downward through the unsaturated zone under the influence of gravity. Contaminant sources may be located permanently or intermittently at the water table or within the saturated zone. Withdrawals from wells may change local hydraulic gradients and induce surface water or saltwater into an aquifer.

Movement Through the Unsaturated Zone

Infiltrating recharge

The natural recharge that percolates from the land surface through the unsaturated zone may dissolve and transport almost any substance with which it comes in contact. Infiltrating recharge carries pesticides applied to agricultural fields, chemicals spilled in industrial areas, salt and other substances in runoff from roads, and airborne substances that have settled on the land surface (fig. 29). Contaminants from infiltrating recharge are often hard to control because they are dispersed over many acres or square miles.

Recharge that has infiltrated through waste-disposal sites (location B in fig. 29) generally contains high concentrations of dissolved constituents. As water percolates through the waste, it dissolves soluble materials. This process is termed leaching, and the water that percolates out of the bottom of a landfill or other waste-disposal site is termed leachate. The quantity and composition of the leachate depend on the size of the site, the age and type of waste, the amount of water percolating through the waste, and the duration of contact between the water and the waste. Leachate commonly reaches the water table and contaminates ground water.



Not to scale

EXPLANATION

1 Domestic drilled well
2 Domestic drilled well
3 Domestic dug well in stratified drift
4 municipal gravel-packed well in stratified drift

A Infiltrating recharge
B Landfill leachate (recharge infiltrating through waste-disposal sites)
C Artificial recharge from septic systems
D Artificial recharge from surface impoundment
E Gasoline from underground storage tank
F Induced infiltration

Figure 29.--Movement of contaminants to ground water and toward drinking-water supplies. Arrows show direction of movement of water. Dashed line is the water table.

Runoff flowing over the land surface may dissolve and transport contaminants. Overland flow on the till-covered hillside shown in figure 29 may carry nitrate, pesticides, road salt, and oil. When the contaminated runoff reaches the permeable stratified drift at the foot of the hill, it is likely to infiltrate the land surface and percolate down to the saturated zone.

In low-lying, flood-prone areas, substances may be dissolved and transported through the unsaturated zone by percolating floodwater. Where development is concentrated in floodplains, floodwater infiltrating the land surface may contain contaminants from many sources.

Artificial recharge

Septic systems disperse domestic, commercial, or industrial wastewater over a large area and allow it to percolate into the ground. The wastewater and many of the constituents it contains move downward to the saturated zone (location C, fig. 29). Unlined surface impoundments used for industrial effluent at some locations in Rhode Island are another form of artificial recharge that may transport contaminants to ground water (location D, fig. 29).

Liquid contaminants

Liquids, such as gasoline from the leaking underground storage tank shown in figure 29 (location E), may move downward through the unsaturated zone under the influence of gravity. The movement of gasoline is shown in detail in figure 30. As the gasoline moves through the unsaturated zone, a residue of fuel clings to rock particle surfaces and remains trapped in the pore spaces (fig. 30). This residue is periodically flushed downward by infiltrating recharge. Contamination of the ground water can thus persist for many years after the leak occurs.

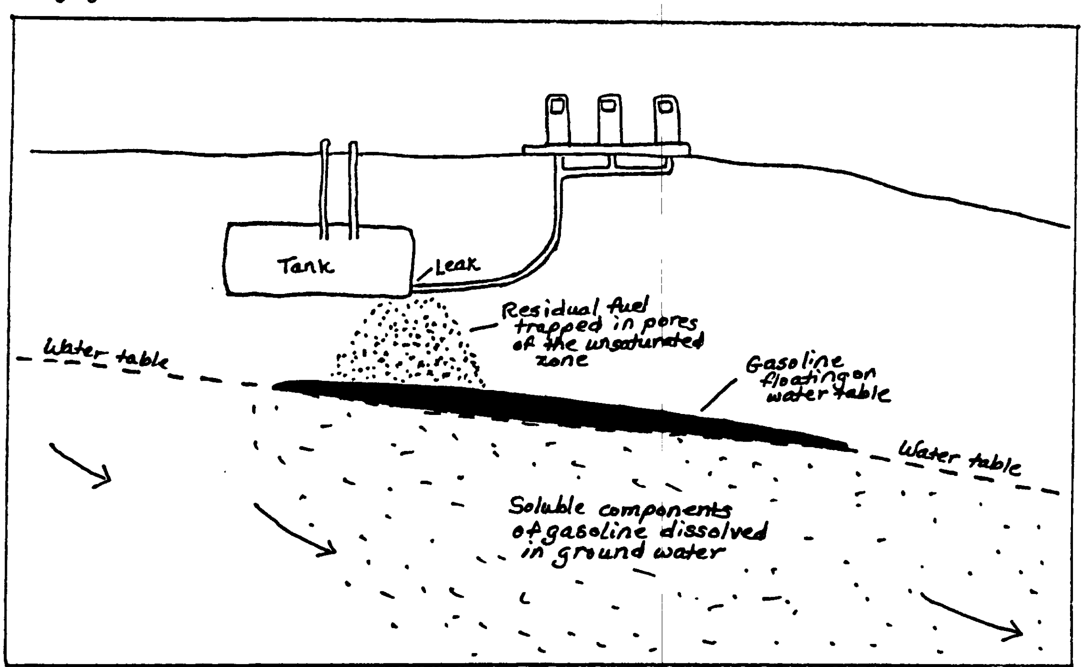


Figure 30.--Gasoline leak from underground storage tank. Arrows show direction of ground-water flow. (Source: Modified from American Petroleum Institute, 1972, The migration of petroleum products in soil and ground water, Publication no. 4149, p. 14, fig. la. Reprinted by courtesy of American Petroleum Institute.)

Attenuation of contaminants

Attenuation refers to the reduction or removal of a contaminant. Physical, chemical, and biological processes in the unsaturated zone may alter the composition of infiltrating recharge or other liquids and may even remove some contaminants before they reach the water table. Soil and sediments act as a filter to remove or retard the movement of large particles such as organic matter and bacteria. Chemical processes such as oxidation and precipitation remove or decompose some substances. Many pesticides and other synthetic organic compounds are degraded by biological and chemical processes. Microorganisms can consume and degrade a large number of synthetic organic substances (Freeze and Cherry, 1979, p. 425). Clay minerals and organic matter can adsorb some ions and organic compounds on their surfaces. VOCs in contact with air can vaporize and disperse into the atmosphere.

All of these attenuation mechanisms are more effective in the unsaturated zone than in the saturated zone. Abundant oxygen, large bacterial populations, and complex soil structure all contribute to faster and more complete filtration, adsorption, and biochemical decomposition than in the saturated zone.

Direct Contact with Ground Water

The potential for ground-water contamination is high when the source is within the saturated zone and thereby exposed to the dissolving power of a large volume of water. The ground water is also flowing; as contaminated water flows away from the site, it is replaced by new water that continues to dissolve contaminants.

Many old waste-disposal sites, large and small, were developed without understanding of the potential for ground-water contamination. It is not uncommon to discover that wastes have been disposed of at or below the water table at such sites. Regulations for sanitary landfills in Rhode Island now require a minimum of 5 feet of soil between the lowest level of deposited refuse and the highest water-table level (Rhode Island Department of Environmental Management, 1982, p. 27).

Climatic fluctuations can also cause ground water to come in contact with contaminant sources. A succession of wet years could cause the water table to rise to the level of the septic systems and underground gasoline tank on the till-covered hillside shown at the left side of figure 29. The lower layers of the landfill near the river shown in figure 29 could also become saturated if the water table rises several feet.

Induced Infiltration of Surface Water

Large-capacity wells commonly induce surface water from nearby streams and ponds into an aquifer (location F in fig. 29). Any contaminants derived from municipal and industrial discharges or other upstream sources can move with the surface water into the aquifer (fig. 29). Contaminants adsorbed on streambed sediments can also be removed and transported into the aquifer by infiltrating surface water.

Surface water in Rhode Island typically contains from 5 to 14 milligrams per liter of dissolved oxygen (Gadoury and others, 1986). Where the streambed is composed of natural organic materials such as plant debris, or where the stream contains organic matter from wastewater-treatment discharges, most or all of the dissolved oxygen can be consumed as the organic matter decomposes. If the water induced into the aquifer contains little or no dissolved oxygen, the water is able to dissolve iron, manganese, and other metals from minerals in the aquifer materials (Silvey and Johnston, 1977).

Manganese concentrations that exceed the SMCL of 0.05 milligram per liter and range as high as 1 to 3 milligrams per liter have been measured in water withdrawn from wells near a pond on the Chipuxet River (Johnston and Dickerman, 1985, fig. 16, p. 62). Excessive manganese has been attributed to infiltration of surface water through natural organic matter on the bottom of the pond (Johnston and Dickerman, 1985, p. 61). Concentrations of manganese that exceed 1 milligram per liter have also been found in water from some public-supply wells along the Blackstone River, possibly because decomposing municipal and industrial wastes discharged to the river have depleted oxygen from the surface water that the wells induce into the aquifer (Johnston and Dickerman, 1974a, sheet 2, fig. 7).

Saltwater Intrusion

Fresh ground water along the coast discharges into estuaries and into the ocean under natural conditions. The dynamic equilibrium between freshwater and saltwater in coastal aquifers (fig. 15) is easily affected by freshwater withdrawal from wells. Disturbance of the interface between freshwater and saltwater may cause saltwater to move into areas formerly occupied by fresh ground water. This process is called saltwater intrusion (fig. 31).

The average dissolved-solids concentration of saltwater is about 35,000 milligrams per liter. Fresh ground water in Rhode Island, which typically has a dissolved-solids concentration of less than 200 milligrams per liter, is much less dense than saltwater. Where fresh ground water meets saltwater, this difference in density determines their distribution (fig. 31A) (Heath, 1983, p. 68). The less dense freshwater floats on the saltwater.

In coastal areas on the mainland, fresh ground water overrides saltwater, and salty ground water extends a short distance inland underneath the freshwater. On islands, recharge from precipitation creates a lens-shaped body of freshwater that floats on the underlying saltwater (Heath, 1983, p. 68). In either location, the layer of fresh ground water becomes progressively thinner toward the shore (fig. 31A). Tidal fluctuations create a transition zone of brackish water along the interface between freshwater and saltwater (fig. 31A).

Freshwater extends below sea level in coastal areas (fig. 31A). The depth of freshwater below sea level at any point is determined by the height of the water table above sea level. The higher the altitude of the water table, the thicker the freshwater lens. This physical principle is expressed mathematically in the Ghyben-Herzberg relation, named for the scientists who discovered it (Todd, 1980, p. 496). Under idealized, hypothetical conditions, the depth of the freshwater zone below sea level is equal to 40 times the height of the water table above sea level (Heath, 1983, p. 68).

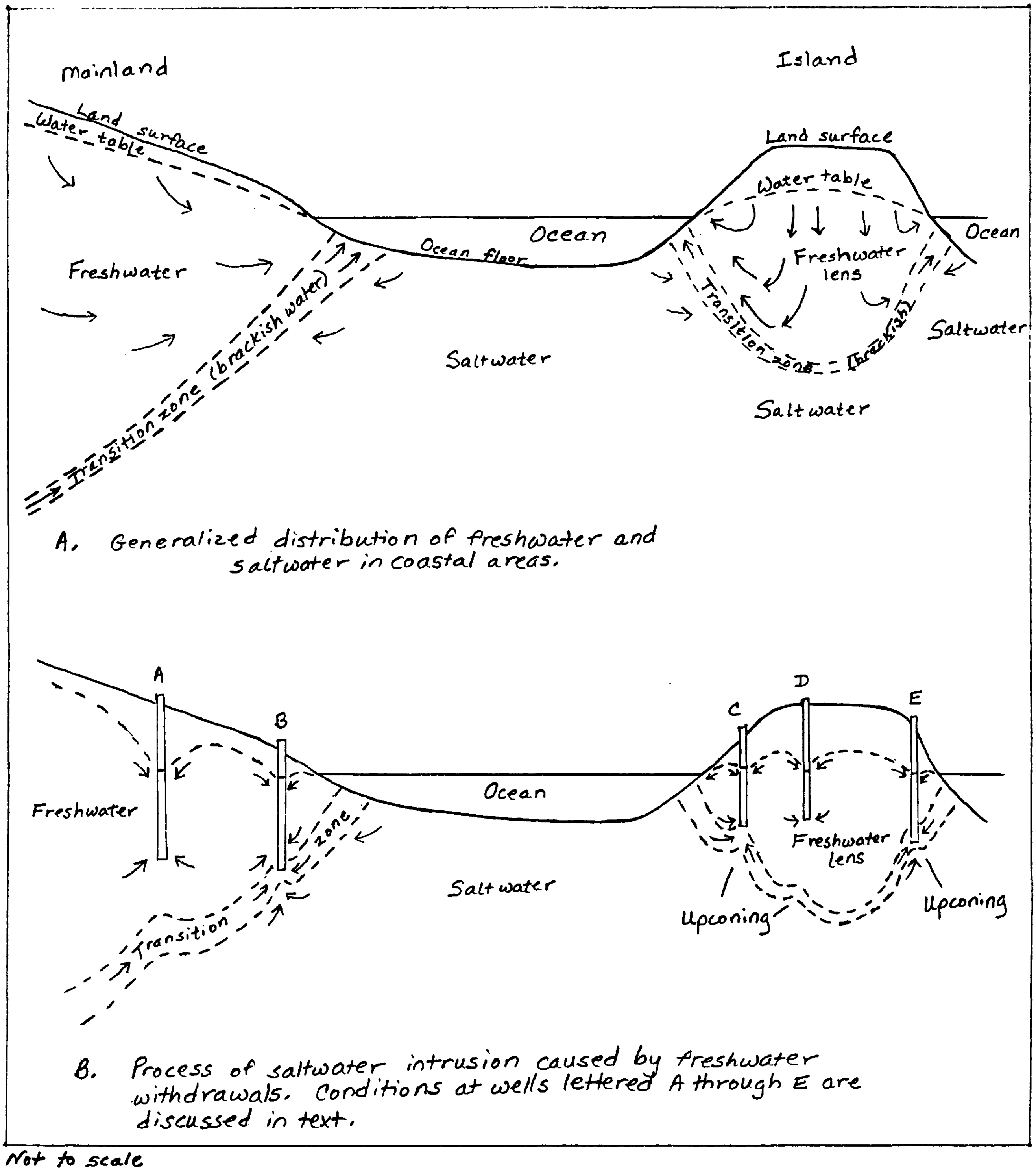


Figure 31.--The relation between freshwater and saltwater in coastal areas and the process of saltwater intrusion. Arrows show flow directions of saltwater, brackish water, and fresh ground water.

Freshwater withdrawals from wells decrease the altitude of the water table and cause the thickness of the freshwater lens to decrease locally (wells A and D in fig. 31B). Thinning of the freshwater lens, and changes in ground-water-flow directions near the well, cause the transition zone to rise underneath the well--a phenomenon known as upconing (fig. 31B) (Todd, 1980, p. 502). Saltwater may rise high enough to reach the well intake (wells B, C, and E in fig. 31B) if the ground-water withdrawal is sufficiently large relative to the thickness of the freshwater lens. Wells on small islands are particularly vulnerable to saltwater intrusion because the freshwater lens is generally thin, even under nonpumping conditions.

The distribution and movement of freshwater and saltwater shown in figure 31 are based on theoretical conditions assumed for a homogeneous, porous material. In layered sediments or fractured bedrock, the location of the interface and the effects of pumping are more complex.

Sodium and chloride (table 1) are the principal ions in saltwater. Thus, sodium and chloride concentrations that are substantially greater than natural levels found in freshwater (table 2) are indicators of saltwater intrusion in coastal aquifers. For example, sodium concentrations exceeded 160 milligrams per liter and chloride concentrations exceeded 250 milligrams per liter in water from two small public-water-system wells near Narragansett Bay during 1987-88 (B.F. Barrette, Rhode Island Department of Health, written commun., 1989). Salty or brackish water from coastal wells has been reported in at least 13 of the 21 cities and towns that border Narragansett Bay and Block Island Sound (Allen, 1953, 1956; Bierschenk, 1954, 1956, 1959; Hansen and Schiner, 1964; Schiner and Gonthier, 1965a, 1965b).

Movement and Fate of Contaminants in Ground Water

The movement of dissolved constituents with ground water is referred to as solute transport. A dissolved substance, whether it is a contaminant or a harmless natural constituent, is referred to as a solute. Solute transport is a complex process because of the numerous interrelated physical, chemical, and biological variables that control it. The movement and fate of contaminants in ground water are determined by the rate and direction of ground-water flow; by physical, chemical, and biological processes; by the materials through which the contaminants move; and by the nature of the contaminants.

Transport of Contaminants by Ground Water

Dissolved contaminants move with ground water from recharge areas toward discharge areas. Contaminants introduced into the flow system at a particular location move along the ground-water-flow paths that pass through that location. Figure 32 shows the hypothetical ground-water-flow system introduced previously in figure 21, but with contaminant sources added at several locations on the land surface. Infiltrating precipitation carries contaminants downward through the unsaturated zone to the water table, after which the contaminants follow the generalized flow paths shown in figure 32.

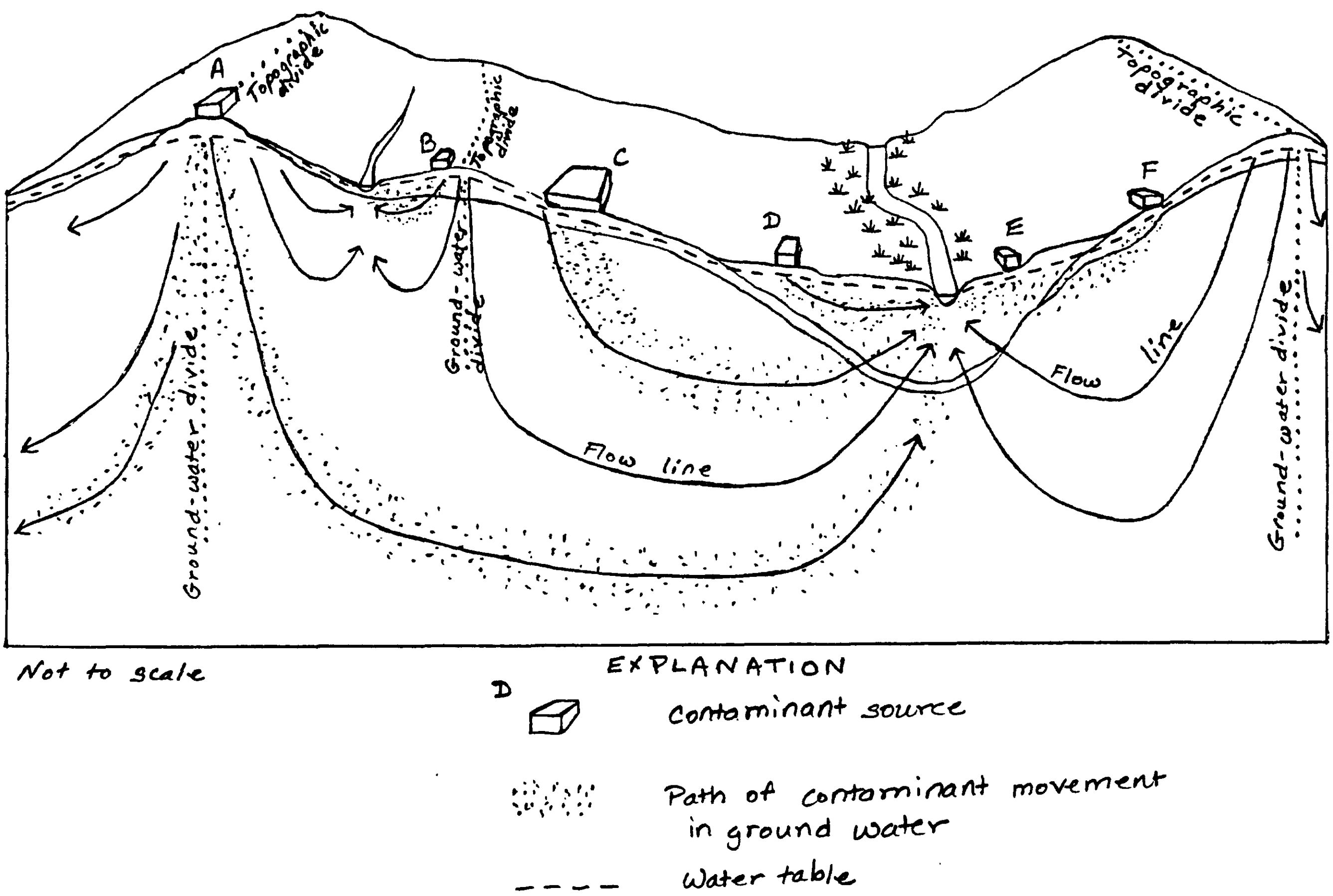


Figure 32.--Movement of contaminants from recharge areas to discharge areas. The ground-water system is as shown in figure 21. A few representative flow lines show generalized directions of ground-water flow. Contaminant sources lettered A through F are discussed in text.

The three-dimensional volume of ground water emanating from a contaminant source is referred to as a contaminant plume. The contaminated water generally spreads out and becomes increasingly dilute with distance from the source, much as a plume of smoke spreads out in the air and becomes increasingly diffuse downwind from a smokestack. The size and shape of a contaminant plume depend on the nature of the local ground-water-flow system (fig. 32), the length of time during which contaminants enter the saturated zone, and the nature of the contaminant.

As figure 32 shows, the volume of contaminated ground water and the depth to which it extends depend in part on the location of the contaminant source in relation to the flow system. Contaminants from source A move deep into the flow system on both sides of the ground-water drainage divide and affect water quality in two drainage basins. Contaminants from source B move along a shallow flow path to a local discharge area, whereas those from source C move along a flow path of intermediate depth to a major discharge area. Contaminants from sources D, E, and F move along shallow flow paths to a major discharge area.

An actual contaminant plume at a low-level radioactive waste site in the Pawcatuck River basin (fig. 28) is shown in figure 33. Ponds and trenches that received liquid industrial wastes from 1966 through 1980 are the source of the contaminants in ground water at this site (Ryan and Kipp, 1985, p. 21). The shape of the contaminant plume shows the direction of ground-water flow.

At the low-level radioactive-waste site, contaminants move along a shallow flow path to a major discharge area, the Pawcatuck River (fig. 33). The distance from the source area to the river is less than half a mile, and contaminants reach a maximum depth of 80 feet below the water table (Ryan and Kipp, 1985, p. 21).

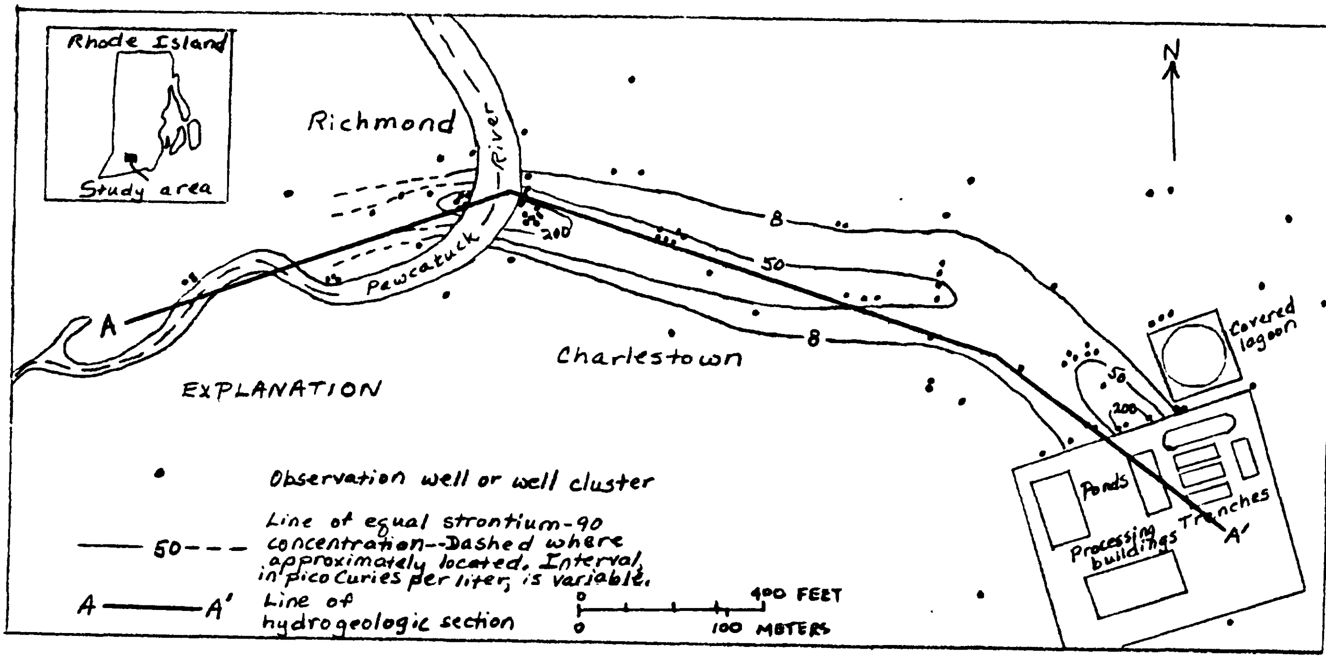
Two zones of high strontium-90 concentration (greater than 200 picocuries per liter) are shown in figure 33. The larger zone, beneath the Pawcatuck River, resulted from the time of active processing at the industrial plant (Ryan and Kipp, 1985, p 30). Ground water has transported this high concentration of solutes through the saturated zone as an identifiable "slug." The smaller zone of high strontium-90 concentration, beneath the source area (fig. 33), is believed to result from mobilization of additional contaminants in the unsaturated zone when sediments were excavated during decommissioning of the site (Ryan and Kipp, 1985, p. 30).

Dissolved contaminants are physically carried along by flowing ground water. This process, called advection, controls the large-scale movement of contaminants (Freeze and Cherry, 1979, p. 389).

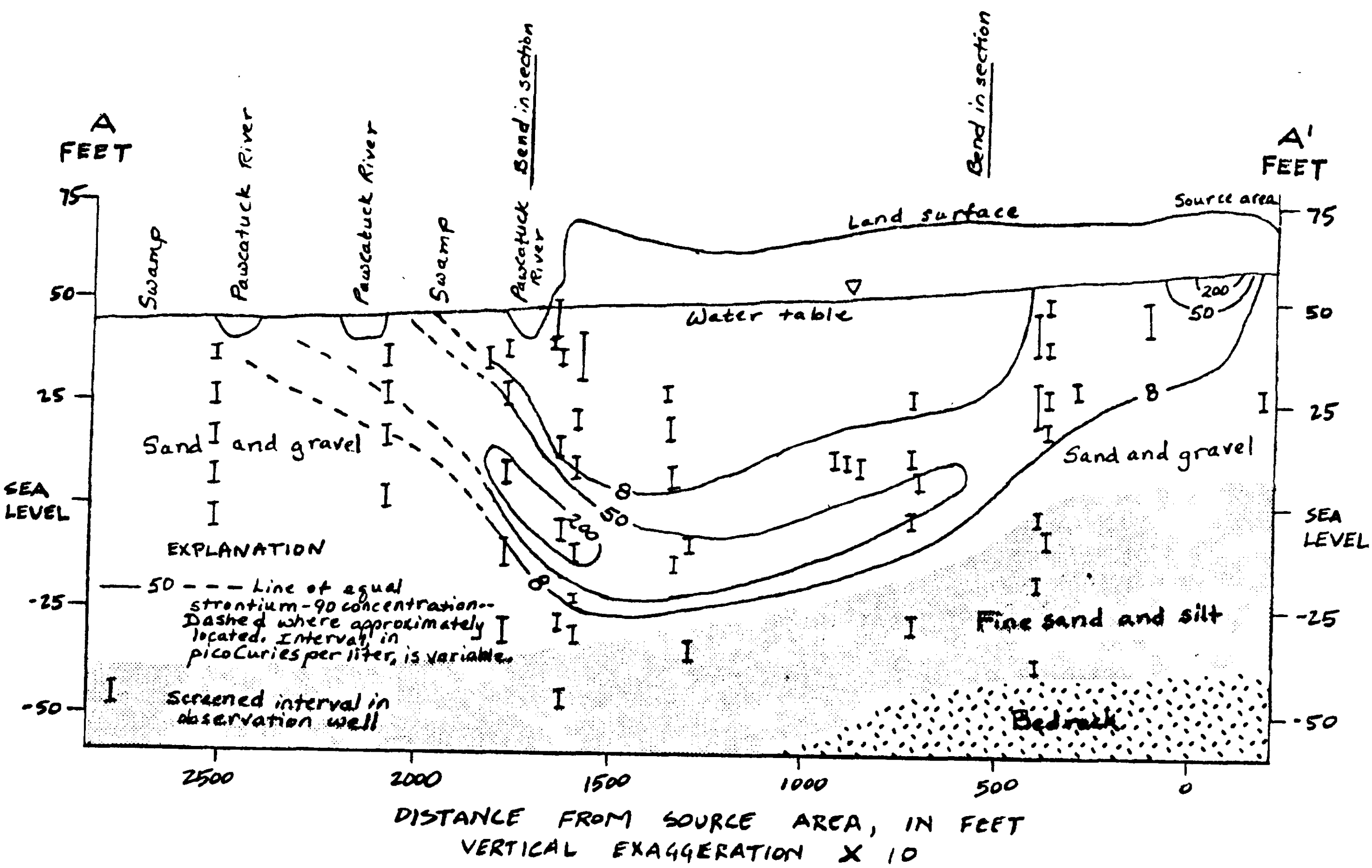
Hydrodynamic dispersion, the tendency for a solute to spread out in three dimensions, dilutes contaminants and causes contaminated ground water to assume a plume-like configuration (Freeze and Cherry, 1979, p. 75). Hydrodynamic dispersion is caused by two processes--dispersion and diffusion. Dispersion, or mechanical mixing, takes place on a microscopic scale as ground water flows through irregular pore spaces and across the rough surfaces of rock particles (Freeze and Cherry, 1979, p. 75-76).

Diffusion is a slow process that results from differences in the concentration of a substance within a volume of fluid. For example, a small lump of sugar or salt will dissolve in a cup of water even if the water is not stirred. A homogeneous concentration of the substance tends to develop throughout the volume of water as ions or molecules move from areas of higher concentration to areas of lower concentration.

The effects of diffusion are usually overshadowed in aquifers by the large-scale effects of flowing ground water. However, in materials such as clay, in which permeability is low and ground-water flow is very slow, diffusion can influence the distribution of dissolved substances over the long term (Freeze and Cherry, 1979, p. 104).



A. Map of source area and contaminant plume



B. Hydrogeologic section

Figure 33.--Strontium-90 concentration in ground water at a low-level radioactive waste site in the Pawcatuck River basin, October 1982. (Source: Modified from Ryan and Kipp, 1985, fig. 7, p. 29, and fig. 9, p. 31).

Reaction Processes

Many reaction processes control the mobility and decomposition of contaminants in ground water. Important categories include adsorption-desorption reactions, solution-precipitation reactions, oxidation-reduction reactions, biological activity, and radioactive decay (Freeze and Cherry, 1979, p. 402).

Adsorption is the process by which an earth material assimilates a gas, liquid, or dissolved substance on its surface. In desorption, the process is reversed, and the sorbed substance is released. Contaminants within the saturated zone may become adsorbed on the surfaces of bedrock fractures or granular particles, but they may be transferred back to the ground water (desorbed) if uncontaminated water moves through the area. Adsorbed contaminants are eventually flushed out of the aquifer if no additional contaminants enter the saturated zone (Freeze and Cherry, 1979, p. 406-407). The sorption process (adsorption and desorption) depends on the nature of the contaminant and on the physical and chemical conditions in ground water and aquifer materials (Todd, 1980, p. 339).

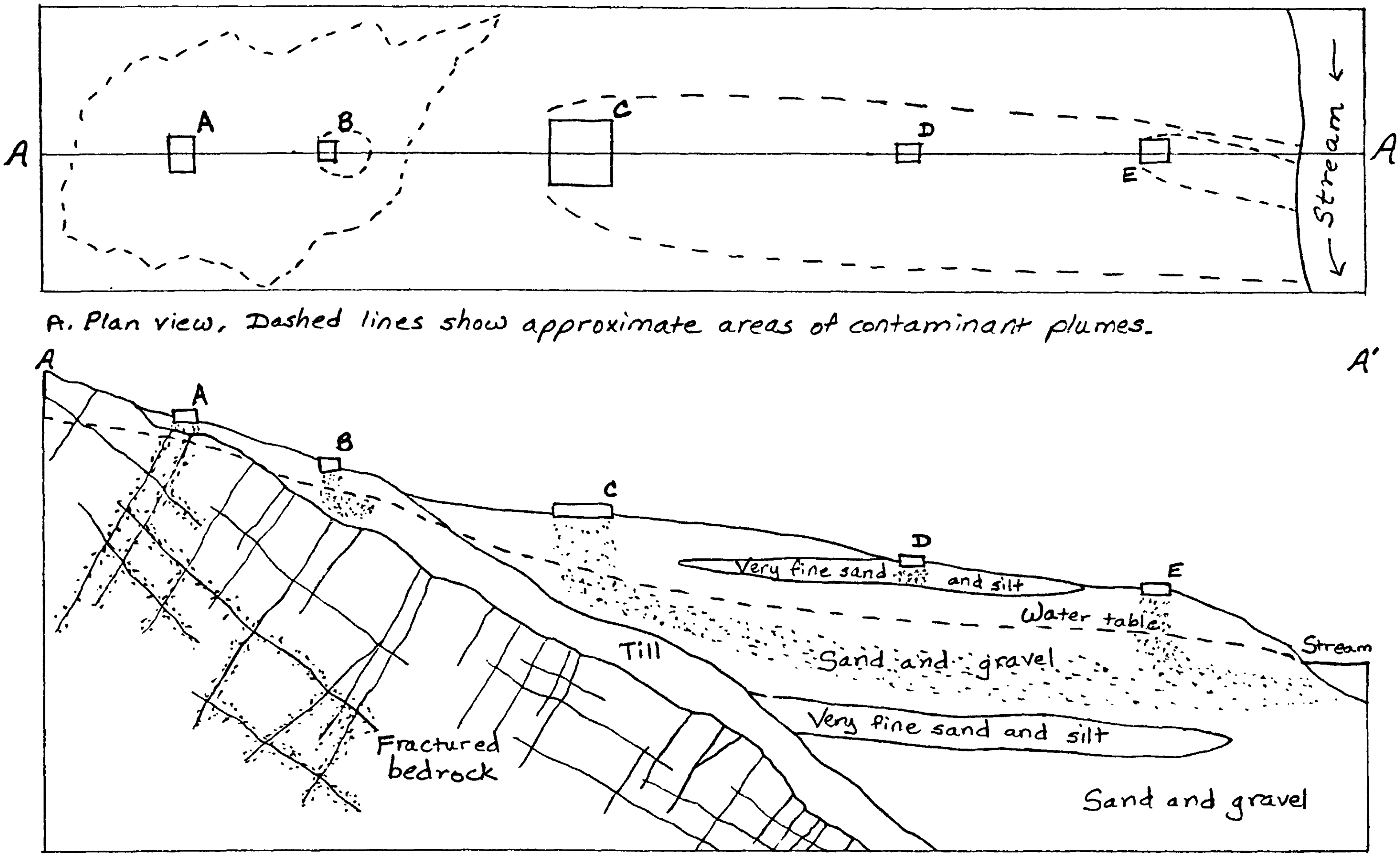
Different substances have different degrees of solubility in water, and many physical and chemical factors affect solubility. As a contaminant moves through a ground-water system, changing conditions may cause it to precipitate, thereby removing it from the ground water. Subsequent changes in conditions may cause the contaminant to redissolve. Reactions that change the acidity or alkalinity of ground water are important because the pH of water affects its capacity to dissolve many substances.

Oxidation-reduction reactions, also referred to as redox reactions, involve the transfer of electrons between dissolved constituents. Oxidizing conditions exist where oxygen is dissolved in ground water. Dissolved oxygen in shallow ground water may be consumed in chemical and biological reactions, thus changing the redox potential of the ground-water environment. Dissolved substances are stable under certain redox conditions and unstable under others. Contaminants may be broken down by the redox reactions, or their mobility may be affected by a change in redox potential resulting from reactions between other constituents. Microorganisms, especially bacteria, promote most of the important redox reactions that take place in ground water; the microorganisms use energy from these reactions for their growth (Freeze and Cherry, 1979, p. 121-122).

Radioactive elements such as strontium-90 (fig. 33) decay to radioactive daughter products and eventually to nonradioactive end products. An element decays in an orderly manner and at a rate that depends on the length of its particular half life. The rate of radioactive decay is not affected by other physical, chemical, or biological processes. As ground water transports radioactive contaminants, radioactive decay steadily lowers their concentrations.

Effects of Earth Materials

The chemical composition and physical properties of earth materials affect the movement of contaminants by influencing chemical and physical processes and by determining the physical characteristics of ground-water flow (fig. 34).



A. Plan view, Dashed lines show approximate areas of contaminant plumes.

B. Diagrammatic section. Stippled areas show contaminant movement along bedrock fractures and through porous unconsolidated materials.

Not to scale

Figure 34.--Contaminant movement in coarse-grained, fine-grained, and fractured materials. Contaminant sites A through E are discussed in text.

Mineral composition

Particles of clay minerals typically have a large electrical charge relative to their surface areas (Freeze and Cherry, 1979, p. 127). This charge enables each small clay particle to adsorb a layer of ions on its flat surface. Ions in this layer may be exchanged for other ions in the surrounding ground water under certain physical and chemical conditions. Cations are more commonly involved in adsorption and ion exchange than are anions, and certain cations are more likely than others to be involved in these reactions.

As ground water flows through material that has a large capacity for adsorption and cation exchange, some cations are adsorbed on earth materials, while other cations move back and forth between the water and the earth materials. The chemical composition of the ground water gradually changes as this happens. In earth materials that contain substantial amounts of clay minerals, these processes affect the quality of the ground water.

Coarse sand and gravel deposits, such as those shown in figure 33, typically contain large amounts of quartz, feldspar, and other minerals that have a low capacity for adsorption. Consequently, dissolved constituents tend to move through sand and gravel without much attenuation. Contaminants that reach sand and gravel layers below the water table may move long distances, as shown in the example of site C in figure 34.

In fractured bedrock, contaminants can be adsorbed on fracture surfaces to some extent if the surfaces are weathered or coated by precipitated minerals. Contaminants may also diffuse into the rock mass if the rock has some primary porosity.

Physical characteristics

Ground water flows slowly through clay, silt, till, and other fine-grained materials because of their low permeability. This low permeability, combined with the capacity of clay minerals to adsorb ions, means that dissolved contaminants also move slowly through fine-grained materials. This is why clay liners are frequently used at waste-disposal sites. Fine-grained materials with their small pore spaces also filter bacteria from wastewater more effectively than do coarse-grained materials. Fine-grained sediments may slow the movement of contaminants from the unsaturated zone to the water table (site D, fig. 34), may retard contaminant movement in ground water (site B), or may greatly reduce the rate at which contaminants move into deep parts of an aquifer, as in the case of the plume emanating from site C.

Coarse sand and gravel deposits are highly permeable, and ground-water flow through these materials is relatively rapid. In layered deposits, coarse layers of sand and gravel tend to function as conduits for the rapid horizontal transport of contaminants (sites C and E in fig. 34). Permeable sand and gravel deposits are Rhode Island's most important aquifers, and contaminants that reach the saturated zone in these deposits may threaten existing or potential drinking-water supplies.

The orientation, size, distribution, and number of fractures in bedrock aquifers are often variable (fig. 34). The rate of ground-water flow may be rapid in some individual fractures and negligible in others. Directions and rates of contaminant movement are therefore difficult to predict in fractured bedrock, and contaminant plumes can be irregular in shape (site A in fig. 34).

Effects of Contaminant Characteristics

Measured concentrations of a particular constituent are used to locate and describe a contaminant plume in three dimensions (fig. 33). If a plume consists of multiple contaminants, the size and shape of the plume will vary depending on the characteristics of the constituent being measured.

Reactive and nonreactive contaminants

Dissolved contaminants may be categorized as either reactive or nonreactive. Reactive contaminants participate in biological and chemical reactions or physical processes that change the nature of the contaminant or remove it from the ground water. The movement of a reactive contaminant is influenced by reaction processes as well as by the local rate and direction of ground-water flow. For example, some VOCs can be biochemically degraded or adsorbed onto aquifer materials (Hess, 1988, p. 91). Ammonia can be adsorbed on sediments or oxidized to form nitrate (Hess, 1988, p. 91). Cations such as potassium, sodium, calcium, and magnesium can be adsorbed on clay minerals.

Nonreactive contaminants are not involved in biological or chemical reactions. The transport of nonreactive contaminants is referred to as conservative transport because the total amount of the contaminant is conserved within the flowing ground water. The movement of nonreactive contaminants, such as chloride, is controlled by the physical processes of ground-water flow. For example, nitrate, the stable form of dissolved nitrogen where abundant oxygen is present, can move long distances without significant attenuation (Freeze and Cherry, 1979, p. 413-414). Boron, a component of detergents and other household cleaners, is considered a possible indicator of the movement of conservative contaminants within a sewage-effluent plume in a sand and gravel aquifer on Cape Cod, Massachusetts (Hess, 1988, p. 87).

The extent to which a contaminant is reactive or nonreactive may depend on the aquifer materials, the presence of other dissolved constituents, and the physical and chemical conditions within the aquifer. For example, if clay minerals are present in an aquifer, sodium may be adsorbed on the clays. By contrast, sodium moves through the saturated zone in sand and gravel or fractured bedrock aquifers without significant attenuation. The mobility of trace metals in ground water is strongly influenced by the potential for adsorption on clay minerals, organic matter, and substances that coat aquifer grains or fracture surfaces (Freeze and Cherry, 1979, p. 416).

The transport of strontium-90 at the low-level radioactive waste site shown in figure 33 illustrates the complexity of interactions between solutes and earth materials. Strontium-90, a cation, may be adsorbed on clay minerals, but laboratory experiments have shown that the coarse sand and gravel deposits at this site have a low capacity for ion exchange (Kipp and others, 1986, p. 525). Moreover, the cations calcium, magnesium, and sodium, which are present in the contamination plume in high concentrations, monopolize the few available adsorption or ion-exchange sites on sediment grains in the aquifer (Kipp and others, 1986, p. 529). Conditions in the aquifer, however, are not static. Numerical simulations indicate that the proportion of strontium-90 sorbed on sediments will increase as the concentrations of other cations in the contaminant plume decrease over time (Kipp and others, 1986, p. 529). The small amount of ion exchange that does take place slows the rate at which strontium-90 is transported through the aquifer and reduces its peak concentrations in ground water (Kipp and others, 1986, p. 529).

Density and miscibility

The density of a liquid contaminant affects the depth at which a plume forms in an aquifer. A liquid that is denser than water tends to sink in an aquifer and form a deeper plume than does a liquid with a density similar to that of water (Freeze and Cherry, 1979, p. 397). The contaminated ground water at the site shown in figure 33 has a density close to that of water (Ryan and Kipp, 1985, p. 29).

Some liquid contaminants are miscible; that is, they mix readily with water. Others, described as immiscible, do not. Immiscible liquids that are denser than water, such as many solvents, sink through the saturated zone and collect on layers of earth material that have low permeability. Gasoline, diesel fuel, and heating oil are immiscible liquids that are less dense than water. When fuel from a leak or spill reaches the water table, downward migration ceases (fig. 30). The fuel floats on top of the ground water, the way oil floats on vinegar in a salad dressing. As the fuel accumulates, it depresses the water table slightly and spreads out laterally, primarily spreading downgradient in the direction of the water-table slope (fig. 30).

Where fuel is in contact with the water table, soluble components in the fuel dissolve and are transported with the ground water in the local direction of ground-water flow (fig. 30). The solubility of some fuel components, such as benzene, is significantly greater than the extremely low concentrations that are considered hazardous in drinking water (table 3) (Freeze and Cherry, 1979, p. 446). An immiscible liquid thus can generate a plume of dissolved contaminants.

Attenuation and Fate of Contaminants

Ground water is very susceptible to contamination where the water table is close to the land surface, where bedrock is close to the land surface, or where highly permeable sediments are present. The thickness of the unsaturated zone, the depth to bedrock, and the local geology are therefore important factors in siting septic systems, landfills, and other potential contaminant sources. A reactive contaminant percolating from site D (fig. 34) may never reach the water table. Nonreactive contaminants introduced at sites A or C may move long distances through bedrock fractures or highly permeable sand and gravel without any significant reduction in concentration.

Contaminant concentrations in ground water tend to decrease with time if no new contaminants enter the saturated zone. Most of the physical, chemical, and biological processes that reduce or remove contaminants in the saturated zone are the same as those that take place in the unsaturated zone; however, these processes generally take place at much slower rates within the saturated zone. Dilution of solutes, caused by dispersion and diffusion, also decreases contaminant concentrations as a plume of contaminated ground water moves through an aquifer. Below the water table, dilution is often the most important of all attenuation mechanisms (Todd, 1980, p. 341).

The ultimate destination of a contaminant in ground water is referred to as its "fate." Contaminants may be transported by ground water and discharged to fresh surface water (fig. 33) or to the ocean. Some contaminated ground water ends up in wells, which are artificial discharge sites (locations 1 through 4 in fig. 29). Some contaminants are adsorbed by aquifer materials. Other contaminants are degraded to end products by biological and chemical processes or by radioactive decay. Some contaminants are not adsorbed or degraded, and the only attenuation is through gradual dilution. Contamination is likely to persist if the source is large, such as a landfill; if new contaminants are constantly added, such as in a septic system; or if the contaminant itself is highly resistant to degradation.

The attenuation and fate of contaminants in ground water is a field of active hydrogeological research. The subject is large and complex, and many of the controlling processes are not fully understood.

Prevention of Ground-Water Contamination

Prevention of ground-water contamination can be technically, financially, and politically difficult. However, cleaning up contaminated ground water is almost always technically complex, expensive, and time consuming. It is often impossible. Furthermore, when a large public supply becomes contaminated, water treatment is likely to be difficult and the location of a suitable alternative source may be necessary.

Government Responsibilities

Federal, State, and local governments have responsibilities for preventing ground-water contamination as part of their general water-quality management authorities. At the Federal level, at least 13 laws include provisions that pertain to ground-water protection (Office of Technology Assessment, 1984). The USEPA has delegated many Federal responsibilities to State agencies.

The Groundwater Section of the Rhode Island Department of Environmental Management is responsible for developing and implementing a comprehensive ground-water protection program in Rhode Island. In accordance with the Groundwater Protection Act (Rhode Island General Laws 46-13.1) passed in 1985, RIDEM has classified all of the State's ground water and has developed ground-water-quality standards for each classification. Regulatory programs to protect ground water also include the Underground Storage Tank Program; the Underground Injection Control Program, which regulates discharges to the subsurface; and the Oil Pollution Control Program. The Groundwater Section responds to emergencies and complaints of ground-water contamination, coordinates investigations of ground-water contamination and associated cleanup operations, provides technical assistance to local governments, and is involved in mapping aquifers and contaminant sources. Other sections of RIDEM and other State agencies also have programs that affect ground-water quality. The Groundwater Section ensures coordination of all those involved in ground-water protection at the State level.

Local governments have significant authority to prevent ground-water contamination because they control land use. Municipal master plans, zoning ordinances, and aquifer-protection ordinances can be used to protect ground water. As of September 1989, 16 towns in Rhode Island had established or were investigating measures for ground-water protection (E.C. Panciera, Rhode Island Department of Environmental Management, written commun., 1989). Seven towns had established ground-water overlay districts or watershed-protection overlay districts, four towns had provisions in town ordinances to regulate the use of underground storage tanks, and seven towns were in the process of investigating or drafting measures for ground-water protection.

Prevention of ground-water contamination is usually the responsibility of more than one level of government and more than one town. Recharge areas for one town's ground-water supply may be in another town. Some large aquifers have regional significance as potential sources of public supply, and their recharge areas often encompass parts of several towns. Cooperative action by several agencies is often necessary to prevent ground-water contamination.

Citizen Responsibilities

Citizens share with government the responsibility for preventing ground-water contamination through laws, ordinances, and regulations. In addition, individual citizens use many household products and generate wastes that have the potential to contaminate private or public drinking-water supplies. Citizens control what goes into their septic systems or onto their property. Careful consideration can be given to the use, storage, and disposal of any hazardous substance.

Private well owners are particularly concerned about protecting their drinking-water supplies. Some sources of contamination are beyond the private well owner's control (fig. 29). However, private well owners often inadvertently contaminate their own wells. Well owners can reduce the likelihood of ground-water contamination by proper location and construction of wells and septic systems, and by proper use, storage, and disposal of hazardous materials.

The Role of Hydrogeologic Information

Hydrologic and geologic information can help agencies and citizens protect the State's ground-water resources. Hydrogeologic studies provide a framework for ground-water-protection efforts by locating and describing aquifers, defining the ground-water-flow system, defining background or natural water quality, and evaluating the movement of contaminants.

A REGIONAL OVERVIEW OF RHODE ISLAND'S GROUND-WATER RESOURCES

Effective development, use, and protection of Rhode Island's ground-water resources depend on knowledge of the hydrogeology of the drainage basins or regions within which these resources are found. The boundaries of Rhode Island's major drainage basins show the regional framework of Rhode Island's water resources (fig. 35). In some areas, surface water and ground water from neighboring areas of Massachusetts and Connecticut flow into Rhode Island. In other areas, surface water and ground water from Rhode Island flow into Massachusetts and Connecticut.

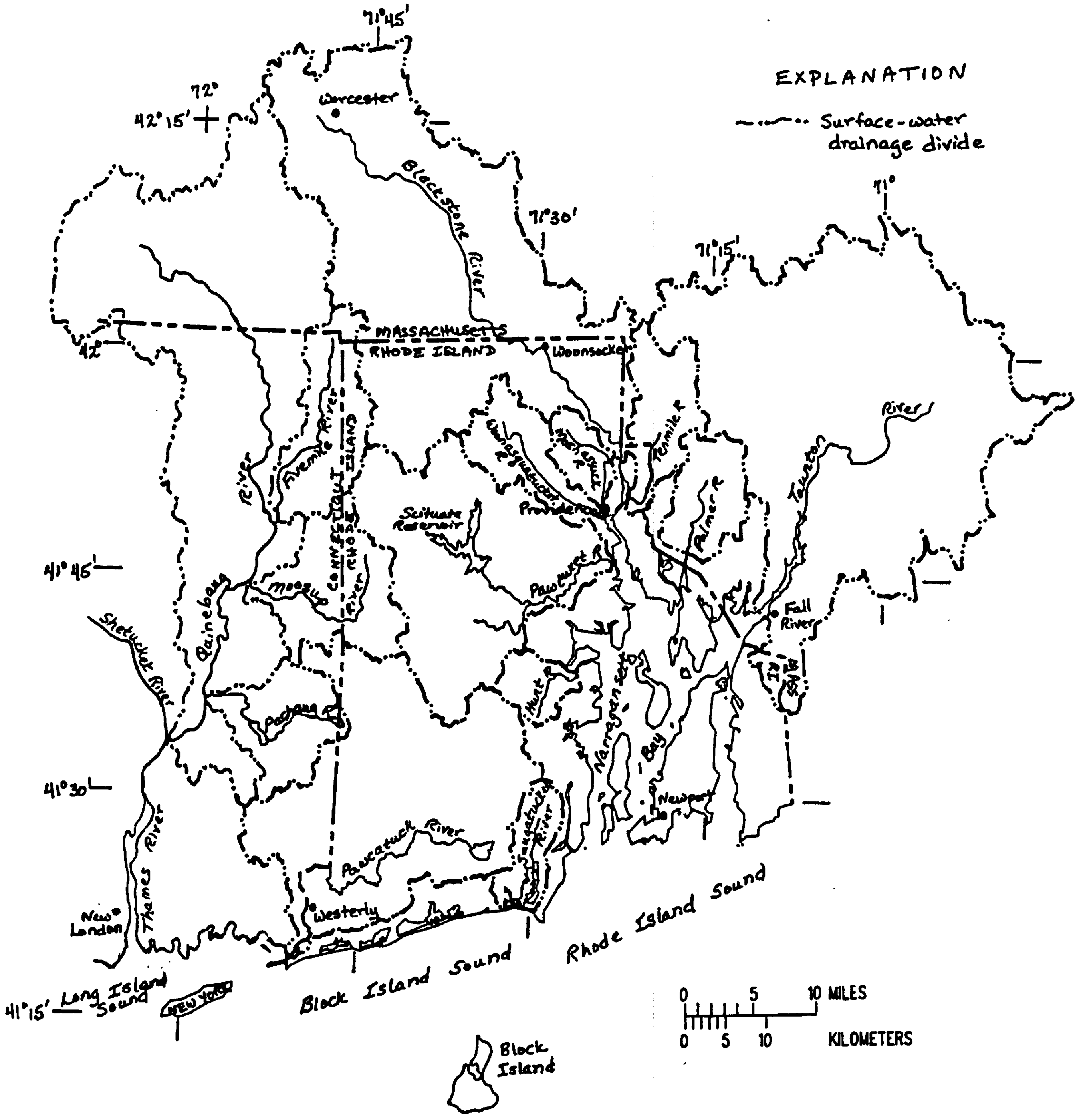
This section provides an overview of ground-water resources in each of the major drainage basins or regions of the State. Surface-water drainage divides have been used as boundaries for these eight regions (fig. 36) because major ground-water and surface-water drainage divides coincide in most areas. Significant aspects of the occurrence, quantity, and quality of ground water are highlighted for each region. Concepts introduced in previous chapters are integrated with specific local information, and references to detailed information are provided for interested readers.

Special attention is given to the areas of stratified drift that the RIWRB has designated as ground-water reservoirs (fig. 13). Public-supply withdrawals from these ground-water reservoirs totaled approximately 15 million gallons per day during 1985 (Solley and others, 1988, p. 13).

Estimates of potential yield are available for many of Rhode Island's ground-water reservoirs. The yield estimates for different ground-water reservoirs are not always comparable, and a yield estimate is not a single definite figure. Each yield estimate depends on the hydrogeologic information available, theoretical assumptions, methods of evaluation, and the alternatives chosen for developing water resources. Political, legal, aesthetic, and economic considerations also affect yield estimates. For example, estimates made during the 1980's are typically based on the assumption that long periods of no streamflow are an unacceptable consequence of ground-water development; studies made before the 1980's, however, commonly estimate maximum ground-water yields independent of the effect on streamflow.

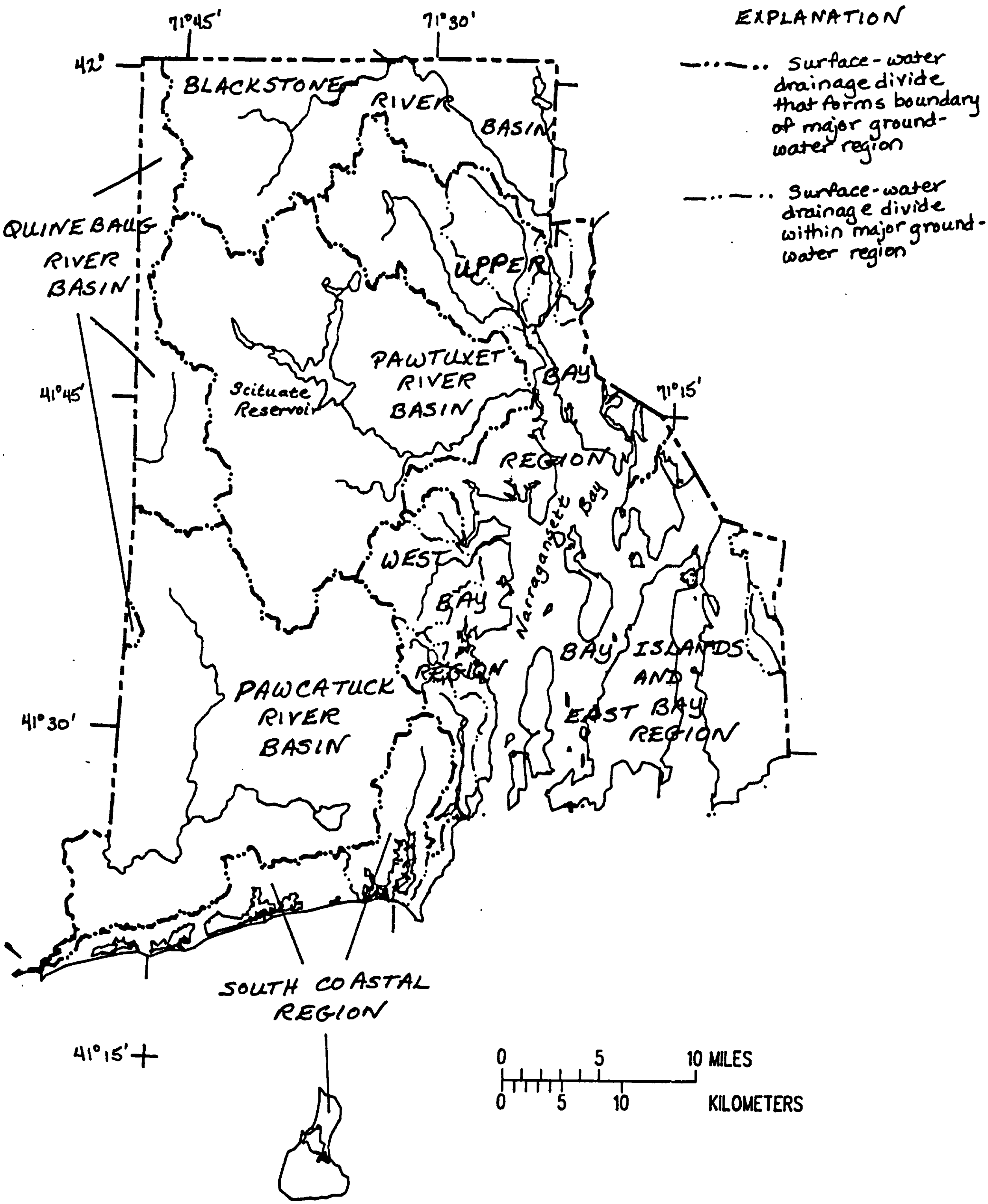
The ground-water reservoirs themselves represent only a small part of the area where water quality is important. Water flows into the ground-water reservoirs from adjacent areas of stratified drift and till-covered bedrock. Surface water from upstream drainage areas is commonly induced to infiltrate into a ground-water reservoir by large-capacity wells. Furthermore, private wells withdraw ground water from all types of aquifers in Rhode Island, in at least 33 of the State's 39 cities and towns. Few areas exist where threats to ground-water quality could be considered insignificant with respect to existing or potential drinking-water supplies.

Ground-water contamination has affected drinking-water supplies in all regions of the State, although some areas have been more severely affected than others (fig. 28). Many contaminant sources are located in urbanized areas. The extent of urbanization differs considerably throughout the State. Figure 37 shows the distribution of urbanized and built-up land in Rhode Island in 1974. The urbanized and built-up land shown in figure 37 corresponds approximately to the category of developed land shown in figure 4. Approximately 27 percent of the State's land had been developed as of 1975, and an additional 11 percent of the total area was developed between 1975 and the mid-1980's (fig. 4).



Base and hydrology for Rhode Island and Massachusetts from the Rhode Island Geographic Information System. Connecticut hydrology from Natural Resources Center, Connecticut Department of Environmental Protection

Figure 35.--Rhode Island's major drainage basins, including basins shared with adjacent States.



Base and hydrology from the
Rhode Island Geographic Information System

Figure 36.--Major ground-water regions of Rhode Island.

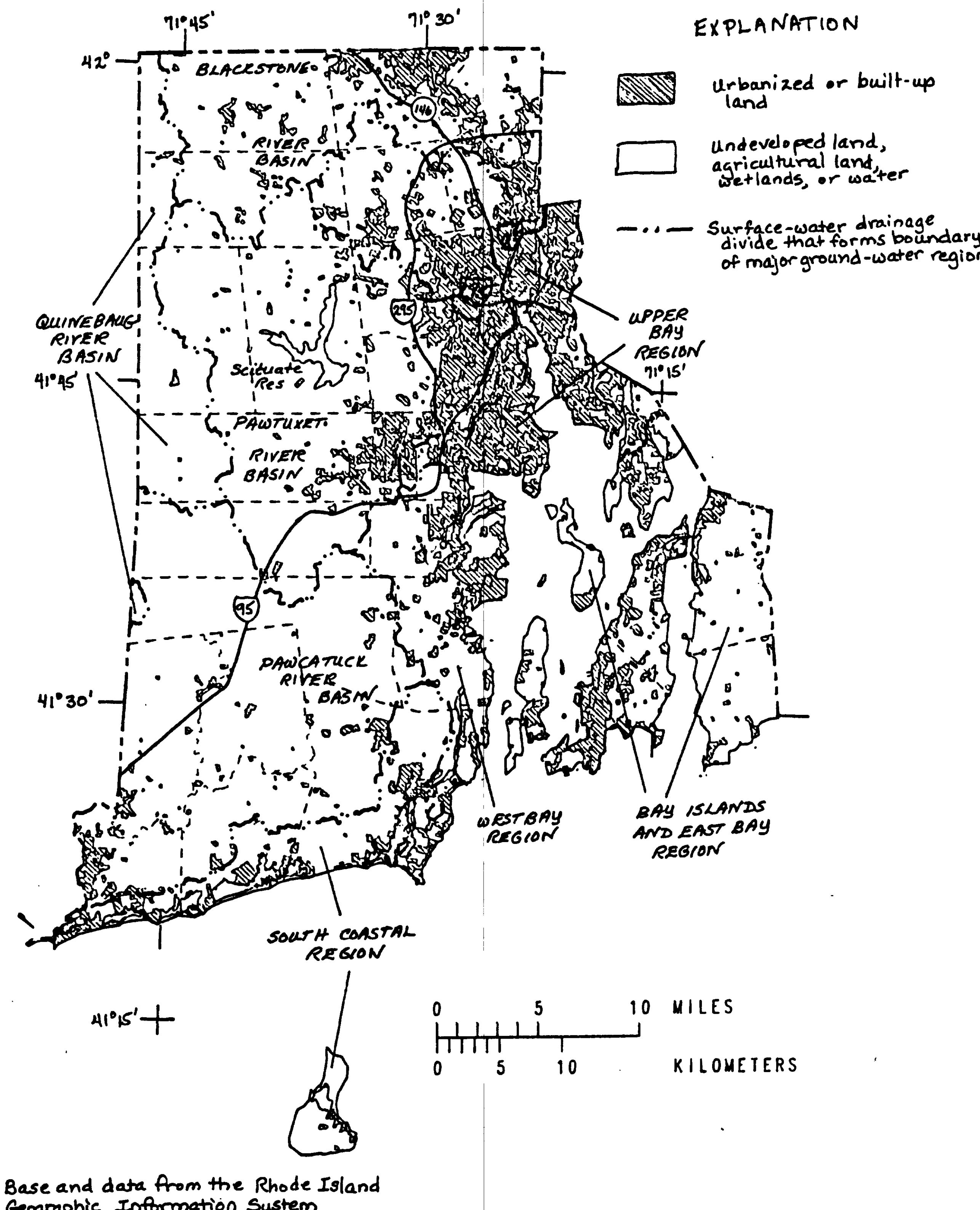


Figure 37.--Distribution of urbanized and built-up land in Rhode Island in 1974. Urbanized and built-up land includes residential, commercial, and industrial areas, and land used for transportation, communications, and utilities. (Sources: Data on urbanized and built-up land from U.S. Geological Survey Geographic Information Retrieval and Analysis System, Fegeas and others, 1983; data on major highways from U.S. Geological Survey Digital Line Graph data.)

The Blackstone River Basin

The Blackstone River originates near Worcester, Massachusetts, and flows southeastward for about 46 miles, entering the tidal Seekonk River in Pawtucket, Rhode Island, at the head of Narragansett Bay (figs. 35 and 38). The drainage area of the Blackstone River totals 478 square miles, of which 373 square miles are in east-central Massachusetts. About 105 square miles, or 22 percent of the drainage area, are in northern Rhode Island. The Blackstone River is the State's largest river in streamflow and total drainage area. The average discharge, or streamflow, of the river near downtown Woonsocket was 498 million gallons per day during water years 1929-84 (Gadoury and others, 1986, p. 64).

The Main Stem of the Blackstone River

The main stem of the Blackstone River has served historically as an industrial corridor (Rhode Island Department of Environmental Management, 1987). During the 19th and 20th centuries, the river has been used intensively for waterpower, industrial processes, and waste disposal. Industries have continued to locate along the river, which is urbanized along much of its course from Worcester to Pawtucket. Surface-water quality has been degraded by industrial discharges and municipal sewage discharges (Johnston and Dickerman, 1974a). Streambed sediments near Manville contain polychlorinated biphenyls (PCBs) and several chlorinated hydrocarbon pesticides (Gadoury and others, 1986, p. 67).

The land near the main stem of the Blackstone River is hilly, and altitudes of many hills exceed 400 feet. Bedrock is exposed at the land surface on many hillsides and hilltops. Where till covers the bedrock surface in upland areas, the till is commonly 10 to 20 feet thick.

Major stratified-drift deposits are generally confined to narrow stream valleys bordered by steep bedrock valley walls. From the Massachusetts State line southeast to the village of Ashton (fig. 38), a stratified-drift aquifer forms a narrow lowland bordering the Blackstone River (fig. 10). In many places the aquifer is less than 500 feet wide (Johnston and Dickerman, 1974a). The average thickness of the aquifer along this reach of the river is 40 feet, and the maximum known thickness is 70 feet (Johnston and Dickerman, 1974a). The stratified-drift deposits become wider and thicker south of Ashton, eventually forming the extensive outwash plain that underlies Central Falls, Pawtucket, and parts of other communities on both sides of upper Narragansett Bay (fig. 10).

The stratified-drift aquifer along the main stem of the Blackstone River can yield large amounts of water. The yield is determined primarily by the rate at which water can be induced to infiltrate from the river into the aquifer (Johnston and Dickerman, 1974a). Streamflow in the river almost always exceeds the potential amount of water that can be induced to infiltrate into the aquifer.

Simplified ground-water-flow models of several aquifer segments have been used to estimate total aquifer yield. Ground-water withdrawals simulated by the models indicate that a total of 22 to 30 million gallons per day can be obtained from wells at various locations along the main stem of the Blackstone River in Rhode Island (Johnston and Dickerman, 1974a). Three segments of the stratified-drift aquifer along the main stem have been designated as ground-water reservoirs (fig. 38).

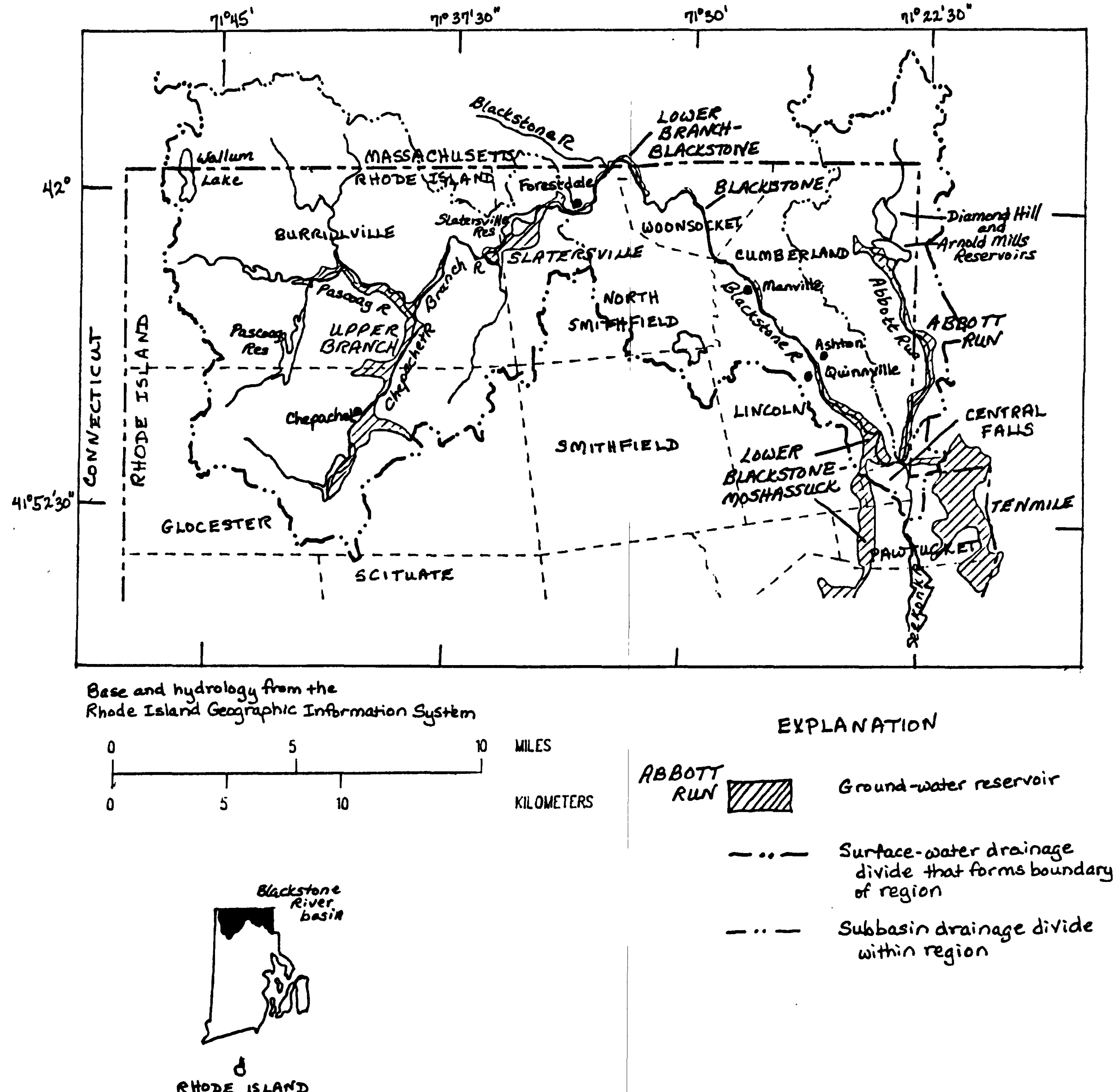


Figure 38.--The Blackstone River basin in northern Rhode Island. (Source: Ground-water-reservoir boundaries from W.B. Allen, Rhode Island Water Resources Board, written commun., 1978.)

The Lower Branch-Blackstone ground-water reservoir occupies a narrow loop of the Branch and Blackstone valleys in North Smithfield, Woonsocket, and adjoining parts of Massachusetts. Its yield has been estimated as 3.6 million gallons per day (Johnston and Dickerman, 1974a).

The Blackstone ground-water reservoir extends from Woonsocket south along the Blackstone River valley between Cumberland and Lincoln. The estimate of its yield ranges from 3.5 to 5.3 million gallons per day (Johnston and Dickerman, 1974a). During 1985, Cumberland withdrew approximately 760,000 gallons per day from the Blackstone ground-water reservoir near Manville (R.W. Bell, U.S. Geological Survey, written commun., 1989).

The Lower Blackstone-Moshassuck ground-water reservoir extends from the village of Ashton south along the Blackstone River and into the Moshassuck River basin in Pawtucket. The segment of the ground-water reservoir within the Blackstone River basin has an estimated yield ranging approximately from 15 to 22 million gallons per day (Johnston and Dickerman, 1974a).

The quality of water in these ground-water reservoirs has been affected by industrial discharges and spills, leachate from waste-disposal sites, the cumulative effects of urbanization, and induced infiltration of surface water that receives substantial quantities of municipal and industrial wastewater. Ground-water contamination at several locations has led to the abandonment of public-supply wells.

Use of two Woonsocket public-supply wells in the Blackstone ground-water reservoir was discontinued during the 1960's because of the presence of detergent and elevated concentrations of manganese (H.V. Patterson, Woonsocket Engineering Department, oral commun., 1983). Use of a public-supply well in the Lower Blackstone-Moshassuck ground-water reservoir in Cumberland was discontinued in 1970 because of elevated iron and manganese concentrations (T.R. Walker, Cumberland Public Works Department, oral commun., 1984). The elevated manganese and iron concentrations in ground water may be caused by induced infiltration of water from the Blackstone River (Johnston and Dickerman, 1974a).

Contamination from synthetic organic chemicals has resulted in the abandonment of six public-supply wells in the Blackstone and Lower Blackstone-Moshassuck ground-water reservoirs. VOCs were detected in water from three wells in Lincoln and one well in Cumberland near the village of Quinnville (fig. 38) in 1979 (Goldberg-Zoino & Associates, Inc., 1982). Use of all four wells was discontinued that year. VOCs were detected in water from two wells in Lincoln near Manville in 1984 (Rhode Island Department of Environmental Management, 1988, table 4-2, p. IV-9). Use of these wells was discontinued in 1985 (R.W. Bell, U.S. Geological Survey, written commun., 1989). The town of Lincoln used local ground water for its entire public supply until 1979. Since that year, surface water has been imported in increasing amounts to meet the town's public-supply needs. By late February 1985, all of Lincoln's publicly supplied water was surface water purchased from the Providence Water Supply Board (M.P. Trudeau, Lincoln Water Department, oral commun., 1990).

The Abbott Run Basin

Abbott Run flows into the downstream end of the Blackstone River near Central Falls (fig. 38). The drainage area of Abbott Run includes about 28 square miles in northeastern Rhode Island and adjacent parts of Massachusetts. A stratified-drift aquifer underlies the stream valley. The thickest part of the aquifer forms the Abbott Run ground-water reservoir (fig. 38). The saturated thickness of the stratified drift in the ground-water reservoir ranges from 40 to 80 feet (Johnston and Dickerman, 1974a).

The estimated yield of the Abbott Run ground-water reservoir ranges from 5 to 12 million gallons per day (Johnston and Dickerman, 1974a). The yield is largely determined by the amount of recharge that can be induced into the aquifer from Abbott Run (Johnston and Dickerman, 1974a). The flow of Abbott Run depends in part on the amount of surface water released from the Diamond Hill and Arnold Mills Reservoirs (fig. 38).

Cumberland withdrew approximately 460,000 gallons of water per day from the Abbott Run ground-water reservoir in 1985 (R.W. Bell, U.S. Geological Survey, written commun., 1989). The Pawtucket public-supply system, which also supplies water to Central Falls, uses surface water and ground water from the Abbott Run basin. Ground water was not used by Pawtucket in 1985 (fig. 3).

Concentrations of common constituents in ground water are generally below MCLs and SMCLs (Johnston and Dickerman, 1974a, sheet 2, fig. 1). Manganese and iron concentrations in water from some public-supply wells exceeded SMCLs, and VOCs were detected in three public-supply wells, during the period 1986-88 (B.F. Barrette, Rhode Island Department of Health, written commun., 1989).

The small drainage area of Abbott Run limits the total amount of water available for use by Cumberland, Pawtucket, and adjoining towns in Massachusetts. During very dry years, virtually all of the available surface water and ground water yield of the basin is used by the Pawtucket system (Johnston and Dickerman, 1974a). Use of water by one community affects the amount of water available to other communities within the basin, and exports of water reduce dependable supplies within the basin (Johnston and Dickerman, 1974a).

The Branch River Basin

The Branch River is the Blackstone River's largest tributary. Its drainage area upstream from the village of Forestdale is 91 square miles, 79 square miles in northwestern Rhode Island and 12 square miles in Massachusetts. The Branch River, formed at the confluence of the Pascoag and Chepachet Rivers, drains much of northwestern Rhode Island (fig. 38).

Steep, till-covered bedrock hills form the landscape of the Branch River basin. Summits of hills along the western drainage divide generally range from 600 to 750 feet above sea level. Most of the Branch River basin is undeveloped or sparsely populated (fig. 37), although a few small villages and industrial areas are located at various points along the major streams. With the exception of a few villages that have public water systems, most of the area is served by private wells.

A stratified-drift aquifer fills the valley of the Branch River and its major tributaries. Two large segments of this aquifer system have been designated as the Upper Branch and the Slatersville ground-water reservoirs.

The Upper Branch ground-water reservoir fills the valleys of the Chepachet, Pascoag, and Branch Rivers (fig. 38). The saturated thickness of the stratified drift generally ranges from 40 to 60 feet near the center of the principal stream valleys, and the maximum known saturated thickness is 110 feet near the village of Chepachet (Johnston and Dickerman, 1974b). The Pascoag and Harrisville Fire Districts withdrew approximately 540,000 gallons of water per day for public supply from this ground-water reservoir in 1985 (R.W. Bell, U.S. Geological Survey, written commun., 1989).

The yield of the Upper Branch ground-water reservoir has been estimated at 6.3 million gallons per day (Johnston and Dickerman, 1974b, p. 21). Withdrawals at this rate are not expected to cause downstream reaches of the Pascoag and Chepachet Rivers to go dry; however, ground-water withdrawals at a rate of 1.3 million gallons per day near the village of Chepachet could cause upstream reaches of the Chepachet River to go dry for periods of several weeks during droughts (Johnston and Dickerman, 1974b, p. 30).

The Slatersville ground-water reservoir extends along the Branch River valley near the Slatersville surface-water reservoirs in North Smithfield (fig. 38). Parts of the area are underlain by as much as 75 feet of saturated, medium to coarse sand and gravel (Johnston and Dickerman, 1974b). Small amounts of ground water are withdrawn by industries and small public water systems.

The yield of the Slatersville ground-water reservoir has been estimated at 5.5 million gallons per day (Johnston and Dickerman, 1974b, p. 24). Induced infiltration from the Slatersville surface-water reservoirs would supply much of the estimated well yield. Sustained withdrawal at a rate of 5.5 million gallons per day would deplete outflow from the surface-water reservoirs, but would rarely cause outflow from the reservoirs to cease (Johnston and Dickerman, 1974b, p. 24).

Ground-water quality in some areas of the Branch River basin has been degraded. Three of the State's eight "Superfund" hazardous waste sites are located on or adjacent to the Slatersville ground-water reservoir (figs. 28, 38) (Rhode Island Department of Environmental Management, 1988, table 4-9, p. IV-18 to IV-20). Ground water, surface water, and soil at these sites have been contaminated by solvents and other chemicals. Private wells in the area have been contaminated, and a small public-water-system well has been removed from service (Rhode Island Department of Environmental Management, 1988, table 4-2, p. IV-9).

The Upper Bay Region

The Upper Bay region includes coastal areas and the drainage basins of streams that flow into the Providence and Seekonk Rivers at the head of Narragansett Bay (fig. 39). The major streams are the Pawtuxet, Woonasquatucket, Moshassuck, and Tenmile Rivers. The area along the main stem of the Pawtuxet River (fig. 39) is discussed in this section as well as in the section on the Pawtuxet River basin because the ground water in this area is hydraulically connected to both regions.

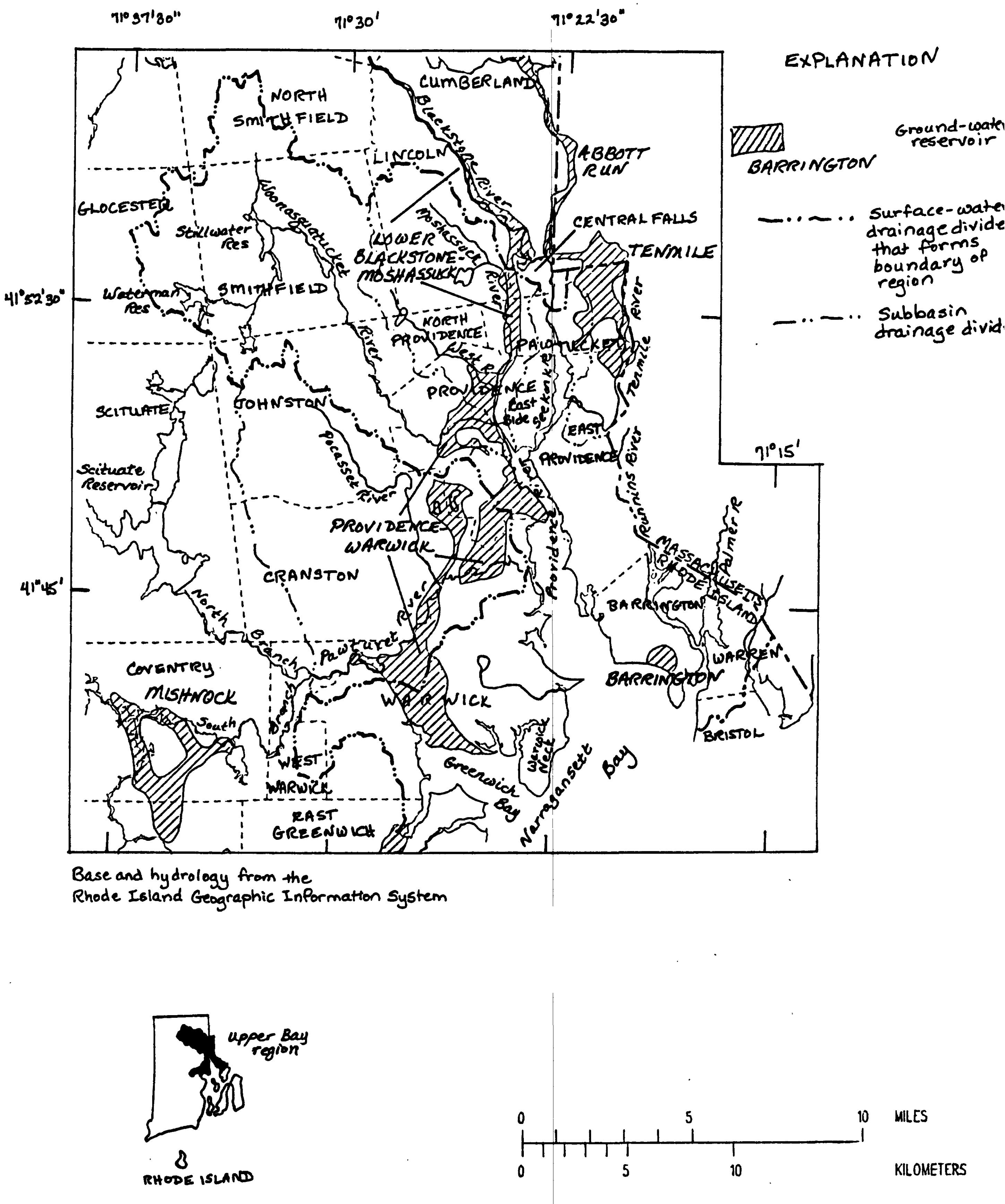


Figure 39.--The Upper Bay region in east-central Rhode Island. (Source: Ground-water-reservoir boundaries from W.B. Allen, Rhode Island Water Resources Board, written commun., 1978.)

With the exception of the upper reaches of the Woonasquatucket River drainage basin, most of the region is within the Seaboard Lowland section of the New England physiographic province (fig. 1). Much of the State's most highly populated, urbanized, and industrialized land is found here (fig. 37).

Coastal areas of this region are underlain by widespread deposits of stratified drift (fig. 10). Outwash plains containing some ice-contact deposits extend from southern Cumberland and Lincoln south to Greenwich Bay on the west side of Narragansett Bay and to Warren on the east side of the bay (figs. 10, 39) (Halberg and others, 1961). Kettle ponds in eastern Warwick and southern Providence mark the former locations of stagnant glacial ice blocks buried in the stratified drift.

The topographic expression of the stratified drift in the coastal area is a flat plain. Land-surface altitudes are generally less than 100 feet. In many locations, drainage divides between streams are formed only by a gentle rise in the land surface. A few steep till-covered bedrock hills such as Warwick Neck in Warwick or the East Side in Providence punctuate the flat landscape.

The glacial deposits of clay, silt, sand, and gravel overlie sedimentary rocks of the Narragansett Basin (fig. 10) in most areas. The stratified-drift deposits may be more than 200 feet thick where they fill preglacial river channels in the bedrock (Halberg and others, 1961).

Large parts of the stratified-drift aquifer are fine grained on both sides of Narragansett Bay. Coarse-grained layers are present in some areas, however, and potential well yields at some locations are high (Halberg and others, 1961). Four areas where conditions are known to be favorable for large well yields have been designated as the Tenmile, Barrington, Lower Blackstone-Moshassuck, and Providence-Warwick ground-water reservoirs (fig. 39). Other parts of the stratified drift have not been investigated extensively, and the potential for ground-water development in these areas is not known.

The Tenmile River Basin

The Tenmile River flows into the tidal Seekonk River at the head of Narragansett Bay (fig. 39). The drainage area of the Tenmile River is about 57 square miles, of which only 7 square miles are within Rhode Island. The downstream reaches of the Tenmile River flow across a large stratified-drift aquifer in Pawtucket and East Providence. The stratified-drift aquifer in this area is composed primarily of thick sequences of fine sand, silt, and clay. Lenses of medium to coarse sand and gravel are present locally. The maximum known depth to bedrock is 130 feet (Johnston and Dickerman, 1974a).

The part of the aquifer with the greatest potential for development, located along the Tenmile River in Pawtucket, East Providence, and adjoining parts of Massachusetts, has been designated the Tenmile ground-water reservoir (fig. 39). The yield of the Tenmile ground-water reservoir has been estimated at 5.9 to 10 million gallons per day (Johnston and Dickerman, 1974a). Much of this yield would be derived from induced infiltration from the Tenmile River and surface-water reservoirs along the river. Ground-water withdrawals at this rate are unlikely to cause periods of no streamflow (Johnston and Dickerman, 1974a).

The Tenmile ground-water reservoir is in a highly urbanized area (fig. 37). In 1974, about 30 percent of the ground-water reservoir was covered by roads, buildings, and other nearly impervious structures that prevent or reduce recharge from precipitation (Johnston and Dickerman, 1974a).

Use of the Tenmile ground-water reservoir has been adversely affected by contaminated surface water. Substantial quantities of metal plating wastes and industrial chemical-process wastes are discharged to the Tenmile River in Massachusetts, upstream from the Tenmile ground-water reservoir (Johnston and Dickerman, 1974a). The city of East Providence formerly withdrew water from four wells near the Tenmile River. The wells derived most of their water from surface-water reservoirs along the river by the process of induced infiltration. The city discontinued use of these wells and surface-water reservoirs in 1970, largely because of the high level of contaminants in the surface water (Johnston and Dickerman, 1974a). Subsequently, East Providence began purchasing water from the Providence public-supply system.

The Barrington Area

Stratified drift, as much as 135 feet thick in some places, blankets most of the Barrington area on the east side of upper Narragansett Bay (Bierschenk, 1954, p. 23). Although some ground water in this area is unconfined, water in deep layers of gravel is confined between layers of glacial-lake clays (Bierschenk, 1954, p. 38). Course-grained deposits in southern Barrington form the <u>Barrington ground-water reservoir</u> (fig. 39), from which the Bristol County Water Company withdrew approximately 850,000 gallons of water per day in 1985 (R.W. Bell, U.S. Geological Survey, written commun., 1989).

No significant freshwater streams traverse the stratified drift. Consequently, the only source of ground-water recharge is precipitation that falls on the aquifer.

The town of Barrington is surrounded by saltwater or brackish water on three sides. The water-table altitude throughout most of the town is less than 10 feet above sea level (Bierschenk, 1954). The natural slope of the water table is toward the sea under nonpumping conditions, but withdrawal of fresh ground water may result in saltwater intrusion (fig. 31).

The saturated thickness of the stratified drift is less than 30 feet in most parts of the town of Warren (Bierschenk, 1954, p.44). The town is also bordered by saltwater or brackish water along much of its perimeter, and saltwater intrusion has been caused by ground-water withdrawals (Bierschenk, 1954, p. 45).

Iron concentrations as high as 5 milligrams per liter have been measured in ground water in the Barrington area (Bierschenk, 1954, table 6, p. 61). Ground water containing elevated concentrations of iron is more likely where the underlying bedrock is black shale of the Narragansett Basin than in other parts of the Barrington area, because of the presence of easily weathered iron-bearing minerals (Bierschenk, 1954, p. 62).

Iron concentrations ranged from 1.94 to 3.55 milligrams per liter in water from the Bristol County Water Company's three public-supply wells during 1987-88 (B.F. Barrette, Rhode Island Department of Health, written commun., 1989). Manganese concentrations ranged from 0.22 to 0.58 milligram per liter. Treated water met the SMCLs for iron and manganese. Sodium concentrations exceeded the health guideline of 20 milligrams per liter (table 1) in water from the three wells; concentrations ranged from 33.9 to 52.6 milligrams per liter. During 1986-87, five VOCs were detected in water from one of the wells. Four of the VOCs were not detected in the treated water, and the concentration of the fifth, a trihalomethane, was less than the MCL.

The Moshassuck River Basin

The Moshassuck River originates in Lincoln and flows generally southward through Pawtucket and Providence (fig. 39). The terrain in the northwestern part of the Moshassuck basin is similar to that of the Blackstone River valley and is characterized by steep, till-covered bedrock hills in most areas. Stratified-drift deposits are confined to the narrow stream valley.

Where the river turns south near Central Falls, its valley widens and stratified-drift deposits are extensive. This stratified-drift aquifer is a continuation of the stratified-drift aquifer that occupies the downstream end of the Blackstone River valley (figs. 10, 39). Near Central Falls, thick layers of sand, gravel, silt, and clay fill a bedrock valley that marks the preglacial course of the Blackstone River. This ancestral Blackstone River followed the course of the present-day Moshassuck River west and south of Central Falls. After the melting of the glacier, thick deposits of glacial sediments dammed the valley and diverted the Blackstone River to its present course, where it flows eastward and then southward around the city of Central Falls (fig. 39).

The thickest, most permeable stratified drift filling this preglacial bedrock valley forms the Lower Blackstone-Moshassuck ground-water reservoir (fig. 39). The Lower Blackstone-Moshassuck ground-water reservoir and the Providence-Warwick ground-water reservoir are actually part of a continuous stratified-drift aquifer that blankets coastal areas on the west side of upper Narragansett Bay (figs. 10, 39).

The surface-water drainage divide between the Blackstone River and the Moshassuck River crosses the ground-water reservoir near Central Falls (fig. 39). Ground water from the Blackstone basin will flow southward into the Moshassuck basin if the water table is lowered significantly by ground-water withdrawals in this part of the Moshassuck valley (Johnston and Dickerman, 1974a).

The yield of the Moshassuck segment of the Lower Blackstone-Moshassuck ground-water reservoir has been estimated at 4 million gallons per day (Johnston and Dickerman, 1974a). Continuous withdrawal of ground water at a rate greater than 1 million gallons per day would cause the Moshassuck River to go dry during droughts if the water was exported from the basin (H.E. Johnston, U.S. Geological Survey, written commun., 1988). The lower reaches of the Moshassuck River valley are highly urbanized (fig. 37). In 1974, about 30 percent of the stratified-drift aquifer was covered with roads, buildings, and other nearly impervious surfaces that reduce recharge (Johnston and Dickerman, 1974a).

No public supplies withdraw water from the stratified-drift aquifer, but water is withdrawn for some industrial uses. Private wells supply drinking water in some of the rural, northwestern parts of the Moshassuck basin.

The Woonasquatucket River Basin

The Woonasquatucket River originates in North Smithfield and flows southeastward toward the city of Providence (fig. 39). It joins the Moshassuck River near the State House in Providence to form the tidal Providence River at the head of Narragansett Bay.

The upper reaches of the Woonasquatucket River are in the New England Upland section of the New England physiographic province (fig. 1). The terrain in this part of the drainage basin is similar to that of the Branch River basin. The summits of many hills are more than 500 feet above sea level. Private wells in till, bedrock, and stratified drift are used for drinking water in rural areas.

A narrow band of stratified drift underlies most of the Woonasquatucket River valley. These deposits generally are less than 50 feet thick and are small in area (Halberg and others, 1961), although thicker, more extensive deposits are present in a few places.

The lower reaches of the Woonasquatucket River basin in North Providence, Johnston, and Providence are highly urbanized and industrialized. The river flows across the coastal Providence-Warwick ground-water reservoir at its downstream end (fig. 39). Use of ground water in the lower reaches of the drainage basin may be limited by the presence of contaminants from industrial and urban land uses, contaminated surface water, and the potential for saltwater intrusion.

The Providence-Warwick Area

Coastal areas of Providence, Cranston, and Warwick are underlain by stratified-drift deposits (figs. 10, 39). The deposits include fairly well-sorted layers of sand, clay, silt, and gravel, although the relative amounts of fine-grained and coarse-grained materials are not known with certainty in some areas (Allen, 1956; Bierschenk, 1959). Ground water in the stratified drift generally is unconfined. Several streams traverse the stratified drift before flowing into the Providence River or Narragansett Bay.

Stratified drift as much as 200 feet thick fills deep channels in the bedrock surface. The bedrock valley that marks the preglacial course of the Blackstone River is the most important of these buried channels. It extends from Central Falls south through Pawtucket, Providence, Cranston, and Warwick to Greenwich Bay.

Parts of the stratified-drift aquifer between the northern boundary of Providence and Greenwich Bay in Warwick have been designated the Providence-Warwick ground-water reservoir (fig. 39). The limited data available indicate that the ground-water reservoir is capable of storing and transmitting large quantities of water (Lang, 1961, p. 14, 15). The ground-water reservoir receives substantial amounts of recharge from precipitation, and induced recharge is available from streams that traverse the area.

No detailed studies have been made to evaluate the potential yield of the Providence-Warwick ground-water reservoir. Such an evaluation requires information on the distribution and water-bearing properties of permeable layers, the potential for induced infiltration, and the effect that pumping stress will have on the interface between fresh ground water and saltwater along the coast. Water quality is an important consideration in evaluating this ground-water reservoir because of the many potential sources of contamination in the area (figs. 28, 37) and the potential for saltwater intrusion.

The Providence-Warwick ground-water reservoir is not currently (1989) used for public supply. Most of the area is served by the Scituate Reservoir (fig. 36). Some ground water is withdrawn for industrial uses. Industrial use of ground water in Providence began in the late 19th century. By the 1940's, industrial ground-water withdrawals had lowered the altitude of the water table locally by 10 to 30 feet and had caused saltwater intrusion in some areas (Roberts and Brashears, 1945, p. 19; Bierschenk, 1959, p. 36-37). The altitude of the water table has risen in recent years as industrial withdrawals of ground water have decreased (Gadoury and others, 1986, p. 203).

The largest stream traversing the Providence-Warwick ground-water reservoir is the Pawtuxet River. The Pawtuxet River valley is densely populated and has been industrialized for more than a century. Ground water along the Pawtuxet River has been contaminated by several industrial waste-disposal sites (fig. 28). Effluent from industries and municipal wastewater-treatment plants in the cities of West Warwick, Warwick, and Cranston is discharged to the river. Streambed sediments have been contaminated by PCBs and several chlorinated hydrocarbon pesticides (Gadoury and others, 1986, p. 74, 77). Thus, although the potential exists for ground-water development along the main stem of the Pawtuxet River, the current quality of surface water and ground water may limit the use of this resource.

The Pawtuxet River Basin

The Pawtuxet River drains 230 square miles in central Rhode Island (fig. 40). It is the largest drainage basin entirely contained within the boundaries of the State. The drainage basin includes remote rural areas in the west and highly urbanized areas in the east (fig. 37). The quality of ground water ranges from pristine to severely contaminated.

The Main Stem of the Pawtuxet River

The Pawtuxet River forms at the junction of the North Branch Pawtuxet and South Branch Pawtuxet Rivers in West Warwick (fig. 40). From there the Pawtuxet River flows eastward and northeastward to Pawtuxet Cove on the west side of the tidal Providence River. The Pocasset River and Meshanticut Brook are the major tributaries.

The Pawtuxet River flows across the coastal Providence-Warwick ground-water reservoir, described in the previous section of this report. Stratified-drift deposits along some reaches of the river are as much as 200 feet thick (Allen, 1956). Smaller deposits of stratified drift fill the valleys of the Pocasset River and Meshanticut Brook. The deposits are fairly well sorted, and different layers include grain sizes ranging from silt and fine sand to gravel composed of cobbles and boulders (Allen, 1956, p. 11). The water-transmitting characteristics of stratified drift in this area have not been investigated extensively.

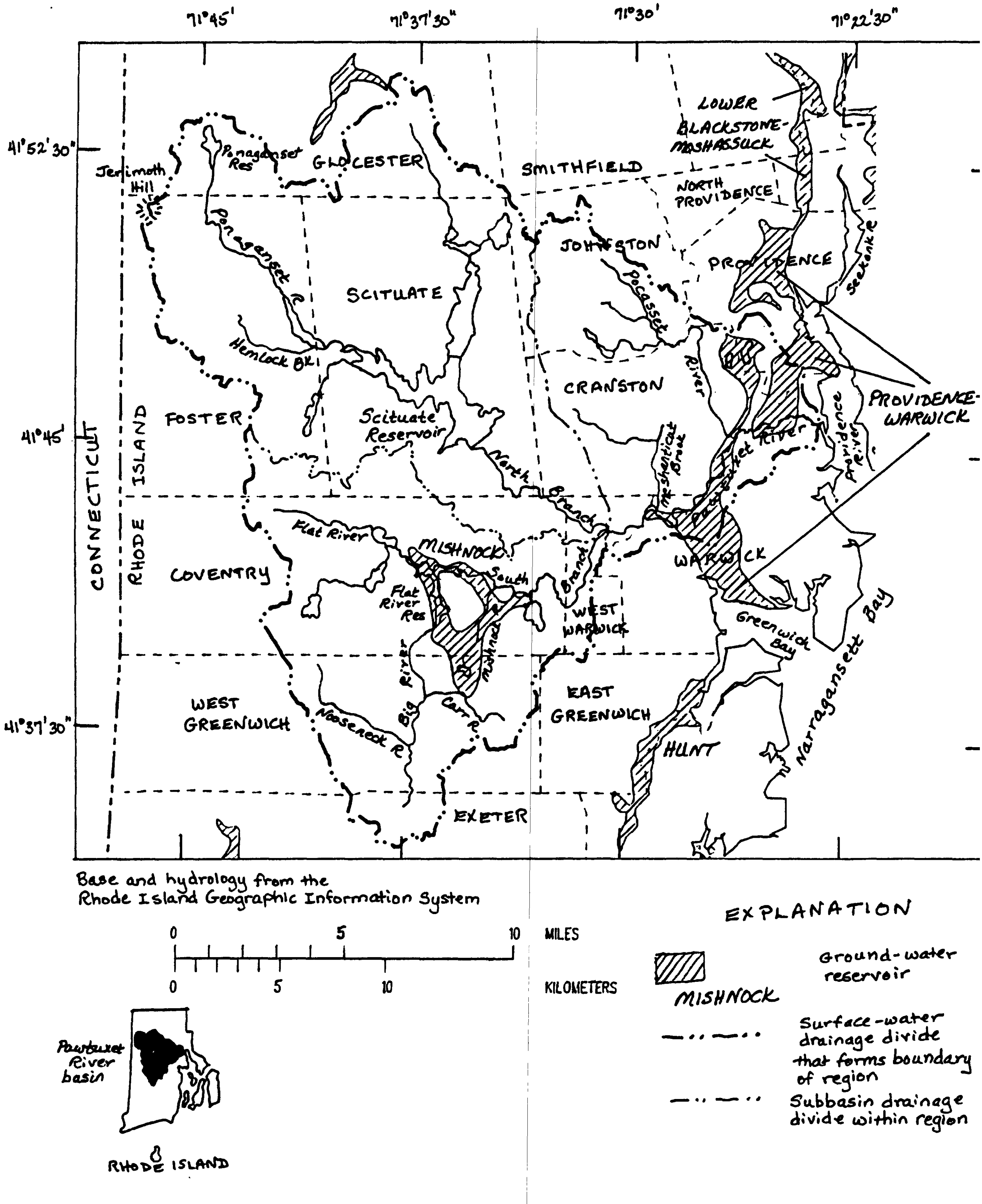


Figure 40.--The Pawtuxet River basin in central Rhode Island. (Source: Ground-water-reservoir boundaries from W.B. Allen, Rhode Island Water Resources Board, written commun., 1978.)

Currently (1989), no ground water is withdrawn for public supply along the main stem of the Pawtuxet River. Many contaminant sources in this highly urbanized area have affected water quality, as noted previously. Drinking water is imported from the Scituate Reservoir, in the North Branch Pawtuxet basin; from the Mishnock ground-water reservoir, in the South Branch basin; and from the Hunt ground-water reservoir, outside the Pawtuxet River basin (fig. 40).

In the rural parts of the Pocasset River and Meshanticut Brook subbasins, drinking water is obtained from private wells. The Rhode Island Central Landfill is in Johnston near a tributary of the Pocasset River; as noted previously, this is a hazardous-waste site on the Federal "Superfund" list (fig. 28).

The North Branch Pawtuxet River Basin

The drainage basin of the North Branch Pawtuxet River, an area of 105 square miles, is hilly and sparsely populated. Altitudes of hills range from 400 to 800 feet, and many summits are at least 600 feet above sea level. The six surface-water bodies that form the Scituate Reservoir system are a dominant feature of the landscape. The North Branch of the Pawtuxet River originates at the outlet of the Scituate Reservoir (fig. 40).

The Scituate Reservoir system was constructed in 1926 to provide an adequate, clean water supply for Providence and surrounding communities. Previously, the area had obtained drinking water from the Pawtuxet River, which was contaminated by untreated human and mill wastes (Providence Water Supply Board, no date).

Surface water from the Scituate Reservoir supplied drinking water for half the State's population in 1985 (H.E. Johnston, U.S. Geological Survey, written commun., 1988). Providence, Cranston, Johnston, and North Providence were served directly by this source. In addition, Warwick, West Warwick, Smithfield, Lincoln, East Providence, Coventry, and Scituate obtained water from this source through purchases from the Providence Water Supply Board (R.J. Kilduff, Providence Water Supply Board, oral commun., 1987).

The drainage area of the Scituate Reservoir system encompasses about 93 square miles of the North Branch subbasin (fig. 40) (Halberg and others, 1961, p. A-31). The reservoir's drainage area includes large parts of Glocester, Foster, and Scituate, as well as small parts of Johnston and Cranston. The population within the reservoir's drainage area has grown substantially in recent years, as people are attracted by the natural beauty of the area.

Surface-water runoff and ground-water runoff contribute water to the Scituate Reservoir system. Thus, protection of ground-water quality helps to protect the quality of the State's largest water supply. The land currently protected as part of the public-water-supply watershed represents only a small fraction of the total area that contributes water to the Scituate Reservoir. Contaminant sources that affect ground water, such as septic systems, road salt, leaking underground storage tanks, and accidental chemical spills, also have the potential to affect the quality of water in the Scituate Reservoir.

Despite the presence of the Scituate Reservoir, most residents of the North Branch subbasin rely on private wells for their drinking water. This ground water is withdrawn from stratified-drift, till, and bedrock aquifers.

Stratified drift underlies some reaches of the North Branch Pawtuxet River valley and its tributaries (fig. 40). The saturated thickness of the stratified drift exceeds 40 feet in parts of Hemlock Brook valley in Foster (Hansen, 1962a). Downstream from the Scituate Reservoir, the saturated thickness is as much as 70 feet (Allen and others, 1959; Lang, 1961; p. 19). The stratified drift along the North Branch, however, is fine grained and may not be suitable for development of ground-water supplies (Lang, 1961, p. 19-20).

The deposits of stratified drift in other parts of this basin are small, and their saturated thickness is generally less than 20 feet. Bedrock is close to the land surface throughout much of the area, and outcrops are common in the valleys as well as on the till-covered uplands (Pollock, 1960; Hansen, 1962a).

Several areas of ground-water contamination have been identified within the North Branch drainage basin by RIDEM (1988, fig. 4-7, p. IV-30). The contaminant sources include former defense installations, small commercial and industrial facilities, and a State road-salt storage site (fig. 28). Private wells and a small public-water-system well have been affected by contaminants from some of these sources (Rhode Island Department of Environmental Management, 1988, table 4-2, p. IV-9; table 4-15, p. IV-31 to IV-35).

The South Branch Pawtuxet River Basin

The South Branch of the Pawtuxet River originates at the outlet of the Flat River Reservoir in Coventry (fig. 40). Altitudes of the highest hills in the western part of the subbasin are about 600 feet.

About half of this drainage basin is underlain by stratified drift (Lang, 1961, p. 21). Extensive stratified-drift deposits underlie the wide valleys of the South Branch Pawtuxet River and its major tributaries, the Mishnock, Big, Nooseneck, and Flat Rivers. The areas underlain by stratified drift are much flatter than the surrounding till-covered uplands. Altitudes in the valley lowlands generally range from 250 to 350 feet.

The thickest part of the stratified-drift aquifer forms the Mishnock ground-water reservoir in Coventry and West Greenwich (fig. 40). The saturated thickness of the ground-water reservoir is approximately 100 feet in some areas (Gonthier, 1966). Ground water is generally unconfined, although confined conditions may be caused locally by lenses of silt and clay (Frimpter, 1973b, p. 2-2).

The total storage capacity of the Mishnock ground-water reservoir is very large, but its yield has not been estimated (Lang, 1961, p. 21). Detailed quantitative studies have been proposed for this area because of the large volume of permeable material present (Lang, 1961, p. 22).

Extensive deposits of stratified drift form a coastal lowland south of Greenwich Bay (fig. 10). Altitudes are generally less than 100 feet. A few hills of till-covered bedrock interrupt the otherwise flat land surface. Moraine deposits of mixed till and stratified drift form irregular hills and depressions near the Annaquatucket and Mattatuxet Rivers.

Near the town line between North Kingstown and Exeter, a hummocky end moraine forms the surface-water drainage divide between the Pawcatuck River basin to the west and coastal drainage basins to the east. The ground-water drainage divide in this area is as much as 1 mile west or southwest of the surface-water drainage divide (fig. 42). Near the Queen River, a tributary of the Pawcatuck, ground water flows eastward into the Annaquatucket River basin (Hahn, 1959b; Johnson and Marks, 1959). Ground water in the northeast corner of the Chipuxet River basin flows northeastward into the Annaquatucket and Mattatuxet River basins (Hahn, 1959b; Johnson and Marks, 1959).

Much of the coastal stratified-drift aquifer in the North Kingstown-East Greenwich area is composed of fine-grained sediments that are not very permeable. Local areas of thick, highly permeable sediments form the Hunt, Annaquatucket, and Pettaquamscutt ground-water reservoirs (fig. 42). The small Annaquatucket and Pettaquamscutt ground-water reservoirs are sometimes referred to collectively as a single ground-water reservoir in State publications.

These three ground-water reservoirs and their recharge areas have been designated a sole source aquifer by the USEPA (U.S. Environmental Protection Agency, 1988a, p. 19027). Ground water is the principal source of drinking water in the area, and it is vulnerable to contamination. The designated area, called the Hunt-Annaquatucket-Pettaquamscutt Aquifer Area, covers 41 square miles. It encompasses most of North Kingstown and East Greenwich, and parts of Warwick, West Warwick, Coventry, West Greenwich, and Exeter. The western boundary of the designated area follows the ground-water drainage divide where it differs from the surface-water drainage divide (fig. 42).

The Hunt River Area

The Hunt River originates in North Kingstown and flows northeastward toward Narragansett Bay. The river is tidal near its mouth, where it is known as the Potowomut River.

The Hunt ground-water reservoir occupies the lowland area near the Hunt River (fig. 42). Most of the ground-water reservoir is within the drainage basin of the Hunt River. Along the main axis of the ground-water reservoir, the saturated thickness of the stratified drift generally ranges from 80 to 100 feet (Rosenshein and others, 1968, pl. 3).

Public-supply wells for the Kent County Water Authority, North Kingstown Water Commission, and Rhode Island Port Authority withdraw water from the Hunt ground-water reservoir. During 1985, these suppliers withdrew approximately 2.1 million gallons per day (R.W. Bell, U.S. Geological Survey, written commun., 1989).

High-yield wells induce infiltration from the Hunt River and affect the low flow of this small stream. The yield of the Hunt ground-water reservoir has been estimated at about 9 million gallons per day (Rosenshein and others, 1968, p. 27, 29). However, continuous withdrawals at a rate of 8 million gallons per day would cause sizable reaches of the Hunt River to go dry for several months during exceptionally dry years (Rosenshein and others, 1968, p. 27).

Iron and manganese concentrations exceeded SMCLs in water from some public-supply wells during 1987-88, and the sodium concentration in water from one public-supply well exceeded 20 milligrams per liter (B.F. Barrette, Rhode Island Department of Health, written commun., 1989). VOCs were detected in water from five public-supply wells during 1987-88.

The area around the Hunt ground-water reservoir includes dense commercial and residential areas as well as sparsely settled areas. Land-development pressures in the area are high, and continued development may affect the quality of water in the Hunt ground-water reservoir. At the downstream ends of the Hunt and Maskerchugg Rivers, saltwater intrusion is a potential problem.

The Annaquatucket-Pettaquamscutt Area

The Annaquatucket River flows southeastward into Narragansett Bay (fig. 42). The Annaquatucket ground-water reservoir is southwest of the Annaquatucket River in North Kingstown. The saturated thickness of stratified drift in most parts of this ground-water reservoir ranges from 60 to 80 feet (Rosenshein and others, 1968, pl. 3).

The yield of the Annaquatucket ground-water reservoir has been estimated at 3.6 million gallons per day (Rosenshein and others, 1968, p. 32). This estimate does not take into account possible effects on pond levels and on the low flow of the river during droughts. This rate of yield is close to the rate of recharge to the ground-water reservoir during dry years (Rosenshein and others, 1968, p. 31). Consequently, withdrawals at this rate would affect low streamflow in dry years.

The Mattatuxet River flows through Pausacaco Pond to the tidal Pettaquamscutt River, locally called the Narrow River. The Pettaquamscutt ground-water reservoir is near the Mattatuxet River and Pausacaco Pond, locally called Carr Pond, in North Kingstown (fig. 42). The saturated thickness throughout much of the ground-water reservoir is about 60 feet (Rosenshein and others, 1968, pl. 3). The greatest saturated thickness is along the southern edge of the ground-water reservoir, near the brackish Pettaquamscutt River. Development of large-capacity wells in this area may cause saltwater intrusion (Rosenshein and others, 1968, p. 34). The areas of highest transmissivity are underneath Pausacaco Pond (Rosenshein and others, 1968, p. 34).

The yield of the Pettaquamscutt ground-water reservoir has been estimated at 1.3 million gallons per day on the basis of estimated recharge to the drainage area of the ground-water reservoir during dry years (Rosenshein and others, 1968, p. 34). This estimate, like the yield estimate for the Annaquatucket ground-water reservoir, does not take into consideration possible effects on pond levels and on the low flow of the river during droughts. The North Kingstown Water Commission withdrew approximately 1.3 million gallons of water per day from the Annaquatucket and Pettaquamscutt ground-water reservoirs during 1985 (R.W. Bell, U.S. Geological Survey, written commun., 1985).

The entire area is underlain by crystalline bedrock. A layer of till that is generally less than 20 feet thick mantles the bedrock surface, and bedrock outcrops are numerous (Mason and Hahn, 1960; Hansen, 1962a, 1962b). Small waterfalls and rapids are common in areas where streams flow through narrow valleys in till or exposed bedrock.

Thin deposits of stratified drift fill some of the valleys. The saturated thickness of the stratified drift is less than 30 feet in most areas (Mason and Hahn, 1960; Hansen, 1962b), but in parts of the Moosup River valley in western Coventry, the saturated thickness is approximately 40 feet (Johnson and others, 1960). Stratified drift covers only 16 percent of the region, and there are no regionally significant stratified-drift aquifers.

The ground-water resources of this area are of great local importance. The entire area is dependent on private wells for drinking water, and the sparse development of the region (fig. 37) indicates that the widespread use of private wells is likely to continue. Wells withdraw water from stratified-drift, till, and bedrock aquifers.

Natural ground-water quality in this area of Rhode Island has not been investigated. A study of adjacent parts of the Quinebaug River basin in Connecticut indicates that the natural quality of ground water in the region is generally suitable for drinking and most other purposes. Wells are likely to yield soft water with dissolved-solids concentrations less than 100 milligrams per liter (Randall and others, 1966, p. 68). Undesirable concentrations of iron have been reported in some areas (Johnson and others, 1960; Hansen, 1962b).

The drainage areas of the Fivemile, Moosup, and Pachaug Rivers are among the least developed parts of Rhode Island (fig. 37). Ground-water quality in the region as a whole is not considered threatened (Rhode Island Department of Environmental Management, 1988, fig. 4-9, p. IV-43), and problems are likely to be localized near contaminant sources.

A hazardous-waste site in western Coventry is one of the State's eight "Superfund" sites (fig. 28). Illegal disposal of wastes--including PCBs, solvents, and other chemicals--has contaminated soil, surface water, and ground water; some private wells have been threatened (Rhode Island Department of Environmental Management, 1988, table 4-9, p. IV-19).

The West Bay Region

The west side of Narragansett Bay includes the drainage areas of several small coastal streams. The largest of these are the Hunt, Maskerchugg, Annaquatucket, and Mattatuxet Rivers (fig. 42). This region includes sparsely, moderately, and densely developed areas (fig. 37). Much of the area is served by public water supplies, but private wells in till, bedrock, and stratified drift provide drinking water for some residents.

The northwestern part of the West Bay region in East Greenwich and Warwick is characterized by till-covered bedrock hills 200 to 400 feet in altitude. The hills to the north and west form the drainage divide between the small coastal drainage basins to the east and the Pawtuxet and Pawcatuck River basins to the west. Tributary streams flow eastward from the till uplands towards the coastal lowlands.

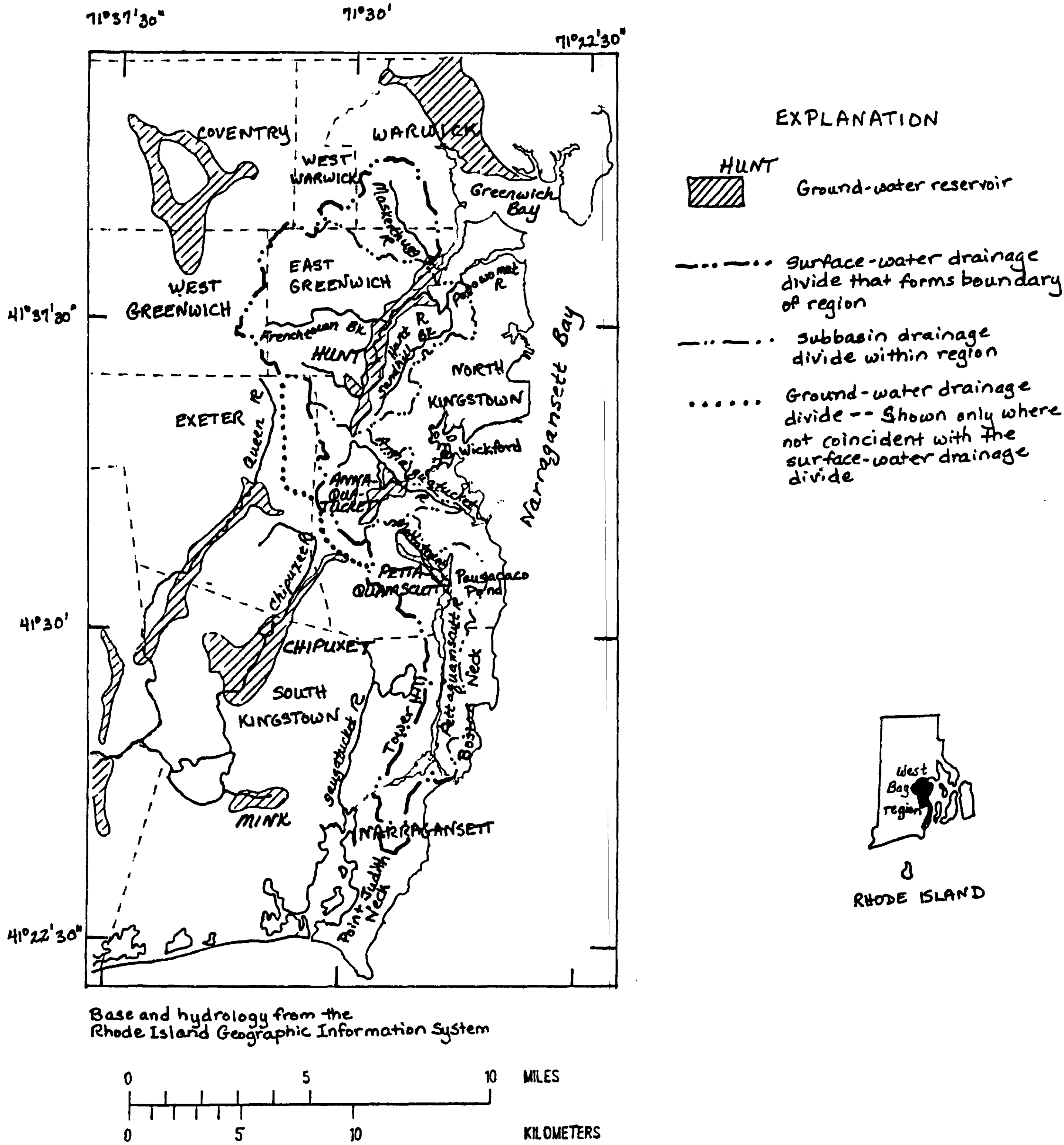


Figure 42.-- The West Bay region in south-central Rhode Island. (Sources: Ground-water-reservoir boundaries from W.B. Allen, Rhode Island Water Resources Board, written commun., 1978; modified by Rhode Island Department of Environmental Management, 1988. Ground-water drainage divides from Allen and others, 1966, pl. 3.)

South and west of the Mishnock ground-water reservoir, the RIWRB had proposed the construction of the Big River Reservoir, an impoundment that would inundate an area of several square miles along the Big, Carr, and Nooseneck Rivers (fig. 40). The USEPA prohibited construction of the project in 1990, after finding that it would result in unacceptable adverse effects to the aquatic environment (D.A. Thompson, U.S. Environmental Protection Agency, oral commun., 1991). The ground-water resources of the area have not been investigated extensively. Layers of fine sand are common, but some coarse materials are also present (Gonthier, 1966, table 3). Stratified-drift deposits are generally less than 50 feet thick (Frimpter, 1973b, p. 2-1). Near the Carr River at the southern end of the Mishnock ground-water reservoir, however, the saturated thickness is approximately 100 feet (Gonthier, 1966, table 2 and pl. 1).

Ground water from the Mishnock ground-water reservoir is used for public water supply by the Kent County Water Authority, which withdrew approximately 2.7 million gallons a day during 1985 (R.W. Bell, U.S. Geological Survey, written commun., 1989). Private wells are also widely used throughout the drainage basin of the South Branch Pawtuxet River.

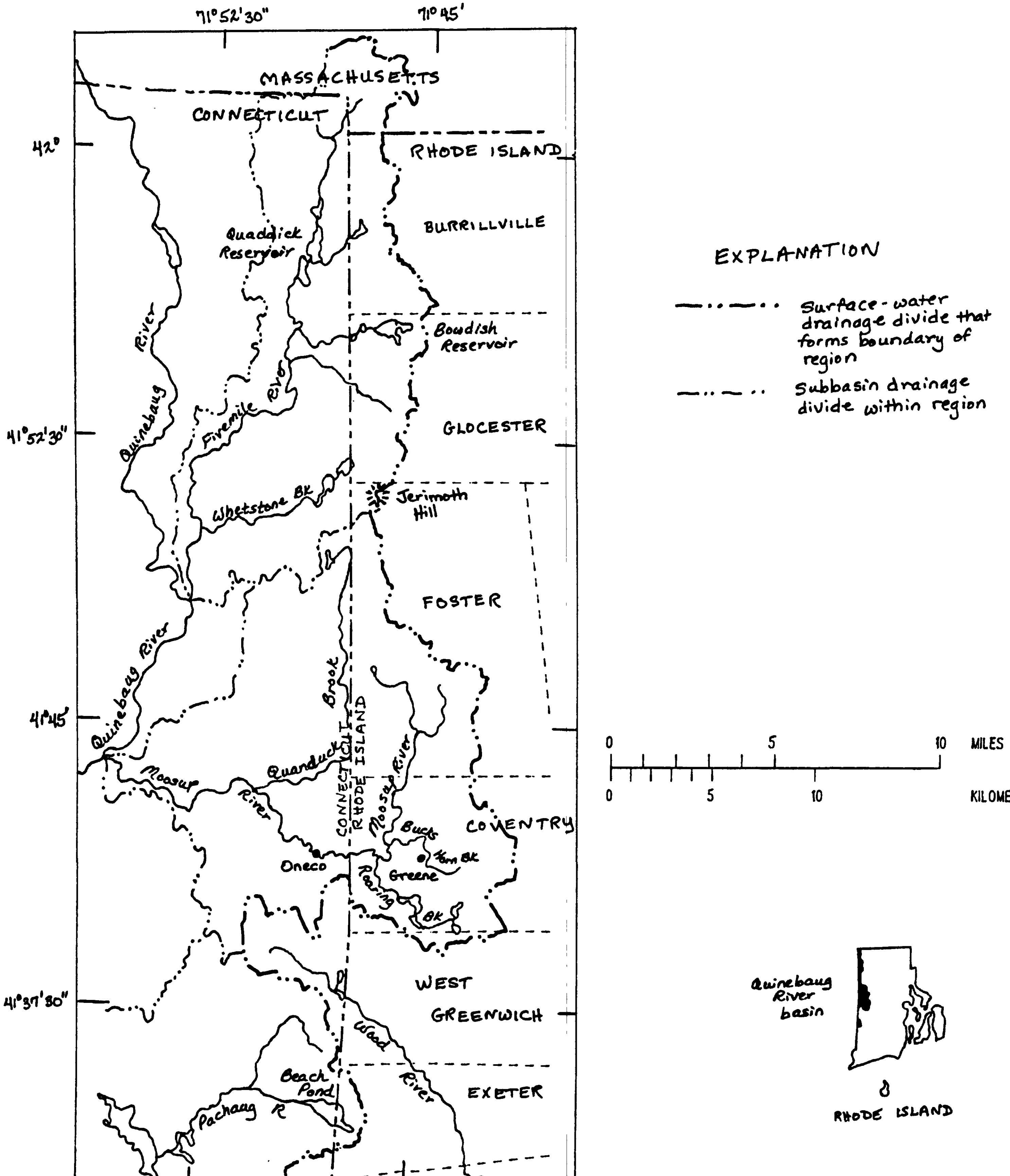
Ground water in the South Branch Pawtuxet basin is generally soft, and the concentration of dissolved solids is generally less than 100 milligrams per liter (Gonthier, 1966, table 5, p. 34). Iron and manganese concentrations exceed SMCLs in some areas (Gonthier, 1966, table 5, p. 34).

Large tracts of land that supply recharge to the Mishnock ground-water reservoir have been developed for residential, industrial, commercial, and transportation uses. Ground water within the South Branch basin has been contaminated by landfill leachate, industrial waste, and leaking underground storage tanks (fig. 28) (Rhode Island Department of Environmental Management, 1988, fig. 4-7, p. IV-30). A Kent County Water Authority well in Coventry was removed from service in 1985 because of contamination by the VOC tetrachloroethylene (Rhode Island Department of Environmental Management, 1988, table 4-2, p. IV-9).

The Quinebaug River Basin

Near Rhode Island's western boundary, an irregular line of high hills forms a north-south trending drainage divide between streams that flow generally eastward toward the Blackstone, Pawtuxet, and Pawcatuck Rivers and streams that flow generally westward into Connecticut (fig. 35). East of this drainage divide, ground water discharges to streams that eventually flow into Narragansett Bay or Block Island Sound. West of the drainage divide, ground water discharges to streams that flow into the Fivemile, Moosup, or Pachaug Rivers (figs. 35 and 41). These three rivers are tributaries of the Quinebaug River, a major stream in eastern Connecticut. The Quinebaug River is a branch of the Thames River, which flows into Long Island Sound (fig. 35).

The Quinebaug River basin encompasses about 61 square miles in Rhode Island. Summits of the steep-sided hills generally range from 600 to 750 feet above sea level. Jerimoth Hill, the highest hill in Rhode Island, is located in northwestern Foster (fig. 41). Its summit is 812 feet above sea level, and it forms part of the drainage divide between the North Branch Pawtuxet River to the east and the Fivemile River to the west.



Base and Rhode Island hydrology from the Rhode Island Geographic Information System. Connecticut hydrology from the Natural Resources Center, Connecticut Department of Environmental Protection

Figure 41.--The Quinebaug River basin in western Rhode Island.

The tidal Pettaquamscutt River occupies a narrow valley between Boston Neck and Tower Hill, two north-south trending hills of till-covered bedrock (fig. 42). The saturated thickness of stratified drift underlying and bordering the Pettaquamscutt River generally ranges from 60 to 100 feet (Hahn, 1959a; Johnson and Marks, 1959). Large ground-water withdrawals are likely to cause saltwater intrusion. Private wells serve some residents of this area. Water from wells tapping till and bedrock is reported to be moderately hard, with undesirable concentrations of iron in some areas (Hahn, 1959a).

The Bay Islands and East Bay Region

This region of the State includes the islands of Narragansett Bay and several towns on the east side of the Bay (fig. 43). The total land area is about 120 square miles. Low rolling hills with summits less than 300 feet in altitude form the landscape. Much of the land is less than 100 feet above sea level, and all parts of the region are within about 4 miles of saltwater. The coastline is irregular, and numerous bedrock outcrops line the shore. Large tracts of formerly rural and agricultural land in several communities have been developed as suburban residential and commercial areas (fig. 37).

Most of the area is underlain by the sedimentary and metamorphosed sedimentary rocks of the Narragansett Basin. Hanging Rock in Middletown is a locally well-known outcrop of one unit of this large and diverse group of rocks. The bedrock in most places is mantled by a layer of till that is derived primarily from Narragansett Basin rocks. The thickness of the till averages about 20 feet, but ranges from a few inches to as much as 100 feet (Schiner and Gonthier, 1965a; 1965b).

Only about 3 percent of this area is underlain by stratified drift (fig. 10) (Lang, 1961, p. 31). Most deposits are probably less than 25 feet thick (Schiner and Gonthier, 1965a; 1965b) and are in shoreline areas vulnerable to saltwater intrusion. Near the Sakonnet River at the northeastern end of Aquidneck Island, the stratified drift is more than 200 feet thick (Schiner and Gonthier, 1965b). Large ground-water withdrawals in this area are likely to cause saltwater intrusion.

Neither surface-water nor ground-water resources are abundant in this region. Drainage areas along the coast are small; consequently, their streams are also small. The till generally yields little water to wells because of its high clay content (Lang, 1961, p. 31-32).

The general direction of ground-water flow is from the hills toward the Sakonnet River, Narragansett Bay, Mount Hope Bay, or Rhode Island Sound. On the islands, ground water flows radially outward from the central uplands toward the shore.

No large public ground-water supplies have been developed in this region of the State. The Prudence Island Utilities Company supplies ground water to about 800 people on Prudence Island, which is part of the town of Portsmouth (figs. 3 and 43) (R.W. Bell, U.S. Geological Survey, written commun., 1989). All other public-supply systems obtain water from small surface-water sources within or near the region. Private wells, used in all the communities except Newport, withdraw water from till, bedrock, and stratified-drift aquifers. Of these aquifers, bedrock is considered the most reliable source of ground water, and well yields are commonly sufficient for domestic supplies (Schiner and Gonthier, 1965a; 1965b).

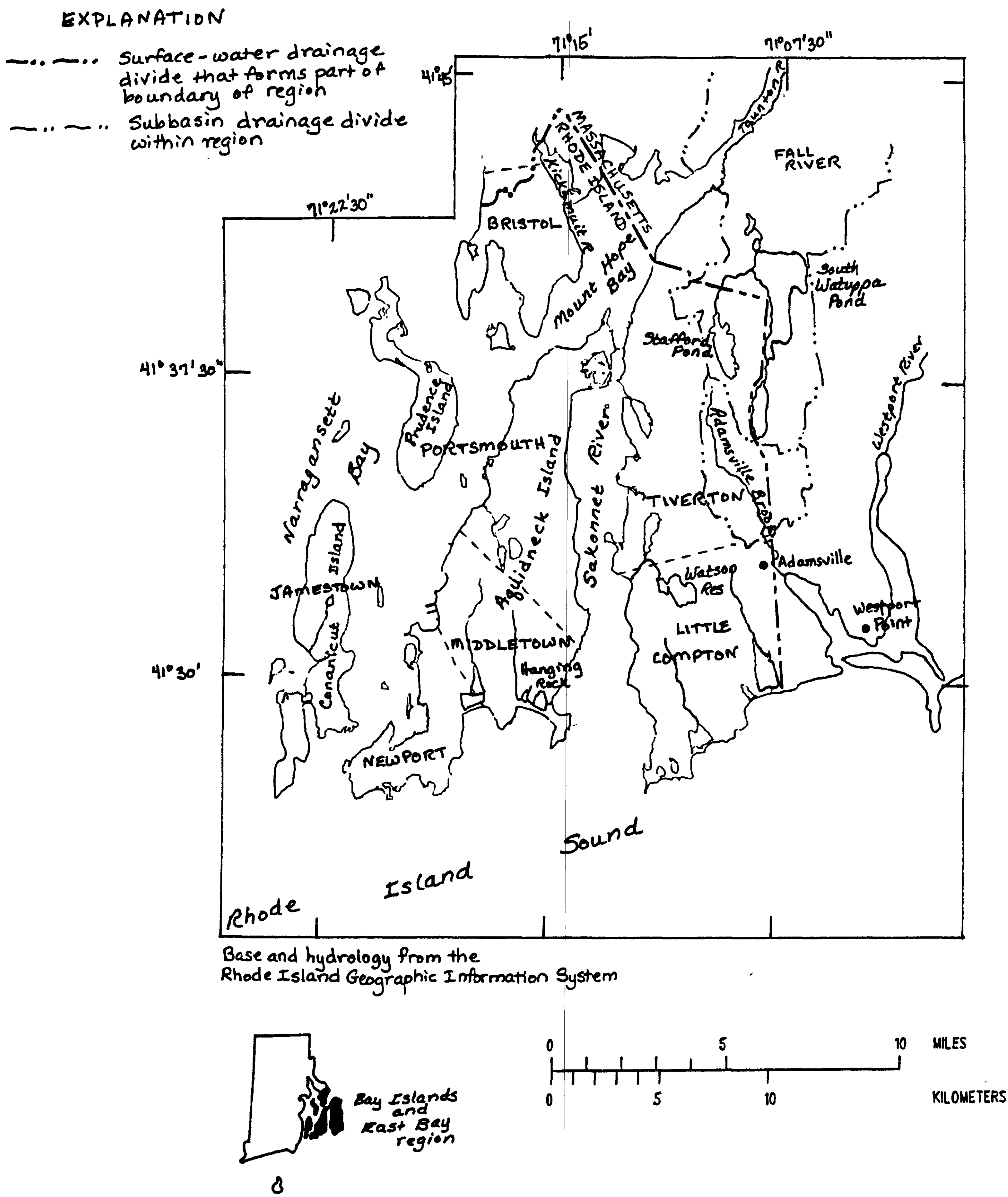


Figure 43.--The Bay Islands and East Bay region in southeastern Rhode Island.

Ground water from the till generally contains less mineral matter and is softer than water withdrawn from wells in bedrock. Iron concentrations greater than the SMCL of 0.3 milligram per liter have been measured in ground water at scattered locations throughout the region. An iron concentration of 4.6 milligrams per liter was measured in water from a bedrock well in Newport (Schiner and Gonthier, 1965a). Many of the wells yielding water with elevated iron concentrations penetrate the coal-bearing layers of the Narragansett Basin rocks (Schiner and Gonthier, 1965a; 1965b).

Saltwater intrusion has occurred in some locations near the shoreline (Schiner and Gonthier, 1965a; 1965b) and is a potential problem wherever wells are used in coastal areas. The quality of ground water has also been affected locally by bacteria and detergents, the pesticide aldicarb, landfill leachate, leaking petroleum and heating-oil tanks, chronic petroleum spills and leaks at a tank farm, road-salt storage facilities, and disposal areas at U.S. Department of Defense facilities (fig. 28) (Schiner and Gonthier, 1965a; 1965b; Rhode Island Department of Environmental Management, 1988, fig. 4-7, p. IV-30).

The small surface-water reservoirs used for public supply are fed in part by ground-water discharge. Consequently, the impairment of ground-water quality could also affect surface-water quality.

The Pawcatuck River Basin

The Pawcatuck River basin encompasses a total of 317 square miles, of which 254 square miles are southwestern Rhode Island and 63 square miles are in southeastern Connecticut (fig. 35 and 44). Major tributaries of the Pawcatuck River include the Chipuxet, Usquepaug-Queen, Beaver, and Wood Rivers. The Pawcatuck River basin is sparsely developed (fig. 37).

The northwestern part of the basin consists of forested and rural uplands. Steep-sided hills of bedrock or till-covered bedrock in western Rhode Island and eastern Connecticut rise 400 to 600 feet above sea level. Stream valleys are narrow, and stratified-drift deposits that underlie the larger valleys are long and sinuous.

In the eastern and southern parts of the basin, summits in the till uplands are generally 200 to 300 feet above sea level. Stream valleys are wide and flat or gently rolling and are underlain by extensive deposits of stratified drift. Farmland dominates these wide valleys. Large swamps border the streams in some areas. The principal areas underlain by stratified drift are generally less than 100 feet above sea level. The hummocky terrain of the Charlestown moraine (fig. 44) forms the southern drainage divide of the basin. Altitudes along this divide generally are in the range of 100 to 200 feet.

Thick deposits of coarse-grained stratified drift are present along the Pawcatuck River and its tributaries. The thickest deposits fill deep preglacial valleys in the bedrock surface. Of the 21 areas designated as ground-water reservoirs by the RIWRB, 9 are located within this river basin (figs. 13 and 44).

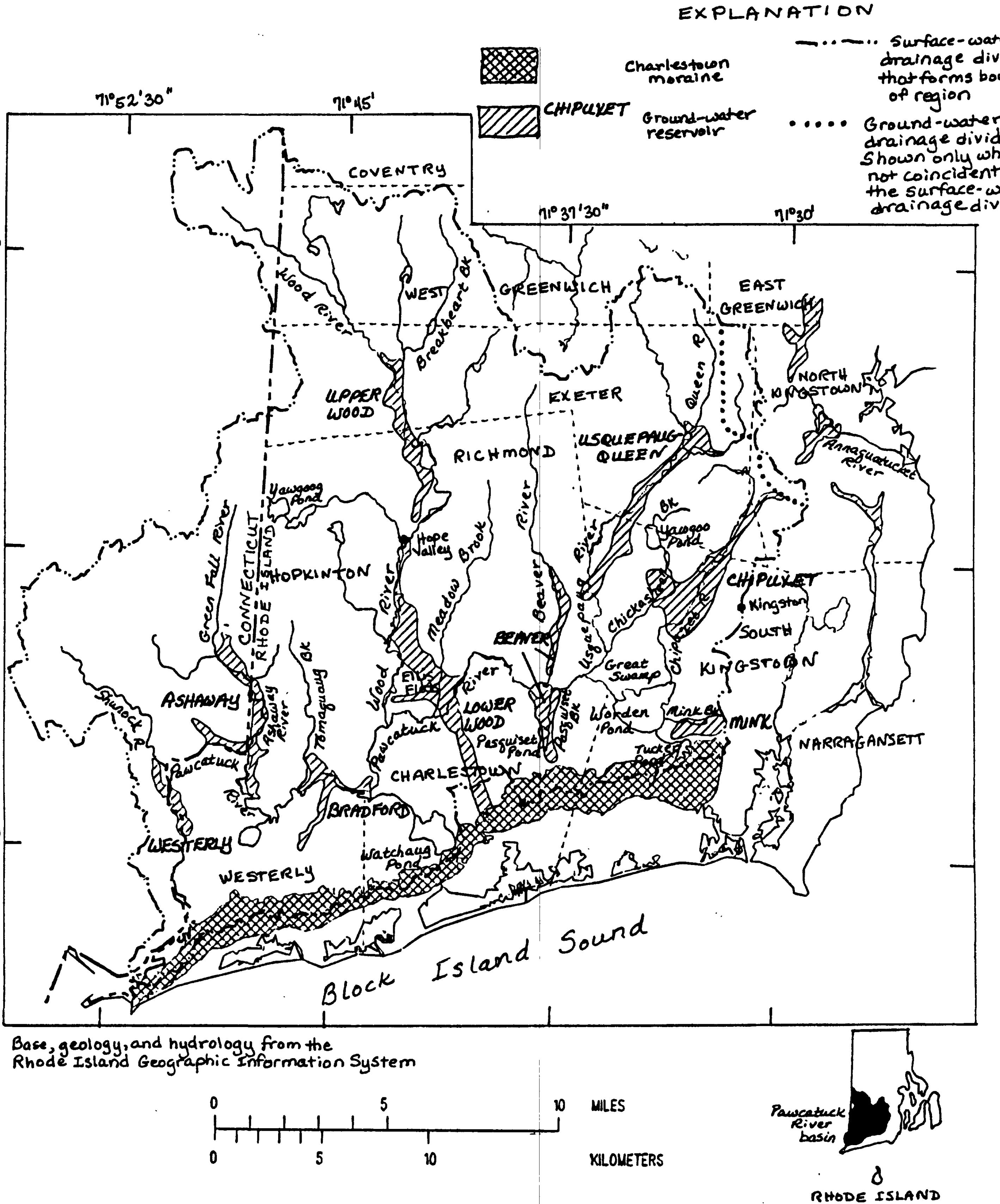


Figure 44.--The Pawcatuck River basin in southwestern Rhode Island. (Sources: Charlestown moraine from Bierschenk, 1956, pl. 1; LaSala and Hahn, 1960; LaSala and Johnson, 1960; Johnson, 1961b. Ground-water-reservoir boundaries from W.B. Allen, Rhode Island Water Resources Board, written commun., 1978; modified by Rhode Island Department of Environmental Management, 1988. Ground-water drainage divides from Allen and others, 1966, pl. 3.)

Most residents of the Pawcatuck River basin use ground water as their drinking-water source, either from public supplies or from private wells (fig. 3). The major public-supply systems within the basin withdrew 5.7 million gallons of ground water per day during 1985, more than one-third of the ground water withdrawn for public supply in the State (R.W. Bell, U.S. Geological Survey, written commun., 1989). Some of this water was exported from the Pawcatuck basin.

Ground water is unconfined throughout most of the basin. Semiconfined conditions occur locally within the stratified-drift aquifers where there are lenses of silt and clay. Streambeds throughout much of the basin are composed of loosely packed sand and gravel. As a result, large-capacity wells near streams and ponds easily induce surface water into the stratified-drift aquifer.

The abundant ground-water resources in the Pawcatuck River basin exceed the foreseeable demand for water within the basin. State agencies have considered proposals to export water from the basin to communities with inadequate water resources (Johnston and Dickerman, 1985, p. 5). If ground water is withdrawn, used, and disposed of locally, the effects on the flow of nearby streams may be minimal. However, exporting large volumes of ground water could substantially reduce or eliminate streamflow along some tributary streams for significant periods of time (Johnston and Dickerman, 1985, p. 5).

The stratified-drift aquifers in the Pawcatuck River basin have been collectively designated a sole source aquifer by the USEPA (U.S. Environmental Protection Agency, 1988b, p. 17108-17109). An area totaling 295 square miles in Rhode Island and Connecticut has been designated as the Pawcatuck Basin Aquifer System. This area includes the valley aquifers and their upland recharge areas. The designation recognizes the importance of ground water in the region and provides some support for ground-water protection.

The quality of ground water in most areas of the Pawcatuck River basin is suitable for drinking and most other uses. The ground water is generally soft and slightly acidic, and dissolved-solids concentrations are generally less than 100 milligrams per liter. Concentrations of iron and manganese, usually from natural sources, exceed SMCLs in some areas (tables 2 and 4).

Ground-water quality in some parts of the Pawcatuck River basin has been degraded by nitrate, the pesticide aldicarb, and other constituents. Although the concentration of nitrate in ground water of the Pawcatuck River basin is generally below the MCL of 10 milligrams per liter, this level is exceeded in some areas. Nitrate concentrations below the MCL but above presumed natural levels are fairly common and indicate low-level degradation of ground-water quality. Aldicarb has not been registered for use in Rhode Island since December 1, 1985 (Rhode Island Department of Environmental Management, 1988, p. IV-36). Concentrations of this pesticide in ground water are expected to decline gradually. Landfills, industrial-waste sites, leaking underground storage tanks, and road salt have also contaminated ground water in a few relatively small areas within the basin (fig. 28).

The Main Stem of the Pawcatuck River

Before glaciation, streams in the area of the Pawcatuck River basin carved north-south trending channels in the bedrock surface as they flowed south into Block Island Sound. As the most recent ice sheet melted, its margin stalled for a long period of time, perhaps several hundred years, a few miles inland from the present-day coastline of Rhode Island (Stone and Borns, 1986, chart 1). Thick sediments accumulated along the ice margin and formed the Charlestown moraine (figs. 14 and 44). This moraine blocked the southward flow of streams after the glacier's margin had retreated northward, and glacial lakes formed north of the moraine. The Great Swamp and Worden Pond, the largest natural pond in the State, are remnants of a larger glacial lake and are underlain by the fine sand, silt, and clay deposited in the lake. Eventually, drainage outlets to the west opened, and the glacial lakes drained. Streamflow toward the south, still blocked by the natural dam of the moraine, was diverted to the west, and the main stem of the Pawcatuck River was formed (fig. 44).

Thick stratified-drift deposits along and near the main stem of the Pawcatuck River form the Westerly, Ashaway, and Bradford ground-water reservoirs (fig. 44). Local ground-water withdrawals in these areas are not expected to affect the low flow of the Pawcatuck River significantly. However, if all the ground-water reservoirs within the Pawcatuck River basin are fully exploited, and the water withdrawn is exported from the basin, the low flow along the main stem of the Pawcatuck River will be significantly affected (Gonthier and others, 1974, p. 32).

The Westerly area

The Westerly ground-water reservoir is located at the downstream end of the Pawcatuck River (fig. 44). The northern end of the ground-water reservoir is in Connecticut. From there the ground-water reservoir extends southward and southeastward along the Pawcatuck River, which forms the boundary between Rhode Island and Connecticut in this area. The maximum saturated thickness of deposits along this reach of the Pawcatuck River is 60 to 80 feet (Gonthier and others, 1974; Melvin, 1974; Johnson, 1961a).

Public-supply wells for the town of Westerly tap the Westerly ground-water reservoir and induce infiltration from the Pawcatuck River. During 1985, public-supply wells withdrew approximately 2.3 million gallons per day from the ground-water reservoir (R.W. Bell, U.S. Geological Survey, written commun., 1989). Ground-water withdrawals of this magnitude would not significantly affect the low flow of the Pawcatuck River in this area.

The yield of the Westerly ground-water reservoir, based on data from the Connecticut side of the Pawcatuck River, has been estimated at 7.2 million gallons per day (Melvin, 1974, sheet 4). Virtually all of this yield would be derived from recharge induced into the aquifer from the Pawcatuck River. The average discharge of the Pawcatuck River at Westerly was 377 million gallons per day for water years 1942-84, and the lowest recorded daily discharge was 16 million gallons per day on August 17, 1941 (Gadoury and others, 1986, p. 89).

Land in the vicinity of the Westerly ground-water reservoir is urbanized (fig. 37). A public-supply well for the town of Westerly was removed from service in 1986 because of contamination from petroleum hydrocarbons (Rhode Island Department of Environmental Management, 1988, table 4-2, p. IV-9). Land-use and waste-disposal practices throughout the Pawcatuck River basin affect the quality of surface water at the downstream end of the river. Surface-water quality has the potential to affect the quality of water withdrawn from wells that induce infiltration from the Pawcatuck. Saltwater intrusion is also a potential problem at the southern end of the ground-water reservoir, where there is a transition from the freshwater of the river to the brackish water of its coastal estuary.

The Ashaway area

The Ashaway ground-water reservoir is composed of stratified drift that fills a north-south trending bedrock valley near the western border of Rhode Island (fig. 44). The Pawcatuck River flows northward across these deposits before turning to the west toward Connecticut. The Ashaway River flows southward across the deposits and joins the Pawcatuck River. Near the upstream end of the Ashaway River, the ground-water reservoir extends northwestward into Connecticut. An arm of the ground-water reservoir extends westward along the Pawcatuck River where the river turns to the west. Along this reach of the river, the ground-water reservoir is partly in Connecticut and partly in Rhode Island.

The saturated thickness of the stratified drift is as much as 100 feet along the axis of the north-south trending buried valley (Gonthier and others, 1974, p. 29). The saturated thickness is less along the east-west arm of the ground-water reservoir.

The yield of the Ashaway ground-water reservoir in Rhode Island is estimated at approximately 10 million gallons per day (Gonthier and others, 1974, p. 37). Withdrawals at this rate are expected to have relatively little effect on the natural low flow of the Pawcatuck River. The withdrawals would substantially reduce the low flow of the Ashaway River, however, and could cause it to go dry during droughts (Gonthier and others, 1974, p. 29-30). The yield in the Connecticut parts of the ground-water reservoir, where the stratified drift is thinner and less permeable, has been estimated at 700,000 gallons per day (Melvin, 1974, sheet 3). The Ashaway ground-water reservoir is not currently (1989) used for public supply.

The Bradford area

The Bradford ground-water reservoir is an irregularly shaped body of stratified drift, composed largely of sand and gravel, that extends along and south of the Pawcatuck River in Hopkinton and Westerly (fig. 44). Public-supply wells for the town of Westerly withdrew approximately 320,000 gallons of water per day from this ground-water reservoir during 1985 (R.W. Bell, U.S. Geological Survey, written commun., 1989).

The thickest and most permeable stratified drift in the ground-water reservoir fills a preglacial bedrock channel that extends southwest from the Pawcatuck River. A yield of 1.3 million gallons per day has been estimated for this part of the ground-water reservoir (Gonthier and others, 1974, p. 28). The saturated thickness along the Pawcatuck River is only about 45 feet, and the transmissivity is only moderate (Gonthier and others, 1974,

p. 27). Development of a large water supply is possible in this area if specialized techniques are used to induce infiltration from the Pawcatuck River (Gonthier and others, 1974, p. 38).

The Wood River Basin

The Wood River is the largest tributary of the Pawcatuck River. The headwaters of the Wood River are in Connecticut and in the western part of West Greenwich, Rhode Island (fig. 44). Stratified drift underlies the valley of the Wood River and its major tributaries. Two thick, highly permeable areas of this stratified drift have been designated as the Upper Wood and Lower Wood ground-water reservoirs.

The upper Wood River area

The upper Wood River area includes the drainage basin of the Wood River upstream from the village of Hope Valley (fig. 44). Much of the area is wooded, rural, and undeveloped. Residents obtain their drinking water from private wells.

The Upper Wood ground-water reservoir extends along or near the Wood River in the towns of Exeter, Richmond, and Hopkinton (fig. 44). This ground-water reservoir is about 7 miles long and as much as 4,000 feet wide (Gonthier and others, 1974, p. 24). The saturated thickness of the stratified drift exceeds 120 feet in some areas near the river.

The yield of the Upper Wood ground-water reservoir has been estimated at 9.6 million gallons per day (Gonthier and others, 1974, p. 24). Withdrawals of this magnitude would reduce the flow of the Wood River near Hope Valley by about 50 percent when streamflow equals the 90-percent duration flow, that is, the discharge that is equaled or exceeded 90 percent of the time under natural conditions (Gonthier and others, 1974, p. 24). Effects on lower flows would be greater. The minimum recorded daily discharge of the Wood River at Hope Valley was 6.5 million gallons per day on October 13, 1941 (Gadoury and others, 1986, p. 84). The estimated yield of the ground-water reservoir exceeds stream discharge under drought conditions. Consequently, withdrawals of this magnitude could cause some reaches of the river to go dry during prolonged droughts (Gonthier and others, 1974, p. 37). A detailed study is currently (1991) estimating yields for the Upper Wood ground-water reservoir under various hydrologic conditions, based on new saturated thickness and transmissivity data (D.C. Dickerman, U.S. Geological Survey, oral commun., 1991).

The Upper Wood ground-water reservoir is considered an important potential source of drinking water. Much of its drainage area is undeveloped, and the State owns a large part of the land overlying the stratified-drift aquifer and its recharge areas. The Richmond Water Supply System withdrew only 7,000 gallons of water per day from the ground-water reservoir in 1985 (R.W. Bell, U.S. Geological Survey, written commun., 1989).

Ranges of common constituents and properties of water in the Upper Wood ground-water reservoir are shown in table 2 (D.C. Dickerman, U.S. Geological Survey, written commun., 1989). The water is soft and somewhat acidic and pH ranges from 5.5 to 6.9. Concentrations of nitrate (as N) were less than or equal to 0.1 milligram per liter in at least half of the samples analyzed (table 2). Iron and manganese, presumably from natural sources, exceeded SMCLs in some areas.

Although no ground water in Rhode Island is totally unaffected by human activities, the quality of water in the Upper Wood ground-water reservoir is probably representative of uncontaminated ground water in areas of Rhode Island where stratified drift is underlain by crystalline bedrock (Johnston and Barlow, 1988, p. 443). Four wells in the Upper Wood ground-water reservoir were each sampled once during the period 1980-85 for 9 trace metals, 2 trace nonmetals, and 21 to 28 synthetic organic chemicals, including VOCs, trihalomethanes, solvents, and chlorinated hydrocarbon pesticides (Dickerman and others, 1989, table 18c-d, p. 265-266). Barium was detected in water from three wells at concentrations of 0.03 microgram per liter or less, well below the MCL of 1 milligram per liter (table 3). None of the other trace elements or synthetic organic chemicals were detected.

The lower Wood River area

The lower Wood River area includes the drainage area of Meadow Brook and the drainage area of the Wood River from the village of Hope Valley south to its junction with the Pawcatuck River (fig. 44). Thick deposits of saturated stratified drift underlie a 3-mile-wide lowland that extends across the valleys of the Wood River, Meadow Brook, and the Pawcatuck River. Much of the area is woodland or abandoned pastureland. Private wells supply homes, schools, and industries.

The Lower Wood ground-water reservoir underlies an area of approximately 8 square miles near Meadow Brook, the Pawcatuck River, and the Wood River (fig. 44). Some reaches of Meadow Brook naturally lose water to the underlying ground-water reservoir (Dickerman and others, 1990, p. 23).

The thickest deposits of stratified drift in the ground-water reservoir fill the preglacial bedrock channel of the Wood River. The outline of the Lower Wood ground-water reservoir shows the approximate location of this deep bedrock valley where it trends southeastward from the river's present course (fig. 44). The buried valley continues toward the southeast underneath the Charlestown moraine and extends to Block Island Sound (Gonthier and others, 1974, p. 26). The stratified drift in the Ellis Flats area has a maximum known saturated thickness of more than 290 feet (Dickerman and others, 1990, p. 14). Elsewhere, the saturated thickness averages about 70 feet. No major confining layers have been found in the ground-water reservoir.

The most favorable areas for ground-water development are along the Wood River, Meadow Brook, and Meadow Brook Pond, and in the area of Ellis Flats (fig. 44). It has been estimated that 36 to 43 percent of the water that could be withdrawn by high-capacity wells in these locations would be derived from induced infiltration of surface water (Dickerman and others, 1990, table 15, p. 87).

Simulations have been made with a ground-water-flow model of the Lower Wood ground-water reservoir to estimate its yield under various conditions. Results indicate a maximum potential yield of 11 million gallons of water per day from several well sites under conditions of average recharge (Dickerman and others, 1990, p. 97). This estimate includes the use of three potential well sites with known ground-water-quality problems. If these three sites cannot be used for drinking water, the maximum estimated yield under long-term average recharge conditions is approximately 6 to 8 million gallons per day. Withdrawals from all sites considered would have to be less than 6 million gallons per day during extreme drought to maintain streamflow in Meadow Brook.

All of the pumping simulations conducted for the Lower Wood ground-water reservoir were based on the assumption that the withdrawals would be exported from the basin and used elsewhere. This assumption means that ground-water discharge to streams is significantly reduced, and the total amount of ground-water withdrawn is limited by minimum streamflow requirements. Higher total yields than those estimated may be possible if the ground water is used within the basin and is returned to streams or the ground within the basin. However, the quality of the water returned after use will be changed.

Water quality in the Lower Wood ground-water reservoir is generally suitable for most purposes. The water is soft and slightly acidic, and typically has a dissolved-solids concentration of less than 100 milligrams per liter (Dickerman and others, 1990, table 4, p. 35). Some promising well sites may be of limited use because of high concentrations of natural constituents in the ground water or because of contamination from land-use and waste-disposal activities.

Concentrations of iron and manganese exceed SMCLs (table 4) in some areas. Ground-water samples obtained near Meadow Brook had concentrations of iron and manganese as high as 17 milligrams per liter and 2.11 milligrams per liter, respectively (Dickerman and others, 1990, table 5, p. 39).

Aldicarb, a carbamate pesticide, was first detected in Rhode Island's ground water in 1983, when the U.S. Geological Survey tested ground water near a potato field north of Ellis Flats for several pesticides (Dickerman and others, 1990, p. 43; table 7, p. 47). Aldicarb concentrations in water from some test wells exceeded the Proposed MCLG of 0.009 milligram per liter (U.S. Environmental Protection Agency, 1985, p. 46986). This finding led to statewide testing for aldicarb by the Rhode Island Department of Health. Two other carbamate pesticides, carbofuran and oxamyl, also were detected at the sampling site.

An area of the Lower Wood ground-water reservoir south of the Pawcatuck River has been contaminated by radionuclides, nitrate, metals, and elevated concentrations of common cations and anions from a liquid industrial waste-disposal site (Ryan and Kipp, 1985). The plume of contaminated ground water was 2,300 feet long, 300 feet wide, and as much as 80 feet deep in 1982 (fig. 33) (Ryan and Kipp, 1985, p. 29). Contamination from radionuclides at this site has rendered water in part of the ground-water reservoir unusable, probably for at least a decade (Kipp and others, 1986, p. 529). Decontamination will take place slowly as the radionuclides decay and as uncontaminated recharge gradually replaces the contaminated ground water that discharges to the Pawcatuck River.

The Beaver River and Pasquiset Brook Basins

The Beaver River flows southward through Richmond and Pasquiset Brook flows northward through Charlestown to the Pawcatuck River (fig. 44). These two streams follow a north-south trending valley underlain by stratified drift. The valley is narrow in the north along the Beaver River and wider in the south near Pasquiset Brook and Pasquiset Pond. Most of the drainage area of these two streams is covered by woodland or abandoned pastureland.

The Charlestown moraine south of Pasquiset Pond forms the surface-water drainage divide between the Pawcatuck River basin and the small coastal streams to the south (fig. 44). Ground-water and surface-water drainage divides do not coincide along this part of the moraine. The ground-water divide is approximately 3,000 feet north of the surface-water divide (Dickerman and Ozbilgin, 1985, p. 5).

Residents, commercial establishments, and industries obtain water from private wells. Domestic wells tap bedrock, till, and stratified-drift aquifers, as well as the mixed till and stratified drift of the Charlestown moraine.

The Beaver ground-water reservoir extends along the Beaver River and Pasquiset Brook and has a total area of about 5 square miles (fig. 44) (Dickerman and Ozbilgin, 1985, p. 7). The stratified drift in the ground-water reservoir is composed primarily of sand and gravel. Layers of fine-grained sediment are not extensive, and ground water is generally unconfined. Locally, lenses of fine sand, silt, and clay may create semiconfined conditions. The saturated thickness of the stratified drift averages 60 to 80 feet, and the maximum known thickness is 120 feet (Dickerman and Ozbilgin, 1985, p. 15). Extensive swamps in the Pasquiset Brook valley have limited test drilling in that area.

The areas most favorable for development of high-capacity wells are along the Beaver River and near Pasquiset Pond. The streambeds of the Beaver River and Pasquiset Brook are primarily composed of loosely packed sand and gravel. Induced recharge from the Beaver River and Pasquiset Pond would supply most of the water withdrawn from high-capacity wells tapping this ground-water reservoir (Dickerman and Ozbilgin, 1985, p. 36). Pumping rates during dry periods would be limited by the effect on streamflow and pond levels.

A ground-water-flow model has been used to estimate the potential yield of the Beaver ground-water reservoir. Results indicate that the ground-water reservoir can yield 4.25 million gallons per day with minimal impact on streamflow, pond levels, and ground-water levels during years of average or above average recharge (Dickerman and Ozbilgin, 1985, p. 94). Withdrawals would probably have to be less than 3.25 million gallons per day during periods of extreme drought, such as occurred during the early 1960's, to maintain some streamflow in the Beaver River and Pasquiset Brook (Dickerman and Ozbilgin, 1985, p. 94).

The quality of ground water in the stratified drift is generally suitable for most purposes. Concentrations of iron and manganese are generally below the SMCLs for these constituents (table 4). Southeast of Pasquiset Pond, an iron concentration of 7.5 milligrams per liter and a manganese concentration of 3.7 milligrams per liter have been measured in water from a test well (Dickerman and Ozbilgin, 1985, p. 38). Ground water in this area would have to be treated to remove iron and manganese in order for it to be used for public supply. Nitrate concentrations in water from selected wells are below the MCL of 10 milligrams per liter (table 3) and have a median value of 0.20 milligram per liter (Dickerman and Ozbilgin, 1985, p. 38). Nitrate concentrations approaching the MCL have been measured in water from two wells downgradient from agricultural fields (Dickerman and Ozbilgin, 1985, p. 38).

The Usquepaug-Queen River Basin

The Queen River originates in the northeastern part of the Pawcatuck River basin and flows generally southward and southwestward (fig. 44). At its downstream end, the river is known as the Usquepaug River. The Usquepaug River flows through the Great Swamp and into the main stem of the Pawcatuck River.

Coarse-grained deposits of saturated stratified drift that underlie the valley of the Usquepaug-Queen River for a distance of approximately 6 miles form the Usquepaug-Queen ground-water reservoir (Allen and others, 1966). In a large part of this ground-water reservoir, the saturated thickness of the stratified drift equals or exceeds 100 feet (Allen and others, 1966, pl. 2). The Usquepaug-Queen ground-water reservoir extends from Exeter southwestward through South Kingstown and into Richmond (fig. 44). The stratified drift south of this area grades into the fine-grained glacial-lake sediments of the Worden Pond area.

Land in the vicinity of the Usquepaug-Queen ground-water reservoir is mostly undeveloped, and ground water is not used for public supply. The ground-water reservoir has not been extensively investigated.

The estimated yield of the Usquepaug-Queen ground-water reservoir is approximately 17 million gallons per day (Allen and others, 1966, p. 48). Ground-water withdrawals of this magnitude would cause streams flowing across the ground-water reservoir to go dry for periods ranging from several days to a month or more during the growing season each year (Allen and others, 1966, p. 62).

The Chipuxet River and Chickasheen Brook Basins

The Chipuxet River and Chickasheen Brook are small tributaries at the eastern end of the Pawcatuck River basin (fig. 44). Stratified drift fills narrow valleys between gently rolling, till-covered bedrock hills in the northern parts of these drainage basins. The underlying bedrock is crystalline. Till in the basin is sandy and generally contains only a small proportion of clay. The thickness of the till ranges from a few inches to 100 feet, and the average thickness is about 20 feet (Johnston and Dickerman, 1985).

At the northeastern end of the Chipuxet River basin, the surface-water drainage divide between the Chipuxet River basin and the Annaquatucket River basin crosses a wide area of stratified drift. The ground-water drainage divide in this area is 2,000 to 4,000 feet southwest of the surface-water drainage divide (fig. 44). Within this part of the surface-drainage area of the Chipuxet River, ground water flows northeastward into the Annaquatucket River basin.

The valleys of the Chipuxet River and Chickasheen Brook widen toward the south and merge in a flat plain underlain by thick deposits of stratified drift. Some reaches of Chickasheen Brook are naturally losing where the stream flows across the stratified drift (Johnston and Dickerman, 1985, p. 10). This broad, flat plain extends from Yawgoo Pond south to Worden Pond and the Great Swamp, broken here and there by till-covered bedrock hills.

The Chipuxet ground-water reservoir (fig. 44) is composed of thick, highly permeable stratified drift that fills preglacial valleys cut in the bedrock surface. The upper layers of stratified drift are generally coarser than the lower layers. Ground water is unconfined in much of the aquifer, although it is semiconfined where lenses of coarse sand and gravel underlie lenses of fine-grained sediment (Johnston and Dickerman, 1985, p. 28-29). The saturated thickness of the stratified drift is as much as 200 feet near the southern end of the ground-water reservoir (Johnston and Dickerman, 1985, p. 29). The saturated thickness exceeds 100 feet in large parts of the ground-water reservoir.

Private wells supply water for drinking, commercial and industrial uses, and irrigation in some parts of the Chipuxet River and Chickasheen Brook drainage basins. Public-supply wells for the Kingston Fire District and the University of Rhode Island withdrew approximately 700,000 gallons of water per day from the Chipuxet ground-water reservoir during 1985 (R.W. Bell, U.S. Geological Survey, written commun., 1989). By 1988, the average daily withdrawal totaled approximately 1 million gallons (H.H. Meyer, Kingston Fire District, Water Department, and C.L. Jones, University of Rhode Island, Physical Plant, oral commun., 1988).

Much of the ground water withdrawn from the Chipuxet ground-water reservoir is exported from the drainage basin after use through the South Kingstown-Narragansett regional sewer system, which discharges to Narragansett Bay (fig. 42) (Johnston and Dickerman, 1985, p. 8). It has been estimated that continuous withdrawal and export of ground water at a rate of 3 million gallons a day would cause periods of no streamflow on the Chipuxet River (Johnston and Dickerman, 1985, p. 93-94).

The Great Swamp and Worden Pond, to the south of the Chipuxet ground-water reservoir (fig. 44), are underlain by fine-grained glacial-lake deposits. These deposits contain a large volume of water but have low permeability. The transition from coarse-grained stratified-drift deposits in the north to fine-grained deposits in the south is gradational and is characterized by interfingering of coarse- and fine-grained lenses.

The common chemical constituents and physical properties of ground water in and near the Chipuxet ground-water reservoir have been summarized by Johnston and Dickerman (1985, p. 53). Natural concentrations of iron and manganese in ground water exceed SMCLs locally (table 4). The extent of elevated iron concentrations is uncertain (Johnston and Dickerman, 1985, p. 60-61). Manganese concentrations that exceed the SMCL of 0.05 milligram per liter (table 4) have been measured in water from all three public-supply wells for the University of Rhode Island (Johnston and Dickerman, 1985). Silvey and Johnston (1977) conclude that the elevated manganese concentrations are derived from manganese coatings on aquifer materials. As wells induce surface water into the aquifer, dissolved oxygen is consumed by decomposing organic matter on the bottom of the Chipuxet River and a small pond along the river. The resulting change in redox potential promotes the solution of manganese oxides that coat aquifer grains.

Agricultural land overlies much of the stratified-drift aquifer. Potato farms and turf farms are common. Nitrate concentrations exceed presumed background levels in many parts of the aquifer, but concentrations are generally below the MCL of 10 milligrams per liter (table 3) (Johnston and Dickerman, 1985, p. 2). The principal source of the nitrate appears to be fertilizer applied to agricultural land (Johnston and Dickerman, 1985).

The pesticide aldicarb was detected in water from a University of Rhode Island well in 1984 at a concentration of 0.006 milligram per liter (6 micrograms per liter) (Rhode Island Department of Health, written commun., 1984). The concentration of the pesticide was below the Proposed MCLG of 0.009 milligram per liter (U.S. Environmental Protection Agency, 1985, p. 46986).

The Mink Brook Basin

Mink Brook is a small stream east of Worden Pond, just north of the Charlestown moraine (fig. 44). The Mink ground-water reservoir is a small body of saturated coarse-grained stratified drift near Mink Brook. This ground-water reservoir is bounded on the north and south by poorly sorted moraine deposits and on the west by fine-grained glacial-lake sediments (Allen and others, 1966, pl. 2). Saturated thickness of the stratified drift in the ground-water reservoir ranges from 50 to 100 feet (Allen and others, 1966, pl. 2).

The Wakefield Water Company withdrew 2.4 million gallons of water per day from the ground-water reservoir during 1985 to supply parts of South Kingstown and Narragansett (R.W. Bell, U.S. Geological Survey, written commun., 1989). This water is exported from the Pawcatuck basin into coastal drainage areas on Narragansett Bay and Block Island Sound (figs. 42 and 44).

The small size of the ground-water reservoir and the small amount of surface water available for induced infiltration limit the potential for ground-water development. The yield of the Mink ground-water reservoir has not been estimated.

The quality of water in the Mink ground-water reservoir has been affected by agricultural land use. A Wakefield Water Company well was removed from service in 1984 after an aldicarb concentration of 0.013 milligram per liter was detected in the water (Rhode Island Department of Environmental Management, 1988, table 4-2, p. IV-9). This concentration exceeded the Proposed MCLG of 0.009 milligram per liter (U.S. Environmental Protection Agency, 1985, p. 46986).

The South Coastal Region

This region includes Block Island and coastal areas in southwestern Rhode Island that drain into Block Island Sound and Rhode Island Sound (fig. 45). Ground water from private wells, small public-water systems, or major public-supply systems provides most of the drinking water for the region. Urbanized land in the South Coastal region is concentrated near the shore (fig. 37).

The water table along the shore is only a few feet above sea level. Saltwater intrusion is a potential problem anywhere along the shoreline in this area whether the underlying material consists of bedrock, till, stratified drift, or mixed deposits. Salty or brackish water has been reported from a number of wells near the shore (Bierschenk, 1956, p. 26).

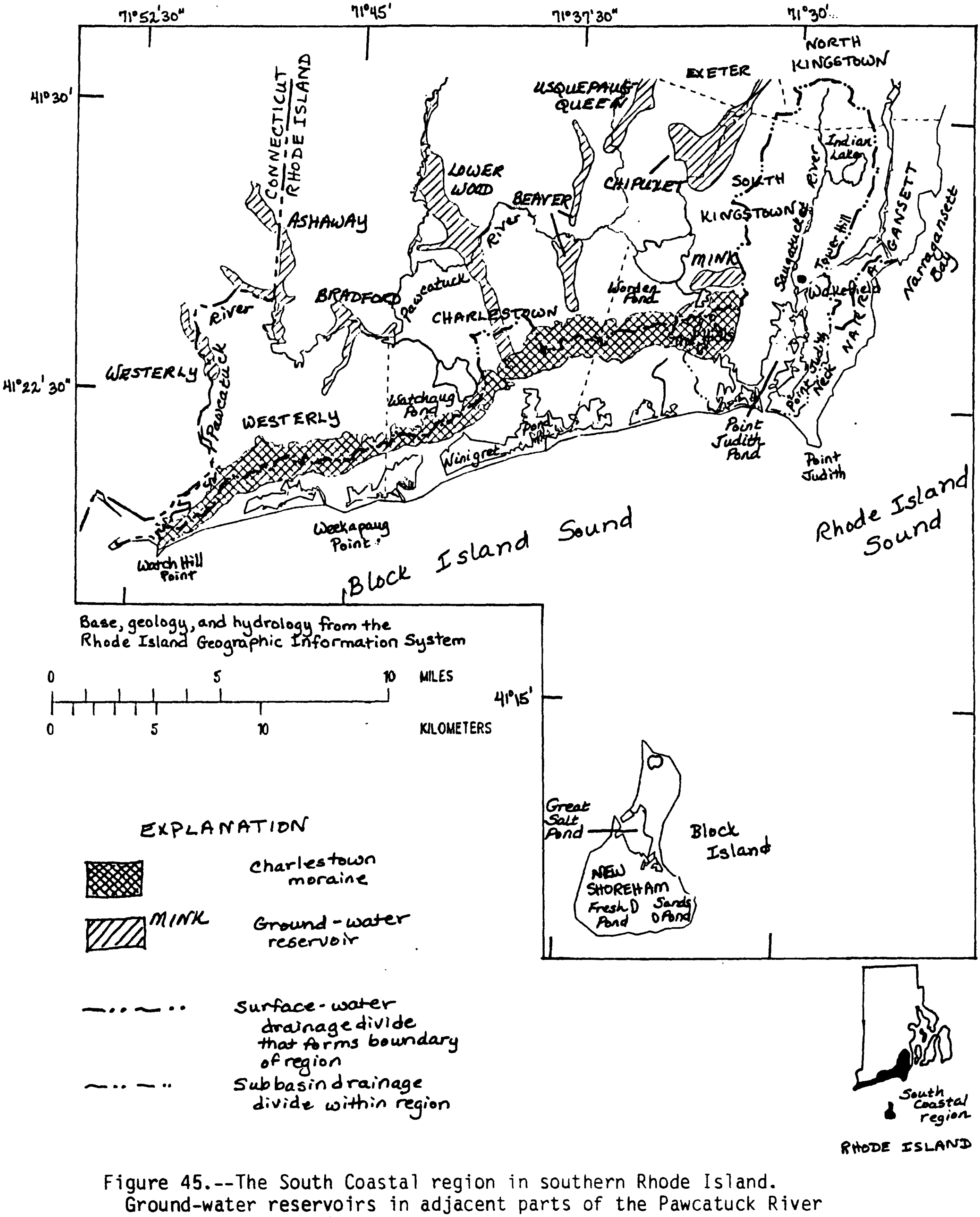


Figure 45.--The South Coastal region in southern Rhode Island. Ground-water reservoirs in adjacent parts of the Pawcatuck River basin are shown. (Sources: Charlestown moraine from Bierschenk, 1956, pl. 1; LaSala and Hahn, 1960; LaSala and Johnson, 1960; Johnson, 1961b. Ground-water-reservoir boundaries from W.B. Allen, Rhode Island Water Resources Board, written commun., 1978; modified by Rhode Island Department of Environmental Management, 1988.)

The Saugatucket River Basin and Point Judith Neck

The Saugatucket River originates in North Kingstown and flows southward through South Kingstown into tidal Point Judith Pond (fig. 45). From the town line between North Kingstown and South Kingstown south to the village of Wakefield, the river flows across stratified drift that has a saturated thickness ranging from about 20 to 70 feet (Hahn, 1959a). Deposits at the southern end of the valley are adjacent to brackish tidal coves.

Tower Hill and Point Judith Neck are part of a north-south trending ridge of till-covered bedrock hills that forms the drainage divide between streams that flow westward into the Saugatucket River and Point Judith Pond and streams that flow eastward into Narragansett Bay and Rhode Island Sound. Altitudes of these hills range from 50 to 100 feet in the south and are as much as 250 feet in the north. The till layer covering the bedrock is more than 100 feet thick at the southern end of Point Judith Neck (Hahn, 1959a). Elsewhere, bedrock is generally within about 20 feet of the land surface, and outcrops are common along the eastern shore of the town of Narragansett.

A lowland area east of the village of Wakefield contains mixed deposits of till and stratified drift that fill a preglacial valley in the bedrock surface (Hahn, 1959a: Lang, 1961, p. 30). Where the stratified drift in this area is capped by a shallow layer of peat and clay, ground water is confined (Lang, 1961, p. 30). Mixed deposits of stratified sand and gravel and sandy till also underlie the shore of Point Judith Pond and the islands within the pond (Bierschenk, 1956; Hahn, 1959a). The maximum known thickness of these mixed deposits is more than 90 feet (Hahn, 1959a).

Private wells withdraw ground water from bedrock, till, stratified drift, and mixed deposits of till and stratified drift. The mixed deposits are the best potential source of ground water for small supplies (Hahn, 1959a). Large withdrawals are probably not feasible because the stratified drift is generally less than 50 feet thick and much of the area is close to brackish water or saltwater (Lang, 1961, p. 30-31). The Wakefield Water Company imports water from the Mink ground-water reservoir in the Pawcatuck basin to the west (fig. 45).

The Southwestern Coast

The Charlestown moraine forms the northern boundary of this area, from Watch Hill Point in Westerly east to an area known as The Hills in South Kingstown (fig. 45). North of the moraine, surface water and ground water flow generally northward toward the Pawcatuck River. South of the moraine, surface water and ground water flow southward toward Block Island Sound. The ground-water and surface-water drainage divides do not coincide in some areas along the moraine. Drainage areas along the southwestern coast are small, and there are no large perennial streams.

The Charlestown moraine is composed of till and stratified drift in variable proportions. The deposits reach a maximum thickness of more than 200 feet where they fill a preglacial valley in the bedrock surface under The Hills in South Kingstown (Bierschenk, 1956). West of this area, the maximum known thickness of the moraine ranges from 75 to 100 feet (LaSala and Hahn, 1960; LaSala and Johnson, 1960; Johnson, 1961b). The southern end of the Lower Wood ground-water reservoir in Charlestown marks another location where thick sediments fill a preglacial valley in the bedrock surface (fig. 45).

The topography of the moraine is hummocky and is characterized by many small kettles (fig. 12B). Where the bottoms of the kettles are above the water table, the depressions are dry. Where the bottoms of the kettles are at or below the water table, swamps and ponds form. Kettle ponds are more numerous toward the eastern end of the moraine than in the western end, but they are scattered throughout the entire area.

Private wells withdraw ground water from the moraine deposits. The sandy till of the moraine includes many gravelly layers that increase the moraine's water-yielding capacity (Bierschenk, 1956, p. 18). Well yields depend on whether or not the wells penetrate permeable lenses of sand and gravel. In places, the water is reported to be moderately hard, with undesirable concentrations of iron (LaSala and Hahn, 1960; LaSala and Johnson, 1960; Johnson, 1961b).

South of the Charleston moraine, a flat outwash plain slopes gently seaward. The stratified drift that forms the outwash plain was deposited by streams flowing south from the ice sheet when the margin of the ice sheet was at the position now marked by the Charlestown moraine (fig. 45). A few till-covered bedrock hills within this flat, sandy plain form small local uplands such as Weekapaug Point. Ocean currents have eroded and transported the glacial deposits to form long barrier beaches that enclose the coastal ponds, creating scenery that is a hallmark of the region.

The saturated thickness of the stratified drift ranges from 10 to 60 feet (Bierschenk, 1956; LaSala and Hahn, 1960; LaSala and Johnson, 1960; Johnson, 1961b). The saturated thickness is greatest in South Kingstown and the eastern areas of Charlestown, and it decreases to the west.

Throughout the southwestern coastal area, the freshwater lens becomes thinner toward the ocean, as shown in the hypothetical diagrammatic section in figure 31. Most of the land underlain by stratified drift is close to brackish or saltwater ponds and coves. Domestic wells withdraw ground water from the stratified drift, and a few wells tap sandy material beneath narrow barrier beaches. The occurrence of fresh ground water beneath a barrier beach is comparable to the occurrence beneath a long, narrow island. All recharge is derived from precipitation on a small land area. The freshwater lens is very thin and is bordered on both sides by saltwater or brackish water (fig. 31). Ground-water withdrawals near the shore or on barrier beaches require careful planning to avoid saltwater intrusion.

Ground water within the southwestern coastal area has been contaminated locally by a leaking underground storage tank and by a road-salt storage facility (fig. 28) (Rhode Island Department of Environmental Management, 1988, fig. 4-7, p. IV-30). As this attractive area continues to be developed for summer and year-round residences, septic-system effluent may also become a significant source of ground-water contamination.

Block Island

Block Island is about 10 miles south of the southern coast of mainland Rhode Island (fig. 45). The town of New Shoreham encompasses the island, which is about 10 square miles in area and had an estimated year-round population of 700 in 1985 (Rhode Island Department of Economic Development, 1987, p. 28, 34). Two irregular, hilly areas at the northern and southern ends of the island are connected by a central sandy lowland in which Great Salt Pond is located. The summit of the highest hill is 211 feet above sea level. Sea cliffs 50 to 150 feet high form the southern shore.

Block Island is part of the Atlantic and Gulf Coastal Plain ground-water region (Heath, 1984, p. 52). In other parts of Rhode Island, glacial deposits rest directly on top of the fractured bedrock. By contrast, glacial sediments on Block Island were deposited on older unconsolidated and semiconsolidated coastal plain sediments of Cretaceous or Triassic age (approximately 63 million to 240 million years old) (Hansen and Schiner, 1964, p. 7; U.S. Geological Survey, 1985, p. 467). These sediments in turn overlie the bedrock, which is about 1,000 feet below sea level near Block Island (Hansen and Schiner, 1964, p. 7). Geologically, Block Island has more in common with Long Island, New York, and with Cape Cod, Martha's Vineyard, and Nantucket in Massachusetts, than with the rest of Rhode Island (fig. 14).

Most of the visible part of Block Island is a fragment of the end moraine that marks the southernmost extent of the most recent continental ice sheet (fig. 14). Features of glacial sediments in the southern part of the island indicate that they were deposited on the changing surface of melting glacial ice, and this area has been referred to as an ablation-moraine complex by Kaye (1960, p. 354-357). Layers of stratified drift were folded and distorted on a large scale at some locations as sediments slid and collapsed. Layered till was formed when successive layers of ablation till, saturated with water, slid into depressions on glacial ice. The thickness and extent of individual layers of glacial sediment differ considerably, and the interbedding of sediment layers is complex.

The glacial sediments include till as much as 100 feet thick, stratified-drift deposits as much as 75 feet thick, and clay layers as much as 75 feet thick (Hansen and Schiner, 1964, p. 7). Layered till is found at the surface in some parts of the island, and in other parts, the till is covered by stratified drift. The till is notably sandy and loose in the western part of the island but compact and less permeable in the southeastern part of the island (Hansen and Schiner, 1964, p. 7).

The complex glacial deposits rest on the uneven eroded surface of the unconsolidated Cretaceous sediments, which consist primarily of clay interbedded with some layers of silt, sand, and gravel (Hansen and Schiner, 1964, p. 7). Some wedges and fragments of Cretaceous sediments that were pushed and disturbed by the advance of the glacier's margin are interspersed in the younger glacial deposits (Sirkin, 1982, p. 37-38). Wave erosion along the shoreline has formed sea cliffs where vertical sections of the island's complex geology can be seen.

Precipitation that falls on the island is the source of all fresh water. Permeable soils cover most of the island (Hansen and Schiner, 1964, p. 11). Consequently, water infiltrates the soil easily and there is little surface runoff.

During the 20th century, Block Island's former maritime and agricultural economy has been steadily replaced by tourism. Although the year-round population is about 700, it has been estimated that the population on peak summer days is as high as 12,000 to 15,000, including summer residents, tourists, day visitors, and mariners (Everett, 1986, p. 3-5, 37-38). Under sparsely populated conditions, long-term discharge of ground water from Block Island is approximately in balance with long-term recharge to the island. Most of the ground water withdrawn is returned to the saturated zone by septic systems. Continued development may impair ground-water quality if the volume of wastewater returned to the ground-water system increases substantially. On the other hand, if the ground water withdrawn is used and then disposed of into sewer mains that discharge directly into the ocean, the amount of water in the freshwater lens will decrease, the freshwater lens will become thinner, and the likelihood of saltwater intrusion will increase. Protection of ground-water resources on Block Island presents a unique challenge because of the limited availability of freshwater, the complex nature of the ground-water system, the seasonal demand for water, the pressures of development, and the importance of clean water and an attractive natural setting to the long-term economic well-being of the island.

SUMMARY

Ground water is a widely used resource in Rhode Island. Ground-water withdrawals averaged 27 million gallons per day during 1985 and provided drinking water to about 25 percent of the State's residents. Public and private wells withdraw ground water from all the hydrogeologic settings of the State, in at least 35 of the State's 39 towns and cities.

The Occurrence, Source, and Flow of Ground Water

Unconsolidated glacial deposits of till or stratified drift overlie fractured bedrock in most areas of Rhode Island. The sediments and the underlying bedrock form two interconnected aquifers. Most ground water is unconfined. At least small quantities of ground water are available virtually everywhere in the State, and ground water is withdrawn from both major and minor aquifers.

Deposits of stratified drift cover about one-third of the State; they fill most major streams valleys and blanket many coastal lowlands. The deposits range in thickness from a few feet to more than 300 feet and are thickest where they fill preglacial channels in the bedrock surface. Thick, coarse-grained deposits of stratified drift are the State's most important aquifers. The parts of these aquifers that have the greatest potential for public supply have been designated as ground-water reservoirs by the Rhode Island Water Resources Board. Public-supply wells tap ground-water reservoirs throughout the State.

Till is the most widely distributed glacial deposit. It forms a nearly continuous blanket on top of the bedrock. In many valleys and lowland areas, it is covered by stratified drift. The average thickness of the till is about 20 feet. Although till is a minor aquifer because of its low permeability, shallow dug wells in till supply water to some households in rural areas of Rhode Island.

Bedrock is a minor aquifer in Rhode Island in terms of yield, but it is the most widely available aquifer in the State. Bedrock is the most common source of water in rural areas not served by public supply. Yields of bedrock wells depend primarily on the characteristics of the fracture network penetrated by the well.

Precipitation is the ultimate source of all ground water in Rhode Island. Precipitation infiltrates the local land surface and percolates downward to the saturated zone. Most recharge takes place during winter and early spring, and the water table that marks the top of the saturated zone is usually highest in early spring. During the growing season, most precipitation evaporates or is transpired by plants before reaching the water table. The water table is usually lowest in late summer or early fall.

Ground water flows under the influence of gravity from recharge areas to discharge areas. Most of the land surface in Rhode Island is a recharge area. Discharge areas, recognizable as streams, swamps, lakes, ponds, and springs, constitute only a small fraction of the State's total area.

Ground-water flow is slow compared to surface-water flow. The average rate of ground-water flow in till has been estimated at a few inches per day in one area of southwestern Rhode Island; in highly permeable sand and gravel, the average rate is 1 to 2 feet per day. By contrast, stream velocity is commonly measured in feet per second.

Water withdrawn from a well is an artificial discharge that affects the ground-water system. A well removes ground water from storage, forms a cone of depression in the surface of the saturated zone, and changes the direction of ground-water flow. As water is withdrawn from a well, a zone of contribution forms within the saturated zone. All the ground water within this zone of contribution flows toward the well. The land overlying the zone of contribution is the contributing area, or recharge area, of the well.

Withdrawal of ground water reduces the natural rate of ground-water discharge to streams. Large-capacity wells in Rhode Island are located in permeable stratified-drift deposits near streams. At these locations, withdrawal of ground water commonly induces surface water to flow from the stream into the aquifer. Streamflow may be severely reduced or the stream may go dry if withdrawals are large relative to the flow of the stream.

Ground-water flow is organized within units of the Earth's crust known as ground-water drainage basins. In Rhode Island, a ground-water drainage basin and the overlying surface-water drainage basin are usually considered to form a single interconnected hydrologic unit. The general direction of ground-water flow is from the hills toward the valleys and from the uplands around the perimeter of the basin toward the valley of the major stream draining the basin.

Ground-Water Quality

The quality of natural ground water is affected by climate, precipitation chemistry, biological processes, soil characteristics, and aquifer materials. Most of the bedrock and sediments in Rhode Island are composed of silicate minerals that do not dissolve easily. Consequently, natural ground water generally contains low concentrations of dissolved minerals. The quality of ground water in most parts of Rhode Island is suitable for drinking with little or no treatment.

Fresh Pond, with an area of 20 acres and a maximum depth of 24 feet, and Sands Pond, with an area of 14 acres and a maximum depth of 8 feet, are the largest freshwater bodies on Block Island (fig. 45) (Guthrie and Stolgitis, 1987, p. 31, 44). Most of the small streams on the island flow only intermittently, and some ponds and swamps go dry during the summer (Hansen and Schiner, 1964, p. 4).

Ground water is the major freshwater resource on Block Island. Block Island has been designated a sole source aquifer by the USEPA because no other source of drinking water is available for its residents (U.S. Environmental Protection Agency, 1984a, p. 2953).

The ground-water system on Block Island is complex because the geology is complex and because saltwater underlies fresh ground water at depth. Most ground water probably is unconfined, although impermeable layers confine ground water in some areas (Hansen and Schiner, 1964, p. 11). Ground water flows radially outward toward the shore from the hilly uplands at the northern and southern ends of the island, and it discharges primarily into Great Salt Pond and the ocean.

Layers of till or clay, present at shallow depths in many places on Block Island, inhibit downward movement of recharge. Infiltrating water accumulates on top of the layer of till or clay and forms a body of perched ground water with a perched water table such as the one shown at location A in figure 8. Perched ground water is separated from the main water table by an unsaturated zone (fig. 8). Recharge to a perched body of ground water is limited by the area of the underlying impermeable layer.

Numerous small ponds on Block Island are part of perched systems that are separated from the main water table by an unsaturated zone (Hansen and Schiner, 1964). The maximum saturated thickness of the small perched bodies of ground water is probably about 20 feet (Hansen and Schiner, 1964, p. 14). Perched ground water is tapped for domestic supplies on Block Island, but is not considered a reliable source.

In addition to the numerous small perched ground-water bodies near the land surface of Block Island, there may be a larger semiperched body of ground water at greater depths. The lower semiperched water zone is probably interconnected in most places with the main saturated zone (Hansen and Schiner, 1964, p. 14).

The main saturated zone is continuous underneath all of Block Island. The thickness of this freshwater lens is not known with certainty, and at some depth, the sediments are saturated with saltwater, as shown in figure 31A. The relation between freshwater and saltwater shown in figure 31 is based on the assumption that sediments are homogeneous and have uniform physical characteristics. The freshwater-saltwater relations on Block Island are more complicated than those shown in figure 31 because of the complex layering of the sediments and the wide variability of their water-bearing characteristics.

Recharge to the main saturated zone is affected by the presence of perched water bodies. The recharge accumulates as perched ground water above the main saturated zone, and the perched ground water discharges through contact springs (fig. 19) around the periphery of the island or into small perched ponds and swamps (Hansen and Schiner, 1964, p. 14).

The most important source of fresh ground water on Block Island is south of Great Salt Pond in the southeastern part of the island's main land mass (fig. 45) (Hansen and Schiner, 1964, p. 24). The water table of the main saturated zone in this area ranges from 50 to 125 feet above sea level (Hansen and Schiner, 1964, p. 17; fig. 14, p. 25). Knowledge of the distribution and water-yielding characteristics of permeable materials in this area is limited. Studies are currently (1989) underway to improve understanding of the complex hydrogeology, provide estimates of ground-water yield, and provide information on ground-water quality (H.E. Johnston, U.S. Geological Survey, oral commun., 1989).

The Block Island Water Works obtains surface water from Sands Pond (fig. 45) and withdraws ground water from wells near the pond. The public-supply wells withdrew about 10,000 gallons of water per day during 1985 (R.W. Bell, U.S. Geological Survey, written commun., 1989). Private wells withdraw ground water for domestic use throughout the island.

The chemical quality of ground water on Block Island has been summarized by Hansen and Schiner (1964, p. 2, 17, 22; table 3, p. 26-27), on the basis of water samples from 47 wells that were analyzed for selected properties and constituents during 1962. Ground water is soft to moderately hard and somewhat acidic; the median pH measured was 6.2. Concentrations of dissolved solids ranged from 82 to 397 milligrams per liter, and the median concentration was 123 milligrams per liter. Iron concentrations exceeded the SMCL of 0.3 milligram per liter (table 4) in about half of the water samples; concentrations ranged from 0.01 to 22 milligrams per liter. Elevated iron concentrations were particularly common in the southeastern third of the island. Median concentrations of dissolved solids, iron, and manganese are higher in ground water on Block Island than in many other parts of Rhode Island (Johnston and Barlow, 1988, fig. 2, p. 444).

Chloride concentrations are generally higher in ground water on Block Island than on the mainland, presumably because of the higher chloride content of precipitation from storms generated over saltwater (Hansen and Schiner, 1964, p. 22). Salt spray during storms also contributes additional chloride to perched zones near the shore. Chloride concentrations ranging from 14 to 248 milligrams per liter (median concentration, 34 milligrams per liter) were measured in ground water from perched zones in 1962 (Hansen and Schiner, 1964, p. 22). Chloride concentrations in the main saturated zone ranged from 23 to 1,950 milligrams per liter, and the median concentration was 39 milligrams per liter. By comparison, the median concentration of chloride in samples from the Upper Wood ground-water reservoir in the Pawcatuck River basin (fig. 44) was 6 milligrams per liter (table 2). Chloride concentrations above 50 milligrams per liter in water from wells tapping the main saturated zone near the shore on Block Island probably indicate that saltwater intrusion has occurred or that well intakes are within the transition zone (fig. 31) (Hansen and Schiner, 1964, p. 22).

Ground water on Block Island has been contaminated locally by a municipal landfill, by unauthorized disposal of oil, and by a leaking underground storage tank (fig. 28) (Rhode Island Department of Environmental Management, 1988, fig. 4-7, p. IV-30). More than 200 homes have underground heating-oil tanks, which may eventually leak (H.E. Johnston, U.S. Geological Survey, written commun., 1989). Residences outside a small area served by sewers in the central business district are served by individual sewage-disposal systems.

Several natural constituents in Rhode Island's ground water affect the use of the water for drinking and other purposes where they are present in high concentrations. Iron and manganese are present in some places at concentrations that cause aesthetic problems in household use. Excessive concentrations of sodium and chloride may be encountered in coastal areas. Radon, a naturally occurring radioactive gas, enters ground water from the rocks and sediments through which the ground water flows.

The quality of ground water has been degraded at a number of locations in Rhode Island. Important contaminants detected include petroleum products, synthetic organic chemicals, sodium, nitrate, trace metals, radionuclides, and bacteria. A total of 57 organic chemicals have been found in ground water in Rhode Island. Contamination by volatile organic compounds has been the major cause of abandonment of public-supply wells in the State.

Most ground-water contamination problems in Rhode Island have been caused by human activities at or near the land surface. Large areas of Rhode Island are urbanized, and the State ranked second in population density among the 50 states in 1985. Rhode Islanders live, work, and dispose of waste in recharge areas. Ground water, which is within 40 feet of the land surface throughout most of the State, is vulnerable to contamination from many sources.

The relation of land use to ground-water quality is complex. Many types of potential contaminants may be produced by a single source, and many different sources may contribute the same contaminant to ground-water. Agricultural areas contribute nitrate and pesticides to ground water. Nitrate, bacteria, and detergents are added to ground water by septic systems in residential areas. Underground heating-oil tanks may leak petroleum products, and the use and disposal of household chemicals may contribute a variety of contaminants to ground water. Industrial and commercial areas are a source of volatile organic compounds, petroleum products, and trace metals. Two locations in Rhode Island where spilled industrial solvents have contaminated ground water are on the U.S. Environmental Protection Agency (USEPA) National Priority List for investigation and cleanup under the Federal "Superfund" program. The underground storage tanks commonly used in industrial and commercial areas are a particularly serious problem because leaks of hazardous substances may go undetected. Ground water has been contaminated by leaks from underground storage tanks at 29 sites in Rhode Island. Sodium and chloride have contaminated ground water at 12 State road-salt storage areas. Transportation routes and facilities may also be a source of petroleum products and other chemicals from accidental spills. Waste-disposal sites are sources of many kinds of contaminants, particularly synthetic organic chemicals and trace metals. The Rhode Island Department of Environmental Management (RIDEM) has inventoried 221 known or potential hazardous-waste sites under the auspices of the Federal "Superfund" program. Of these, three municipal landfills and three industrial waste-disposal sites are on the USEPA National Priority List. Ground water has been contaminated by at least 29 landfills and by an uncertain number of underground injection facilities and surface impoundments.

Contaminants reach ground water in several ways. They may be dissolved and carried from the land surface through the unsaturated zone by percolating water. Liquid contaminants such as gasoline move downward through the unsaturated zone under the influence of gravity. Below the water table, contaminants may be dissolved by direct contact with flowing ground water. Wells may induce contaminated surface water into an aquifer, or may cause saltwater intrusion. Ground water is very susceptible to contamination where the water table is close to the land surface, where bedrock is close to the land surface, where highly permeable sediments are present, or where an aquifer is hydraulically connected to a source of unpotable water.

Contaminants dissolved in ground water move with the ground water from recharge areas toward discharge areas. The movement and fate of a contaminant are controlled by the rate and direction of ground-water flow; by physical, chemical, and biological processes; by the characteristics of the earth materials; and by the characteristics of the contaminant itself. Contaminants transported by ground water may be diluted, decomposed, or adsorbed on aquifer materials. They may be discharged to wells, streams and ponds, or the ocean. Contamination is likely to persist if the source is large, such as a landfill; if new contaminants continue to be added, such as in a septic system; or if the contaminant itself does not degrade easily.

Prevention of ground-water contamination is usually the responsibility of more than one level of government and more than one town, particularly in the case of regionally significant aquifers. The RIDEM is responsible for Rhode Island's ground-water protection program. Sixteen of the State's 39 towns and cities have enacted or are investigating measures for ground-water protection. Private citizens can help prevent ground-water contamination by minimizing or eliminating the use and disposal of hazardous substances on their own property. Geologic and hydrologic information can help agencies and citizens protect ground-water resources.

Ground-Water Regions of Rhode Island

The eight regions described in this report include several hydrogeologic environments. The regions have different potential for ground-water development and face different types of ground-water-quality problems.

Six ground-water reservoirs are located along narrow stream valleys in the hilly Blackstone River basin in northern Rhode Island. Some parts of these ground-water reservoirs are used for public supply or have the potential for large-scale ground-water development. Other parts have been affected by waste disposal and industrial spills, and six public-supply wells have been removed from service because of contamination by synthetic organic chemicals. Private wells are widely used in the rural parts of the basin.

The Upper Bay region includes coastal areas and small drainage basins at the head of Narragansett Bay. Stratified drift blankets the coastal lowlands on both sides of the bay, and four ground-water reservoirs are located in this region. Ground water is used for public or private supply in some areas. However, ground water has been contaminated in many areas by waste disposal, industrial and commercial spills and discharges, and the cumulative effects of urban activities. Saltwater intrusion is a potential problem in coastal areas.

The Pawtuxet River basin is in central Rhode Island. The main stem of the Pawtuxet River crosses a highly urbanized lowland underlain by stratified-drift deposits. Ground water, which has been contaminated by various sources, is not used for public supply in this area. The drainage basin of the North Branch Pawtuxet River is dominated by till-covered bedrock uplands and the large Scituate Reservoir system. Most residents are served by private wells. Public and private wells withdraw ground water from the South Branch Pawtuxet River basin. Ground-water quality in the North Branch and South Branch basins is generally suitable for most purposes, although there are contamination problems in some areas. One public-supply well has been removed from service because of contamination by a volatile organic compound.

High, till-covered bedrock hills dominate the landscape of the sparsely populated Quinebaug River basin in western Rhode Island. There are no large deposits of stratified drift. Residents obtain water from private wells in bedrock or unconsolidated glacial deposits. Ground-water-contamination problems are typically small in area.

Ground-water reservoirs in the small coastal drainage basins of the West Bay region provide drinking water for several growing communities on the west side of Narragansett Bay. Private wells also are used. Large ground-water withdrawals reduce the low flow of the small streams in the area, and could cause streams to go dry under some conditions. Saltwater intrusion is a potential problem along the shore.

Low, till-covered bedrock hills form the landscape of the Bay Islands and East Bay region in southeastern Rhode Island. The few deposits of stratified drift are small and thin or adjacent to saltwater, and most public water supplies are served by surface-water sources. Private wells withdraw ground water in most communities. Much of the area is underlain by bedrock of the Narragansett Basin, which may contribute to elevated iron concentrations in ground water. Saltwater intrusion is likely where wells are near the shore.

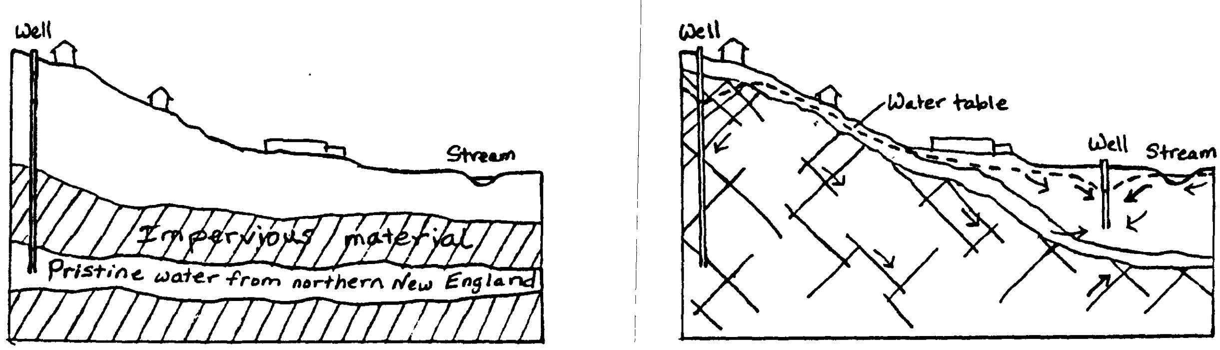
The Pawcatuck River basin in southwestern Rhode Island, with nine ground-water reservoirs, contains some of the most important ground-water resources of the State. Some of the ground-water reservoirs are of regional significance and have the potential to export ground water to other parts of the State. Large ground-water withdrawals would affect the low flow of small streams and could cause them to go dry under some conditions. Ground water, whether from public or private wells, supplies all of the drinking water for residents of the sparsely developed Pawcatuck basin. Ground-water quality is generally good, although it has been degraded in some areas. Two public-supply wells have been removed from service, one because of contamination from petroleum hydrocarbons and the other because of contamination from the pesticide aldicarb. Contamination from fertilizers and pesticides used on agricultural land is a potentially widespread problem.

The South Coastal region, which includes Block Island, relies heavily on ground water from private wells and public water systems. Wells withdraw ground water from stratified drift, till, mixed deposits of till and stratified drift, and bedrock. Saltwater intrusion is a potentially serious threat to ground-water quality throughout this low-lying coastal region. Increased residential and commercial development is also likely to affect ground-water quality.

Conclusions

Ground water, an important resource throughout the State, is part of a dynamic system. General principles of hydrology and specific local information can be used to determine how much ground water is available, where it comes from, and where it is going.

Ground water in Rhode Island comes from local sources, and the sources of ground-water contamination are also local (fig. 46). Ground water has been contaminated at more than 100 specific sites in Rhode Island, and in many cases, drinking water has been affected. Incidences of ground-water contamination are likely to increase as more of the State's rural land is developed. Protection of drinking-water resources requires an understanding of where contaminants come from, how they reach ground water, and what happens to them in the ground-water system. The citizens of Rhode Island face the challenge of using ground water effectively and protecting its quality.



A. Myth: Ground water is sometimes pictured as a subterranean stream from distant sources, unaffected by local activities on the land surface.

B. Reality: The source of ground water is precipitation that falls on the local land surface. Infiltrating water can dissolve and transport contaminants with which it comes in contact. Withdrawal of ground water from wells affects the local flow system.

Not to scale

Figure 46.--Mythical and actual sources of ground water in Rhode Island.

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GLOSSARY

Ablation: All processes by which snow or ice is lost from a glacier, including melting, evaporation, and wind erosion.

Ablation till: Loosely consolidated rock debris, formerly contained by a glacier, which accumulated in place as the ice melted.

Absorption: The process by which substances in gaseous, liquid, or solid form are assimilated or taken up by other substances.

Adsorption: The adhesion of gas molecules, ions, or molecules in solution, to the surfaces of solids with which they are in contact.

Agricultural water use: Water used for irrigation, stock watering, feed lots, dairy operations, fish farming, and other farm needs.

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

Bacteria: Microscopic one-celled organisms, often aggregated into colonies. Some bacteria perform an essential role in nature in the recycling of materials, such as by decomposing organic matter into a form available for reuse by plants; others cause disease. See also Coliform bacteria.

Bedrock: Solid rock, commonly called "ledge" in Rhode Island, which forms the Earth's crust. It is locally exposed at the surface but more commonly is buried beneath a few inches to more than 300 feet of unconsolidated deposits.

Brackish water: Water intermediate in salinity between saltwater and freshwater. Brackish water contains between 1,000 and 10,000 milligrams per liter of dissolved solids.

Casing: A tubular retaining structure, generally metal, which is installed in an excavated hole to maintain a well opening.

Coliform bacteria: A particular group of bacteria, some of which inhabit the intestinal tracts of vertebrates. Although generally considered to be nonpathogenic, their presence in a water sample is regarded as evidence of possible pollution by sewage.

Color unit: A standard of color in water measured by the platinum-cobalt method. The color produced by 1 milligram per liter of platinum in water equals one color unit.

Commercial water use: Water for motels, hotels, restaurants, office buildings, and other commercial facilities, and institutions, both civilian and military. The water may be obtained from a public supply or may be self-supplied.

Concentration: The amount of a solute, such as a mineral, dissolved in a specified amount of a solvent, such as water.

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

Confined aquifer: An aquifer bounded above and below by impermeable beds, or by beds of distinctly lower permeability than that of the aquifer itself. Also called an artesian aquifer. See also Unconfined aquifer.

Confined ground water: Water in an aquifer that is bounded by confining beds. The ground water is under pressure that is significantly greater than that of the atmosphere.

Contact: A plane or irregular interface between two types or ages of rock or sediment. Also refers to the interface between two fluids, such as gasoline and water.

Contamination: The degradation of water quality as a result of human activity.

Crystalline bedrock: A general term including several igneous and metamorphic rocks. The most common types in Rhode Island are granite, gneiss, and schist.

Discharge: In hydraulics, the rate of flow, especially fluid flow; a volume of fluid passing a point per unit time, commonly expressed as cubic feet per second, million gallons per day, or gallons per minute.

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

Domestic water use: Water for household purposes. Also called residential water use. The water may be obtained from a public supply or may be self-supplied.

Drainage area: The land area, as measured on a map, that contributes water to a particular stream channel, lake, reservoir, or other body of water.

Drainage basin: A part of the surface of the earth that is occupied by a drainage system, consisting of a stream or body of impounded surface water and all its tributary streams and bodies of surface water. Also referred to as river basin or watershed.

Drainage divide: The boundary between one drainage area and another. The rim of a drainage basin. Unless otherwise specified, usually refers to a surface-water drainage divide.

Drawdown: The lowering of the ground-water level or potentiometric surface by pumping. It is equal to the difference between the static (nonpumping) level and the pumping level.

Estuary: The tidal mouth of a river valley where freshwater mixes with, and measurably dilutes, saltwater and where tidal effects are evident.

Evapotranspiration: Loss of water to the atmosphere by evaporation from water surfaces and moist soil and by transpiration from living plants.

Filtration: The separation and removal of particles from a gas or liquid as it passes through porous material.

Formation: A part of the Earth's crust that is more or less distinct from other parts, either because of its origin, its mineral composition and arrangement, or its structure.

Fracture: A structural break or opening in bedrock along which water is able to move. A crack, joint, or fault.

Freshwater: Water that contains less than 1,000 milligrams per liter of dissolved solids. Generally, more than 500 milligrams per liter of dissolved solids is undesirable for drinking and many industrial uses.

Gaining stream: A stream or reach of stream whose flow is being increased by inflow of ground water.

Glacier: A large mass of ice, formed on land by the compaction and recrystallization of snow, which moves slowly by creep downslope or outward in all directions because of the stress of its own weight and which survives from year to year. Included are small mountain glaciers as well as ice sheets continental in size, and ice shelves that float on the ocean but are fed in part by ice formed on land. See also Ice sheet.

Gravel: Unconsolidated rock debris composed principally of particles larger than 0.08 inch in diameter.

Gravel-packed well: A type of well, commonly used for public-supply wells in stratified drift, in which gravel is placed in the space around the well screen to increase the effective diameter of the well and to prevent fine-grained sediments from entering the well.

Ground water: Water in the saturated zone.

Ground-water discharge: The release of water from the saturated zone by (1) natural processes such as ground-water runoff and ground-water evapotranspiration, and (2) artificial discharge through wells.

Ground-water drainage divide: A ridge or hill in the irregular surface of the saturated zone. The water table slopes downward in a direction away from the divide on both sides of the divide. A ground-water drainage divide is analogous to, but not always coincident with, a topographic drainage divide on the land surface between two surface-water drainage basins.

Ground-water recharge: The amount of water that is added to the saturated zone. Also refers to the process by which water is added to the saturated zone.

Ground-water reservoir: As defined by the Rhode Island Water Resources Board, an area underlain by stratified drift with transmissivity equal to or greater than 4,000 feet squared per day and a saturated thickness equal to or greater than 40 feet.

Ground-water runoff: Ground water that has discharged into stream channels, lakes, estuaries, or the ocean by seepage from saturated earth materials.

Hardness (water): A property of water causing formation of an insoluble residue when the water is used with soap, and forming a scale in containers in which water has been allowed to evaporate. It is caused primarily by the presence of ions of calcium and magnesium. Generally expressed as milligrams per liter (mg/L) as calcium carbonate ($CaCO_3$).

A general hardness scale is: soft, 0-60 mg/L; moderately hard, 61-120 mg/L; hard, 121-180 mg/L; very hard, more than 180 mg/L (U.S. Geological Survey, 1985, p. 461).

Hazardous waste: Any substance that is toxic, or otherwise is a threat to life, that is discharged through human activity to the land, water, or atmosphere. Synthetic organic chemicals and trace metals are some of the more significant contaminants associated with hazardous waste.

Head (static): The height above a standard datum of the surface of a column of water that can be supported by the static pressure at a given point. The static head is the sum of the elevation head and the pressure head.

Humus: An organic substance, found in the soil zone, consisting of partially or totally decayed plant matter.

Hydraulic conductivity: The volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow, in an isotropic porous medium. More simply, hydraulic conductivity is a measure of the ease with which a fluid will pass through a porous earth material, such as stratified drift or till. Hydraulic conductivity is determined by the size and shape of the pore spaces in the material, and their degree of interconnection, as well as by the viscosity of the fluid. In this report, hydraulic conductivity is given in units of feet per day, which is a simplified form of cubic feet of water per day per square foot cross-section of earth material.

Hydraulic gradient: In an aquifer, 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.

Hydrocarbons: A large and diverse group of natural and synthetic organic compounds, composed primarily of hydrogen and carbon, with varying amounts of other elements.

Hydrogeology: The science that deals with subsurface waters and with related geologic aspects of surface waters.

Hydrology: The science that relates to the water of the earth.

Ice-contact deposit: Stratified drift deposited in contact with melting glacial ice. The sediments are characterized by a wide range in grain size, the presence of till layers, and layers that are collapsed or folded (Flint, 1957, p. 146).

Ice sheet: A glacier of considerable thickness and more than 20,000 square miles in area, forming a continuous cover of ice and snow over a land surface, spreading outward in all directions and not confined by the underlying topography; a continental glacier. Ice sheets are now confined to polar regions (as on Greenland and Antarctica), but during the Pleistocene Epoch, they covered large parts of North America and northern Europe.

Inches of water: Water volume expressed as the depth, in inches, to which it would accumulate if spread evenly over a particular area.

Induced infiltration: The process by which water in a stream or lake moves into an aquifer when a hydraulic gradient from the surface-water body toward the aquifer has been established because of the withdrawal of water from a pumped well or wells.

Induced recharge: The amount of water entering an aquifer from an adjacent surface-water body by the process of induced infiltration.

Industrial water use: Water used for industrial purposes such as fabrication, processing, washing, and cooling. The water may be obtained from a public supply or may be self-supplied.

Infiltration: The passage of a gas or liquid into or through soil or rock by way of pores or small openings in the earth material.

Ion: An atom or group of atoms that carries an electric charge as a result of having lost or gained electrons.

Isotropic: Having properties that are uniform in all directions. Earth materials are seldom isotropic.

Kettle: A depression in stratified drift, caused by the melting of a buried or partially buried block of glacier ice (Flint, 1957, p. 151). Sometimes colloquially referred to as a kettlehole.

Kinematic: Pertaining to the motions of materials.

Leachate: Liquid that has filtered or percolated through porous or soluble material, such as refuse in a landfill, and contains dissolved and suspended solids leached from the material.

Leaching system: A structure, excavation, or other facility designed to allow liquid to percolate into and filter through the underlying soil without overflow. For example, the leach field of a residential septic system is a leaching system.

Lodgment till: A compact till deposited beneath a moving glacier. Particles are unsorted, crushed, and abraded, and stones tend to lodge with their long axes parallel to the direction of ice flow.

Losing stream: A stream or reach of a stream from which streamflow infiltrates into the ground.

Low-level radioactive waste: Nuclear wastes resulting from a variety of activities, including university research programs, medical treatment, and electrical power generation. The radioactivity of low-level wastes is considerably less than that of high-level nuclear wastes associated with nuclear fuel.

Mean: The arithmetic mean of a set of observations. The average value of a set of numbers.

Median: The middle item of a group of numbers arranged according to rank. Half the numbers are greater than the median and half the numbers are less than the median.

Metamorphic rock: Any rock derived from preexisting rocks by mineralogical, chemical, and structural changes, essentially in the solid state, in response to marked changes in temperature, pressure, shearing stress, and chemical environment at depth in the Earth's crust.

Methylene blue active substance (MBAS): A measure of apparent detergents, as indicated by the formation of a blue color when methylene blue dye reacts with synthetic detergent compounds.

Micrograms per liter (μg/L): A unit for expressing the concentration of chemical constituents in solution. Micrograms per liter represents the weight of solute per unit volume of water; 1,000 micrograms equal 1 milligram. Micrograms per liter and parts per billion (ppb) are approximately equivalent, with 1 μg/L equal to 1 ppb. However, micrograms per liter is the standard unit for reporting dissolved constituents.

Milligrams per liter (mg/L): A unit for expressing the concentration of chemical constituents in solution. Milligrams per liter represents the weight of solute per unit volume of water; 1 milligram equals 1,000 micrograms. At the low concentrations of dissolved solids typically found in fresh ground water, milligrams per liter and parts per million (ppm) are approximately equivalent, with 1 mg/L equal to 1 ppm. However, milligrams per liter is the standard unit for reporting dissolved constituents.

Mineral: A naturally occurring inorganic element or compound having an orderly internal structure and characteristic chemical composition, crystal form, and physical properties.

Moraine: A ridge-like accumulation of till, containing variable amounts of stratified drift, deposited along the margin of a glacier.

Nonpoint source of pollution: An activity or process that introduces contaminants over a broad area rather than from discrete points. Examples include fertilizer and pesticide application and leaking sewer systems. A nonpoint source can range in size from several acres to many square miles and can consist of multiple point sources.

Nutrients: Compounds of nitrogen, phosphorous, and other elements essential for plant growth.

Organochlorine compounds: A group of synthetic organic compounds that are toxic and persistent in the environment. They include aldrin, chlordane, DDT, lindane, and toxaphene.

Outcrop: A place where a geologic formation is visible at the Earth's surface.

Outwash: Stratified drift deposited in a flat plain beyond a glacier's margin by meltwater streams emanating from the glacier. The grain size of the sediments decreases with increasing distance from the glacier.

Overland flow: The flow of rainwater or snowmelt over the land surface toward stream channels. After it enters a stream, it becomes runoff.

Percolation: Streamline flow of water, usually downward, by the force of gravity or under hydrostatic pressure, through small openings within a porous material such as a rock or sediment.

Perennial stream: A stream that flows during all seasons of the year.

Permeability: A qualitative term used to describe the ease or difficulty with which water will pass through a porous earth material. See also Hydraulic conductivity, the quantitative term used by the U.S. Geological Survey to define this property.

Pesticides: Chemical compounds used to control undesirable plants and animals. The major categories of pesticides include insecticides, miticides, fungicides, herbicides, and rodenticides.

pH: The hydrogen-ion activity of a solution. A pH value is a number, on a scale of 1 to 14, that is equal to the negative logarithm of the hydrogen-ion concentration. This value is used by chemists to measure the reactive characteristics of water. A pH value of 7 is neutral. Values less than 7 indicate acidic solutions that are corrosive and tend to dissolve metals and other substances. Values greater than 7 indicate alkaline or basic solutions that tend to form scale when heated. The difference between each unit on the scale represents one order of magnitude. For example, a pH of 5 is 10 times more acidic than a pH of 6, and a pH of 5 is 100 times more acidic than a pH of 7.

Phenols: A class of aromatic organic compounds, commonly toxic. Derived from coal tar or benzene.

Picocurie (pCi): A measure of radioactivity. One pCi is equal to one trillionth of the amount of radioactivity represented by one curie (Ci). A curie is the amount of radioactivity that yields 3.7×10^{10} radioactive disintegrations per second. A picocurie yields 2.22 disintegrations per minute (U.S. Geological Survey, 1988, p. 550).

Pleistocene Epoch: A geologic time unit extending from about 2 million years ago to about 10,000 years ago. Sometimes known as the Ice Age or Great Ice Age because the epoch was characterized by repeated global climatic cooling and repeated extensive glaciation in the Earth's high and middle latitudes, accompanied by related worldwide fluctuations of sea level.

Point source of pollution: Any discrete source of pollution, such as a waste-disposal site, underground storage tank, or chemical spill. Point sources are localized and have areas of a few acres or less.

Pollution: The presence in or addition to water of any substance that is or could become injurious to the public health, safety, or welfare; or that is or could become injurious to domestic, commercial, industrial, agricultural, or other uses being made of the water.

Polychlorinated biphenyls (PCB); Polychlorinated naphthalenes (PCN): Industrial chemicals that are mixtures of chlorinated biphenyl or naphthalene compounds having various percentages of chlorine. They are similar in structure to organochlorine insecticides.

Potentiometric surface: A surface that represents the total head in an aquifer, that is, the level to which water will rise in tightly cased wells that penetrate the aquifer. The water table is a particular potentiometric surface.

Precipitation: (1) The discharge of water from the atmosphere in the forms of rain, sleet, snow, or hail. The opposite process is evaporation. (2) The process by which ions dissolved in a solution join together to form solid particles that settle out of the solution by gravity or adhere to nearby solid surfaces. The opposite process is solution, or the process of becoming dissolved.

Private well: A well serving self-supplied domestic, commercial, industrial, or agricultural users.

Public supply: Water withdrawn by public water systems and delivered to groups of users. As used in this report, public supply refers to water supplied by Rhode Island's 34 major public water systems, which include cities, towns, county water authorities, fire districts, large public institutions, and large private companies. These 34 major systems provide most of the publicly supplied water. More than 300 smaller systems also meet the State's definition of a public water system; most of these serve nursing homes, condominiums, and small housing developments (H.E. Johnston, U.S. Geological Survey, written commun., 1988). See also Public-water system.

Public water system: "A system for the provision to the public of piped water for human consumption, provided such system has at least 15 service connections or regularly serves an average of at least 25 individuals daily at least 60 days out of the year" (Rhode Island Department of Health, 1983, p. 1). Federal and State laws protect and mandate monitoring of the quality of water from public water systems. See also Public supply.

Radionuclide: A species of atom that emits alpha, beta, or gamma rays for a measurable length of time.

Reach: The length of a stream between two points.

Recharge: (1) Water that infiltrates to and supplies the saturated zone. Recharge may be natural or artificial depending upon the source of the water. (2) The process that allows water to infiltrate to an aquifer.

Recharge area: An area in which infiltrating water reaches the zone of saturation. More specifically, a land area that contributes ground-water recharge to a location of interest, such as a well field or an entire aquifer.

Redox potential: A numerical index of the intensity of oxidizing or reducing conditions within a system.

Rock: An aggregate of one or more minerals. Granite, shale, and marble are rocks.

Runoff, total: That part of the precipitation that appears in streams. It includes ground-water and surface-water components. Runoff is the same as streamflow that is unaffected by artificial diversions, storage, or other artificial works in or on stream channels.

Safe yield (ground water): The amount of water that can be withdrawn from an aquifer without producing an undesired effect.

Saltwater: Water containing about 35,000 milligrams per liter of dissolved solids, including about 19,000 milligrams per liter of chloride (Cl).

Saltwater intrusion: The movement of saltwater or brackish water into an aquifer as a result of the pumping of freshwater near the sea.

Sanitary landfill: A solid-waste-disposal site at which refuse is deposited, compacted, and covered with a specified amount of soil daily.

Saturated thickness: The thickness of an aquifer below the water table.

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

Screened interval: The intake section of a well through which water is obtained from an unconsolidated aquifer, such as stratified drift. Ground water enters the well only along the screened interval; the rest of the well is cased to prevent entry of water.

Sedimentary rock: Rock formed of sediment. The most common types in Rhode Island are the conglomerates, sandstones, and shales of the Narragansett Basin.

Self-supplied water: Water withdrawn from a surface-or ground-water source by a user rather than being obtained from a public supply.

Septage: Liquid and solid material (sludge) pumped from a septic tank or cesspool during cleaning.

Septic tank: A watertight receptacle used for the treatment of sewage and designed and constructed to permit settling of solids, digestion of organic matter, and discharge of the liquid part to a leaching system.

Sewage: Wastewater carried off by sewers and drains.

Soft water: Water in which the concentration of calcium carbonate is 60 milligrams per liter or less. Generally recognized as water in which it is easy to produce a lather with soap. See also Hardness (water).

Sole source aquifer: An aquifer that provides 50 percent or more of the drinking water for an area; for which there are no viable alternative sources of supply; and which, if contaminated, would create a significant hazard to public health and a serious financial burden (U.S. Environmental Protection Agency, 1988a, p. 19026-19027). All projects receiving Federal financial assistance within the designated area must be evaluated to reduce the risk of ground-water contamination. The designation of a Sole Source Aquifer is made by the U.S. Environmental Protection Agency. There are currently (1989) three Sole Source Aquifers in Rhode Island: the Block Island Aquifer, the Hunt-Annaquatucket-Pettaquamscutt Aquifer Area, and the Pawcatuck Basin Aquifer System.

Solid waste: Garbage, refuse, rubbish, trash, and other solid materials from domestic, commercial, and other sources.

Specific conductance (of water): A measure of the ability of water to conduct an electric current, expressed in microsiemens per centimeter at 25 degrees Celsius. It is related to the concentration of dissolved solids, for which it serves as an approximate, indirect measure.

Specific yield: The ratio of the volume of water that a saturated rock or sediment will yield by gravity, to the volume of the material.

Stratified drift: Predominantly sorted sediments laid down in layers, by or in meltwater from a glacier. Includes gravel, sand, silt, or clay deposited in layers of similar grain size. The term "drift" is a historical remnant from the early 19th century, when scientists believed that glacial materials had been deposited when debris-filled icebergs melted as they drifted across prehistoric oceans (Flint, 1957, p. 4).

Stream-aquifer system: Consists of a stream that is hydraulically connected to the aquifer across which it flows. Ground water generally discharges from the aquifer to the stream. Surface water may infiltrate the aquifer along losing reaches of the stream or may be induced into the aquifer where ground water is withdrawn from wells near the stream.

Superfund: The popular term for a financing mechanism of the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) of 1980, which is implemented by the U.S. Environmental Protection Agency. Funds under the act may be used to respond to releases or threatened releases of hazardous substances into the environment (Pye and others, 1983, p. 242, 254-255).

Surface runoff: Water that travels over the land surface to the nearest stream channel. See also Overland flow.

Till: Predominantly unsorted, unstratified sediments deposited directly by a glacier and composed of boulders, gravel, sand, silt, and clay mixed in various proportions. Sometimes called unsorted drift. Colloquially, it is sometimes referred to as "hardpan."

Trace element: An element that always or nearly always occurs in concentrations of less than 1.0 milligram per liter in natural water (Hem, 1985, p. 129).

Transmissivity: The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient. More simply, transmissivity is a measure of the ability of an aquifer to transmit water. An aquifer's transmissivity is equal to its average horizontal hydraulic conductivity multiplied by its saturated thickness. Reported in units of feet squared per day, which is a simplified form of cubic feet of water per day per vertical prism of aquifer 1 foot wide.

Transpiration: The process whereby plants release water vapor to the atmosphere.

Turbidity: The extent to which penetration of light is restricted by suspended sediment, microorganisms, or other insoluble suspended material in water.

Unconfined aquifer: An aquifer in which the upper surface of the saturated zone, the water table, is at atmospheric pressure and is free to rise and fall. Also called a water-table aquifer.

Unconsolidated: A term used to describe earth materials in which the particles are loose, not firmly cemented or interlocked. For example, sand is unconsolidated and sandstone is consolidated.

Unsaturated zone: The subsurface zone between the land surface and the water table, containing air, gases, and variable amounts of water.

Viscosity: The property of a fluid that allows the fluid to resist motion and deformation under an applied force. The greater the viscosity of a fluid, the more slowly it flows. Viscosity in liquids is caused by the cohesiveness of the molecules, and is affected by temperature and pressure.

Volatile organic compounds (VOCs): Synthetic organic compounds that include hydrocarbon or halogenated hydrocarbon molecules. Many are industrial solvents and degreasers.

Water table: The upper surface of the saturated zone in an unconfined aquifer. It is defined by the levels at which water stands in wells that penetrate just deep enough to contain standing water. In wells that penetrate to greater depths, the water level will stand above or below the water table if an upward or downward component of ground-water flow exists.

Water year: A continuous, 12-month period, selected to present data relative to hydrologic or meteorologic phenomena, during which a complete annual hydrologic cycle normally occurs. The water year used by the U.S. Geological Survey is October 1 through September 30. For example, October 1, 1984 through September 30, 1985 is the 1985 water year.

Watershed: (1) Drainage basin; (2) the divide separating one drainage basin from another. The first meaning is the more current usage, whereas the second meaning was common in the past. The terms "drainage basin" and "drainage divide" are preferred, because the meaning of the term "watershed" may be ambiguous.

Well screen: The intake section of a well, specially designed for obtaining water from unconsolidated materials, such as sand. The screen allows water to flow freely into the well and prevents sand from entering with the water.

Wentworth grade scale: A commonly used grade scale for particle-size classification, proposed by Wentworth (1922). A grade scale is a systematic division of a continuous range of particle sizes into a series of classes or grades. The Wentworth grade scale ranges from clay particles to boulders.