

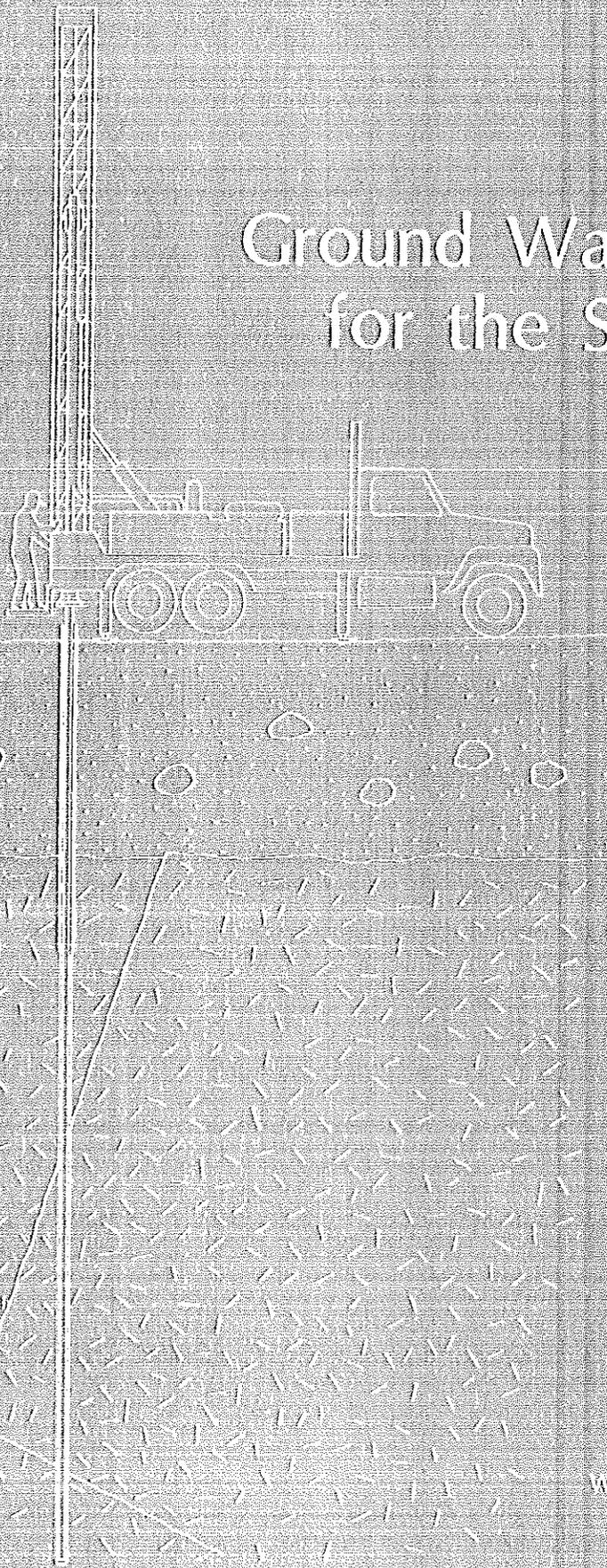
BULLETIN 39

Ground Water Handbook for the State of Maine

Second Edition

by
W. Bradford Caswell

Walter A. Anderson, State Geologist
Maine Geological Survey
DEPARTMENT OF CONSERVATION



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for the
STATE OF MAINE

Second Edition

W. BRADFORD CASWELL, Ph.D.

Maine Geological Survey

DEPARTMENT OF CONSERVATION

Walter A. Anderson, State Geologist

1987

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INTRODUCTION

Ground water is a plentiful and widely used natural resource in Maine. Not only do thousands of households obtain their potable water supply from private wells, but a large number of municipalities obtain at least some of their supply from ground water sources. Commercial and industrial businesses also use ground water, sometimes in large quantities, for processing, cooling, and other purposes.

As population and economic growth increase, the demands on ground water and the threat of ground water pollution will also increase. Individuals, municipalities, and other government agencies need to make, and are making, decisions about obtaining useful quantities of water and about protecting these water supplies from contamination and depletion. To make thoughtful decisions, however, people need a basic knowledge of ground water as it occurs in Maine and New England. This handbook is written to provide such ground water information in a format that is both useful and interesting to the general and specialized reader.

The Ground Water Handbook is divided into four major chapters. The first chapter is a general introduction to ground water geology, or hydrogeology. It begins with the basic concepts of the origin, occurrence, and movement of ground water, then expands from the ground water theory to discuss more practical aspects such as aquifers, springs, wells, and changes in ground water quantity and quality caused by nature and by man.

The second chapter of the handbook is a brief summary of ground water use, abundance, quality, and sources in Maine.

The third chapter describes ground water and related maps and reports that are available in Maine from the Maine Geological Survey and the U.S. Geological Survey. These publications provide additional details about the abundance, quality, and sources of ground water in Maine. Their use requires at least a background knowledge of geology and hydrology, thus the use of these available materials in conjunction with this handbook is recommended.

The final chapter of the handbook discusses and gives examples of some typical problems encountered in Maine with providing suitable ground water supplies, and with preventing ground water contamination and other undesirable changes in natural ground water conditions.

Throughout the handbook, key technical words and phrases are underlined to indicate their common use in technical discussions of ground water. The Index of this handbook will help the reader locate the definition and discussion of these important terms, while the Bibliography will identify other useful publications with more specific and detailed technical information than is presented here. Also included at the end of the handbook is a table of letter symbols commonly used in ground water reports.

CHAPTER 1

GROUND WATER HYDROLOGY

GENERAL GEOLOGY OF MAINE'S GROUND WATER SOURCES

Maine obtains useful supplies of ground water from two sources of very different geologic origin--unconsolidated surface sediments deposited by glaciers over the last two million years, and underlying consolidated bedrock formations that began forming hundreds of millions of years ago.

The bedrock formations that form the foundation of Maine and New England come from the same variety of sources active in the world today, including volcanoes (lava and ash), intrusion of molten rock (granite and gabbro), and weathering and erosion of landforms (sandstone and mudstone). Regardless of their various origins, however, these bedrock formations have very similar ground water bearing characteristics because of metamorphism and crustal deformation that has left them first brittle and now highly fractured. Metamorphism, caused by high heat and pressure associated with deep burial in the crust, changed the texture and mineralogy of the original formations giving us today the hard schists and gneisses that are seen nearly everywhere in Maine and New England except where there are granitic rocks.

Like the numerous granites and gabbros that cooled slowly from intrusions of molten rock several miles beneath the ancient crust, the metamorphic rocks are water bearing only where they are fractured. This is quite in contrast to bedrock formations in other parts of the country, for example along the Atlantic coast south of New York City. Sandstone formations in this region are unmetamorphosed and therefore retain their original high potential for ground water storage and transport in the open spaces and channels among the sand grains.

Unconsolidated sediments that overlies the bedrock formations are largely products of continental glaciers that spread across Maine and New England as far south as Long Island, New York. Much of what is seen today was deposited during the last 100,000 years by the most recent period of glaciation that ended in Maine around 10,000 years ago.

Advance of the mile thick ice across the land left widespread deposits of mixed clay, silt, sand, cobbles, and boulders called till. The ice-sheet's annual, and eventually complete, melting left more restricted deposits of sand and gravel that are important sources of ground water today.

An unusual event occurred in Maine as the climate warmed and the ice sheet melted away. The weight of the ice had so depressed the underlying bedrock formations in Maine's coastal region that the ocean flooded the area for a period of perhaps 600 years until the land surface rebounded again. Throughout this area of temporary marine transgression, glacio-marine silt and clay deposits now cover the glacial till and sand and gravel deposits. The clay and silt are not a source of abundant ground water in Maine, but are important because their low permeability has a strong influence on the occurrence and quality of ground water in the underlying glacial and bedrock aquifers.

(A more complete description of glacial events in Maine can be found in the "Surficial Geology Handbook for Coastal Maine", by Woodrow B. Thompson, Maine Geol. Surv., 1978.)

GENERAL GROUND WATER PRINCIPLES

GLOBAL DISTRIBUTION AND CIRCULATION OF WATER

Ground water is a part of the hydrosphere¹, which includes all of the water of the oceans, rivers, lakes, lower atmosphere, and subterranean environments. Ground water accounts for less than 1% of all the water in the hydrosphere. As tiny as this amount might first appear, it is nearly seven times the amount of fresh surface water available at any one time.

There is a constant interchange of water throughout the hydrosphere from sea water to atmospheric moisture to surface water to ground water. This change of water forms is known as the hydrologic cycle. The basic components of this cycle are illustrated in Figure 1.

There is no beginning or end to the hydrologic cycle, which involves a layer of the atmosphere 10 miles thick and at least 1/2 mile of the lithosphere (soil and rock).² Precipitated water returns to the earth in a variety of forms

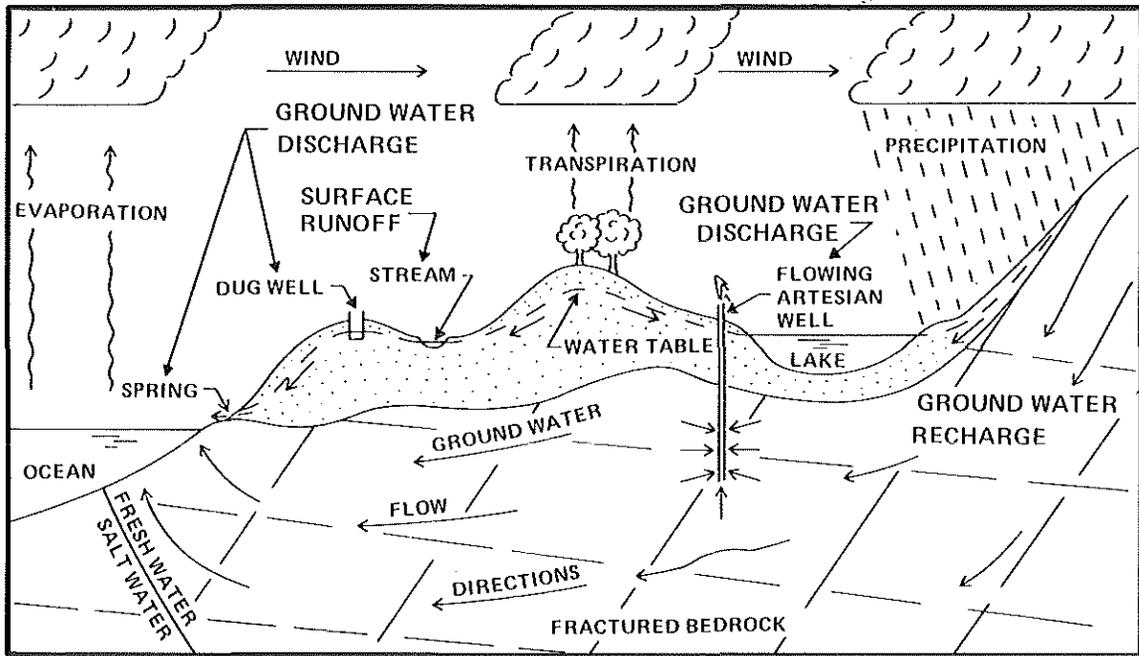


Figure 1. The hydrologic cycle.³

and may be intercepted or transpired back to the atmosphere by plants. It may run over the ground into streams and lakes or may soak into the soil. Much of the precipitation is soon evaporated back into the air. A small amount moves downward through the soil to a zone of saturation.

This ground water is later discharged directly to streams and lakes or to springs and seeps, from which it may run off to streams or be evaporated into the atmosphere. Ultimately, surface and ground water flow back to the oceans to complete the cycle, which may take hours, or thousands and even millions of years.

THE HYDROLOGIC EQUATION AND RECHARGE

All of the water on the continents originates as precipitation. The hydrologic equation is a simple expression of the relationship between this precipitation and evaporation, infiltration, and streamflow:

$$\text{precipitation} = \text{evaporation} + \text{infiltration} + \text{streamflow}$$

Although it is difficult to measure, except through estimates from the hydrologic equation, infiltration is the amount of precipitation that soaks into the ground. Part of this infiltration soaks into the soil and moves slowly downward to a depth below the ground surface where all the open spaces in rock or soil are full of water. This water that saturates the soil and rock is called ground water.

Ground water occurs in the saturated zone of the earth's crust (Figure 2). The upper surface of the saturated zone is the water table. Above the water table the open spaces are partly filled by water and partly by air; thus, overlying the zone of saturation is the unsaturated zone (or zone of aeration, or vadose zone). Between the saturated and unsaturated conditions is an intermediate zone where water is held above the water table in tiny interconnected openings by adhesion, cohesion, and surface tension, that is, by capillary attraction. This capillary fringe does not readily release water to springs or wells, but movement of water and its dissolved constituents does occur. It is only a few inches thick in coarse sand and gravel deposits, but can be as much as ten feet thick in clay and silt deposits.

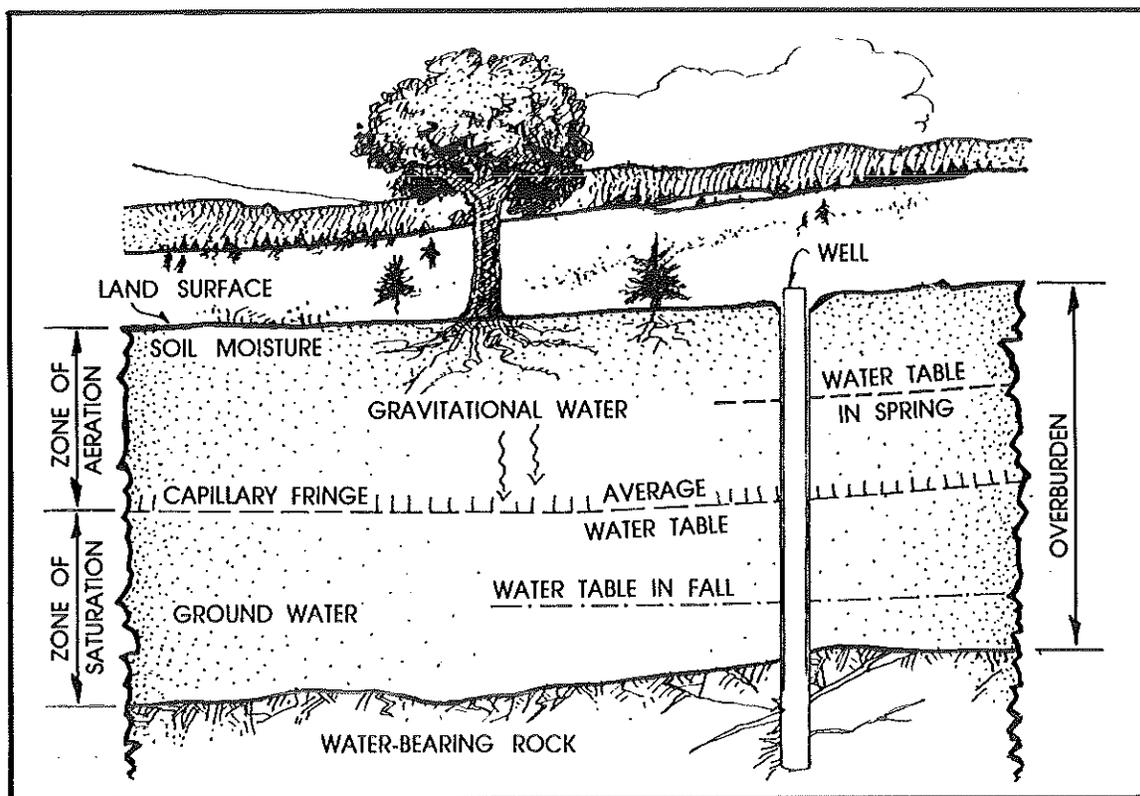


Figure 2. Divisions of subsurface water.⁴

Water infiltrates at greatly differing rates from place to place and time to time. The chief variables that determine infiltration rate are soil moisture from previous precipitation, soil texture, vegetational cover, land slope, and frost penetration. Some infiltrated water never penetrates the soil deeply, but that which does and is added to the saturated zone is called recharge water, or simply recharge.

Cumulative values for precipitation, evaporation, and recharge during the course of a normal year are shown in Figure 3. Even though there is a continuous accumulation of

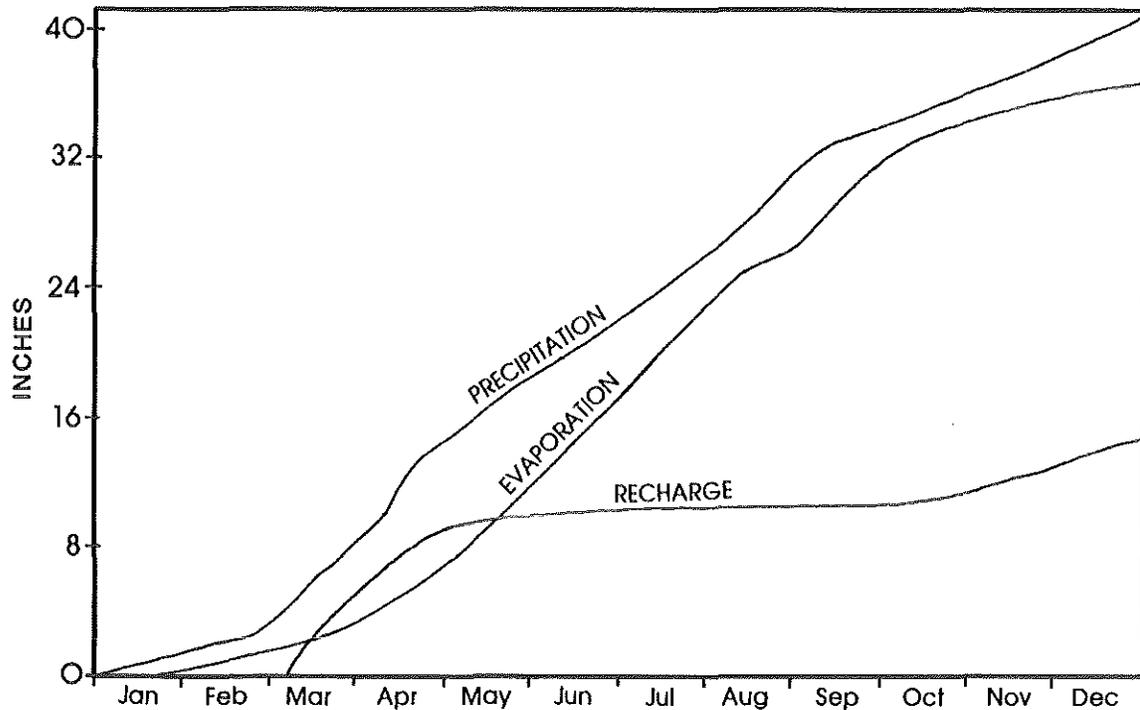


Figure 3. Annual accumulated precipitation, evaporation, and recharge.⁵

precipitation, recharge of ground water occurs mostly during the late winter, spring and fall months. This phenomenon is explained partly by the decrease in rainfall and increase in evaporation during the summer (Figure 4), but mostly by the fact that water cannot pass through the zone of aeration when the soil in this zone holds less than a particular level of moisture, often called the field capacity. Vegetation transpires water into the atmosphere and tends to keep the aerated zone relatively dry during the summer and early fall months. For most of the growing season, there is a soil moisture deficit; that is, the soil will absorb rainfall without letting any water pass through to a depth of more than a few inches. Water in the soil is held by strong tensional forces that are not overcome by gravitational forces until the soil is very wet. The soil will let gravitational water pass through only when the overall moisture content is large enough to satisfy the tensional attraction of the soil particles. Soil at field capacity contains all the water it can hold against gravity. Thus, any additional water will flow through a soil that is at field capacity. Other factors affecting recharge in Maine include frozen ground that restricts infiltration, and precipitation that falls as snow and is therefore not immediately available for infiltration and recharge.

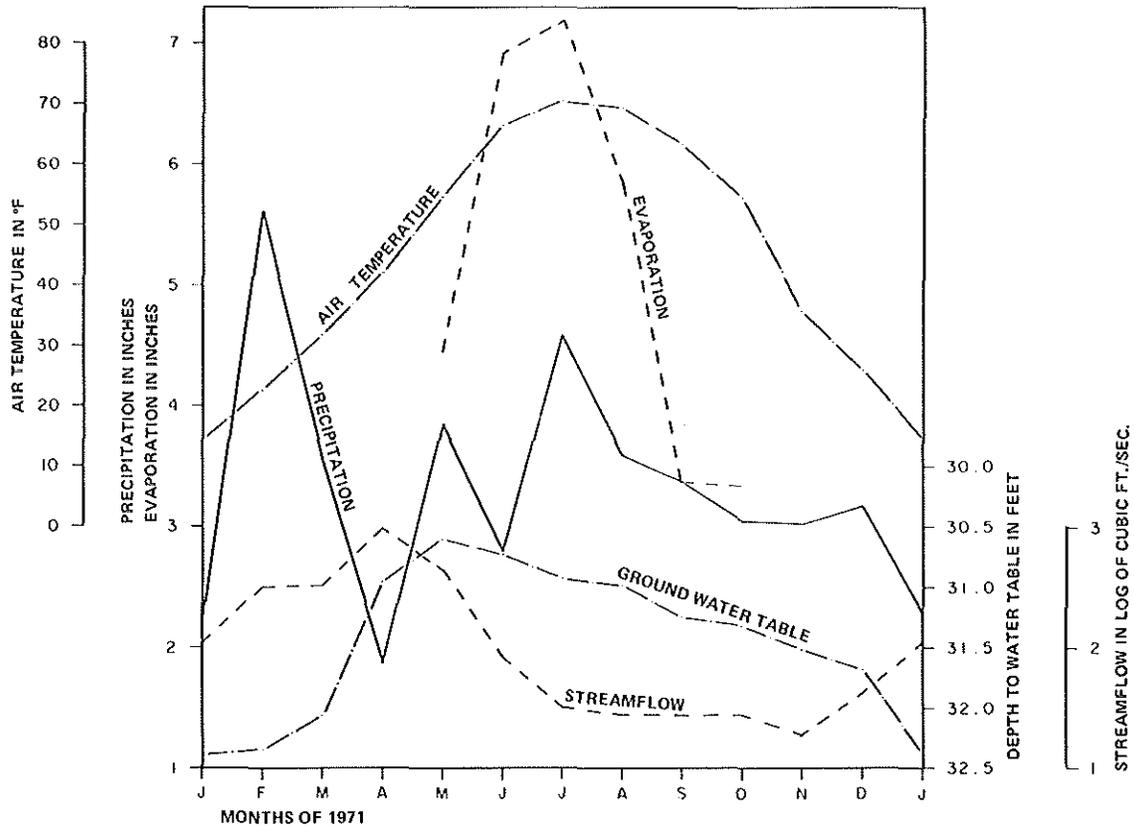


Figure 4. Comparison of hydrologic measures for 1971 in Maine. ^{6, 7}

In the most general situation, recharge water migrates downward to the zone of saturation and forms a permanent water table, as depicted in Figure 2. Where there are intervening layers of poorly permeable material, such as clay lenses in a gravel deposit, downward movement of water is impeded, and a perched water table will form (Figure 5). Ground water whose upward movement is impeded because it is trapped beneath a poorly permeable layer becomes confined and forms an artesian water system (Figure 6).

Peak levels for ground water in the spring occur somewhat after peak streamflow because of the time required for downward percolation of the recharge water. The most important aspect of ground water levels, however, is that they decline at a very much slower rate than streamflow. The chief reasons for this much slower decline are that ground water discharges at a slower rate and is not affected as much as streamflow is by evaporation and transpiration by plants (Figure 4).

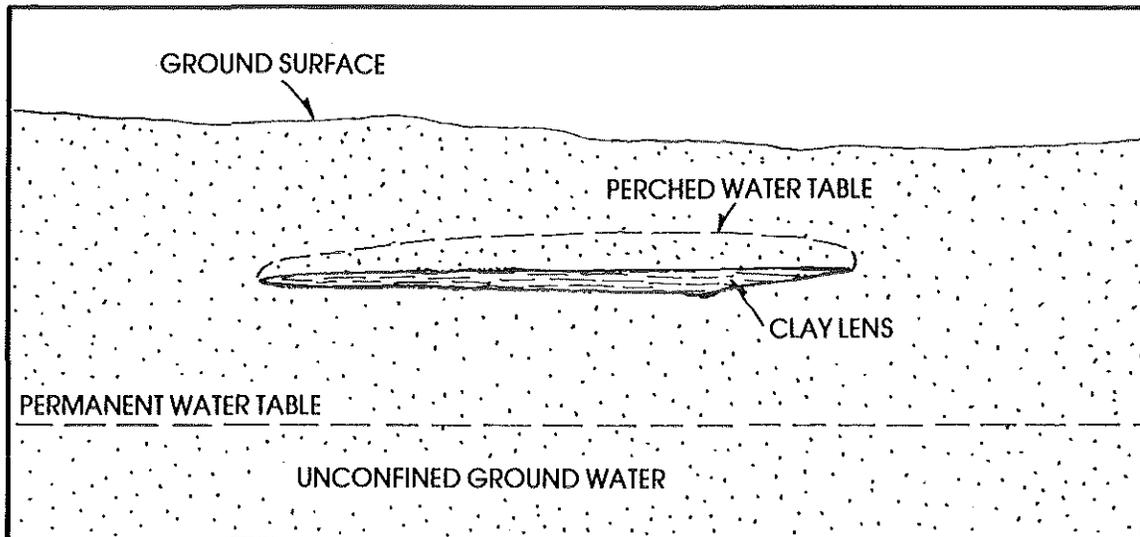


Figure 5. Permanent and perched water tables.

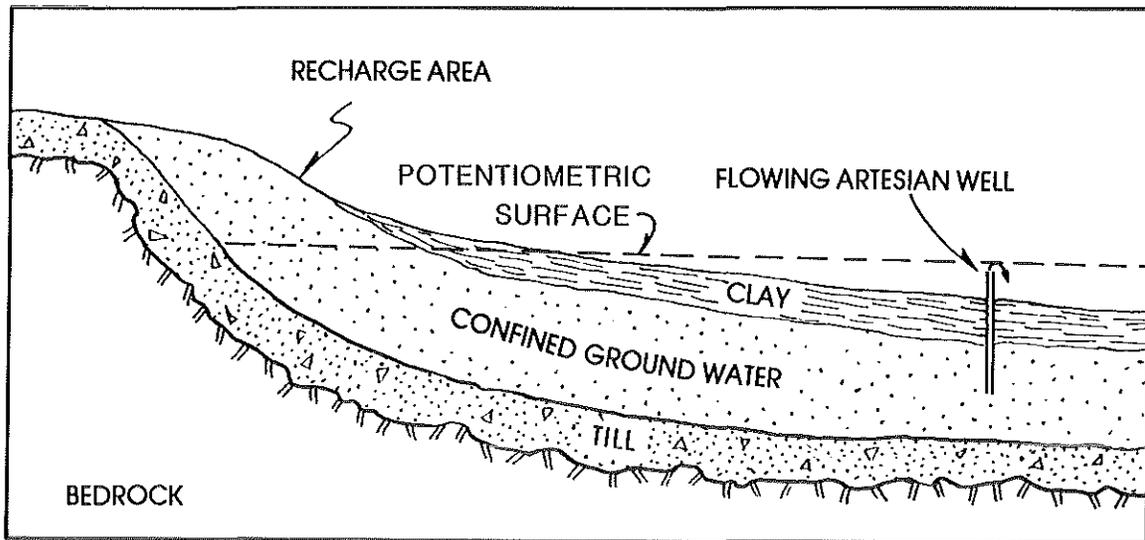


Figure 6. Artesian water system.

GROUND WATER IN POROUS MATERIALS

The origin, number, and total volume of open spaces in the crustal materials in which ground water occurs vary considerably from one material to another, most noticeably between loose sediments and bedrock. Loose, unconsolidated materials have internal spaces among the constituent particles called interstices (Figure 7). A pail of sand, for example, will absorb a large volume of water before overflowing. The water fills the voids among the grains of sand. The percentage of the bulk volume of material occupied by interstices is its porosity. As indicated in Table 1, the porosity varies from one material to another. The greatest contrast in porosity is

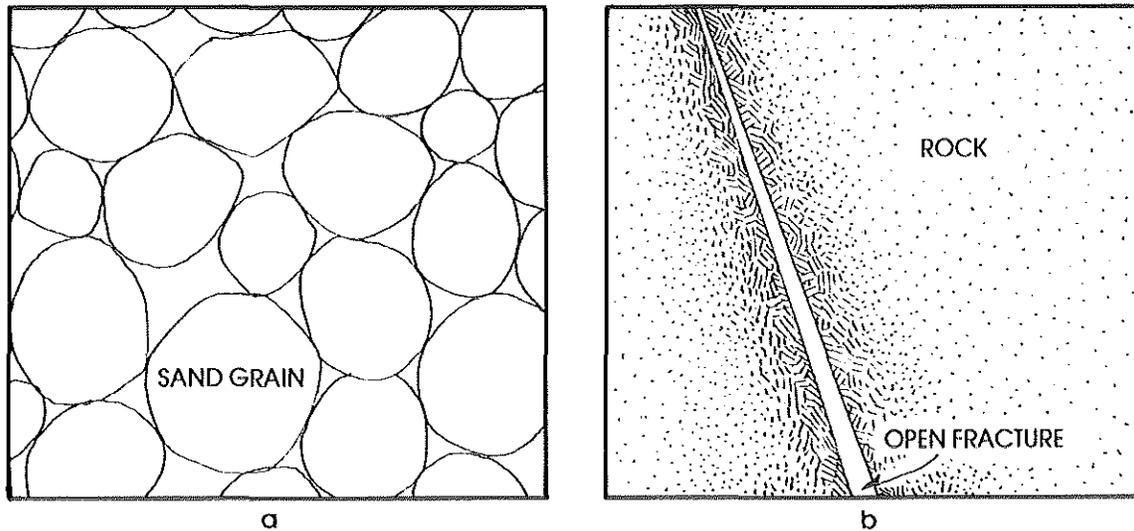


Figure 7. Openings in unconsolidated material (a), and consolidated bedrock (b), in which ground water can be stored.

Table 1. Representative values of porosity, specific yield, and hydraulic conductivity of consolidated and unconsolidated materials.⁸

	Porosity %	Specific Yield %	Hydraulic Conductivity (Permeability) gal/day.ft ²
clay	45	3	1
sand	35	25	800
gravel	25	22	5000
gravel and sand	20	16	2000
dense limestone and shale	5	2	1
granite	1	0.5	0.1

between unconsolidated sediment and dense rock types. Most rocks in Maine and New England have lost their original porosity due in part to recrystallization (metamorphism), which occurred under conditions of elevated temperature and pressure in the geologic past. This crystalline bedrock, as it is called, also includes large areas of intrusive bedrock, such as granite, that crystallized from a melt, and therefore contains few open spaces. There are essentially no primary openings in

crystalline rocks, but there are secondary openings where the rock is broken by faults and joints. A fault is a fracture in rock along which there has been displacement of the two sides relative to one another parallel to the fracture, while a joint is a fracture along which no appreciable movement has taken place. These cracks, or fractures, are generally spaced several feet apart in crystalline rock. Thus, the bulk porosity of the underlying bedrock is very small.

If all the interconnected interstices of a material are filled with water, the material is considered saturated. The volume of water that drains freely from a saturated substance generally is less than the volume of water it initially absorbed when dry. Because of tensional forces, some water clings to the walls of the interstices and reduces the size of the interconnected openings that transmit ground water. These openings represent the effective porosity, which is the ratio of the void space through which flow can occur, compared to the total volume of the porous material. Similarly, specific yield is the ratio of the volume of water that drains from the material, as compared to the total volume of the porous material. Referring to Table 1, it is seen that the coarser texture and larger pore size of gravel allows more water to drain through it than does clay. Clay is very porous, but the individual openings are so tiny that tensional forces are relatively large. A cubic foot of gravel drains more water from its void spaces than does a cubic foot of clay, even though the total percent of void space in clay is nearly twice that of gravel.

Specific yield indicates the volume of water that drains from a porous substance, but does not tell how quickly the water drains out. Hydraulic conductivity (generally called permeability) refers to the relative ease with which a porous substance can transmit a liquid. For ground water work, it is typically defined as the rate of flow of water in gallons per day through an aquifer cross section of one square foot under a hydraulic gradient of one at the prevailing temperature. The term relates physical properties of both a porous medium and the fluid passing through it. Table 1 compares the permeability of various geologic materials, and it can be seen that sand and gravel have high values, while clay and dense bedrock (typical of Maine) have very low values.

It is interesting to note that there is no direct relationship between porosity or specific yield and permeability. This is because the rate at which water passes through a substance is very sensitive to the arrangement of individual particles. The same material deposited under two sets of conditions has different permeabilities, even though the specific yields are similar. The permeability of a sand and gravel deposit in place in the field is likely to be different from the permeability of that same material dug up and measured in a laboratory.

GROUND WATER FLOW

Flow Potential and Hydraulic Gradient

Precipitation falling on the land at any elevation above sea level is drawn by the force of gravity to lower and lower elevations, and finally back to the sea. Water carried aloft and precipitated at higher elevations acquires potential energy, or flow potential, that is given up as it journeys downward. Whereas surface water loses its potential very rapidly in time, ground water may retain the potential to flow for long periods of time. A stream flows at several feet per second, while ground water in the adjacent soil and rock flows only several feet per year. Were it not for the slow rate of water movement through the porous materials of the earth's crust, ground water would not occur at high elevations and within only a few feet of the ground surface; it would pass back to the oceans as rapidly as streamflow. Because ground water is maintained at higher elevations under hills, the water table tends to retain the general form of the surrounding topography, and is often referred to as a "subdued replica of the land surface".

The elevation of the water table in Figure 8 indicates the relative potential for ground water flow. Flow always follows the ground water slope, or hydraulic gradient, from areas of high potential to areas of low potential. This hydraulic gradient is maintained because of the slow downward movement of ground water. During prolonged drought, however, water tables lower and hydraulic gradients become flatter and flatter until there is much less potential for water movement. Note that Figure 8 and the following figures are highly exaggerated in the vertical dimension and that in reality hydraulic gradients are less, or flatter, than shown.

Recharge and Discharge

High potentials occur where water is added (recharged) to a ground water system, and low potentials occur where ground water is removed (discharged). This relationship is illustrated in Figure 8 where the water table is shown as being higher under the hills and sloping downward to where it intersects the surface of the water in the stream and swamp. Lines representing typical flow paths (also called flow lines) show that ground water is moving down away from the hilltops and up towards the stream and swamp into which ground water discharges. The stream and swamp are discharge areas, and the hilltops are recharge areas. There are a great variety of geologic situations that determine whether an area is one of recharge or discharge. Man-made situations, such as pumping a well, also affect recharge and discharge areas. Some of these complexities are discussed later in this handbook.

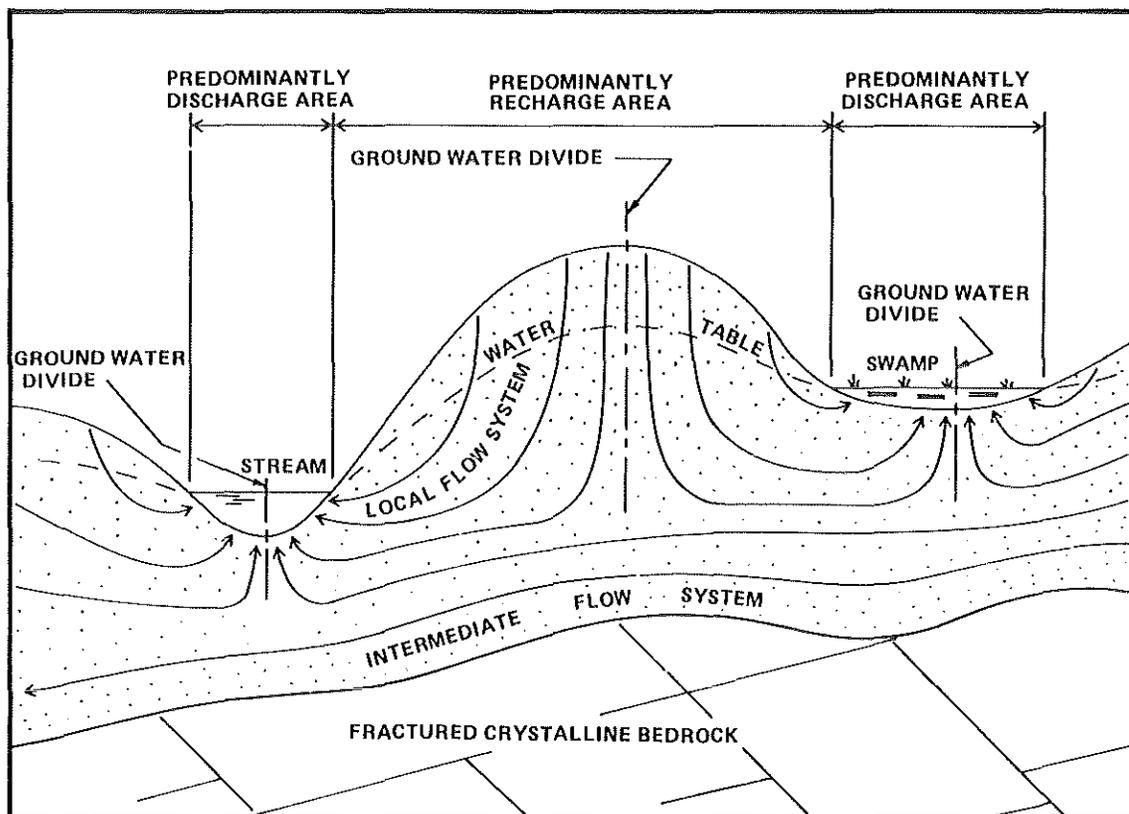


Figure 8. Ground water flow systems in unconsolidated materials.³

Flow Divides

Topography has much to do with the movement of both surface and ground water. Just as streams have drainage basins that are defined by divides that follow ridge lines, ground water flow systems are defined by ground water flow divides. The simplest type of ground water divide occurs beneath a hill where the gradient of the water table indicates that ground water flows essentially in opposing directions, similar to rain that falls on the hilltop (Figure 8). Usually in Maine, surface water divides and ground water divides coincide along ridge lines, but the situation illustrated in Figure 9 is also possible.

Ground water flow divides also occur where two directions of flow converge in a region of discharge, such as beneath the stream and swamp in Figure 8. The shallow ground water flow does not cross under, but discharges into the stream and swamp. The analogy with overland runoff can be applied here, as with the ridge line described above. Streams are not recognized as surface water divides, but it is obvious that overland runoff cannot cross from one side of a stream to another, and that, in fact, two directions of overland runoff converge at a common region of flow into a larger surface water body.

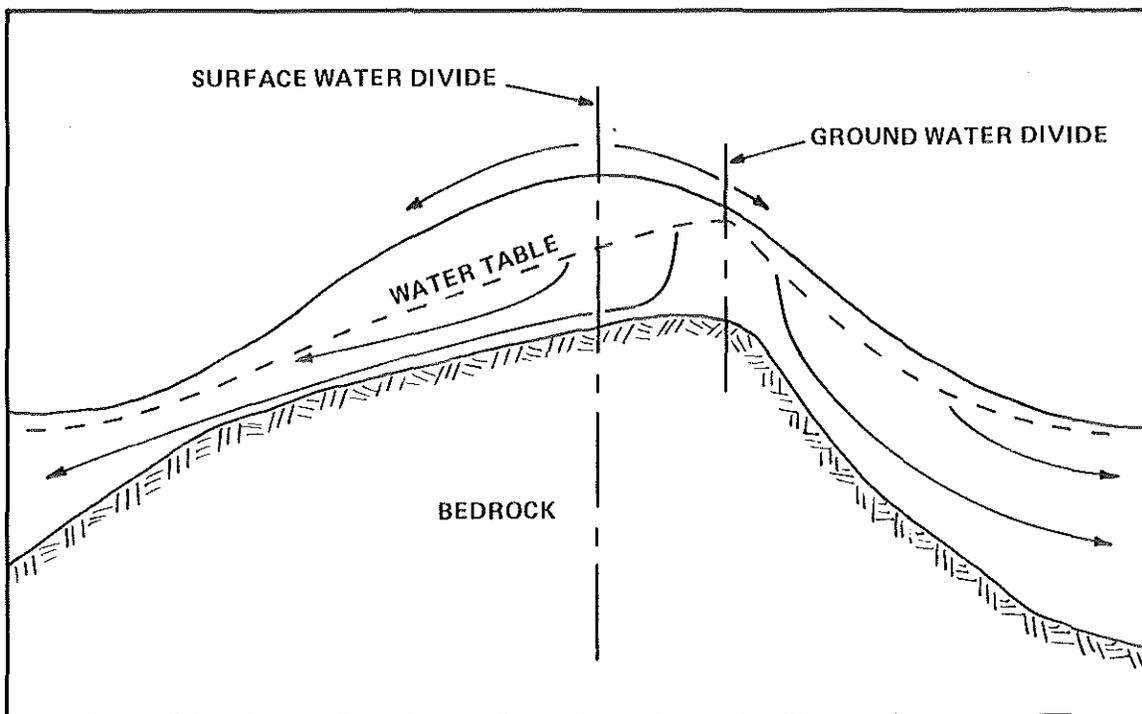


Figure 9. Non-coincident surface and ground water divides.

Shallow and Deep Flow Systems

Ground water divides are imaginary surfaces across which flow does not take place. In Figure 8, shallow ground water flow does not take place from the right to the left side of the central hill, nor from the right side of the stream to the left side. Deeper ground water flow, however, does pass under the hill and the stream and swamp. This deeper, or intermediate flow system bypasses local, shallower points of recharge and discharge. This ground water is derived from some recharge area outside of the figure; it will ultimately discharge at some point, probably the river to which the small stream shown in the figure drains. Still deeper, regional flow systems may occur in the underlying materials, whether loose sediments or fractured bedrock. All of these flow systems may occur within a ground water drainage basin. Overall ground water flow within the basin is from the higher elevations to the mouth of the stream that drains the basin. Many local ground water divides and directions of ground water flow occur within this larger drainage basin.

Most ground water flow patterns in Maine could not be classified as being "ideal"; rarely are the unconsolidated deposits texturally similar throughout (homogeneous) and equally permeable in all directions (isotropic), and bedrock is probably never so. The change in permeability between a sand or gravel overburden and the underlying bedrock can be very large. In some cases, the bedrock may be more permeable than

an overlying unit, but for the most part, the poor permeability of the bedrock surface has a strong influence on the directions of ground water movement in overlying sediments that are about 20 feet or less thick (typical of Maine). Water will follow the path that offers the least resistance to its movement; thus, it will flow more freely in the more permeable overburden. Figure 10 indicates how contrasts in permeability affect general directions of ground water movement.

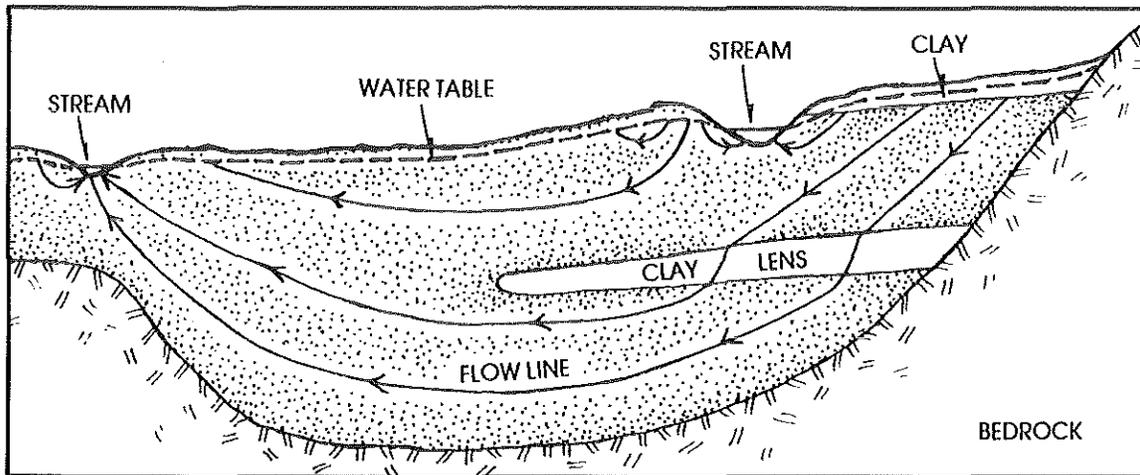


Figure 10. Idealized ground water flow in sandy glacial outwash deposit overlying bedrock.

Within the overburden, intermediate flow systems are usually controlled by the bedrock surface topography, as suggested by Figure 8. Ground water flow within the fractured bedrock is influenced by the overall topography of the land surface, the topography of the bedrock surface, and the geometry of the fracture systems. Faults have definable directions, and joints occur in what are called "sets", that have similar map directions and attitudes in space (dips). These fracture sets and their interconnections give bedrock preferred directions of permeability. On a local scale, fractured rock is strongly anisotropic, that is, permeability parallel to an open fracture is very high, but is essentially zero perpendicular to that fracture (Figure 11). On a regional scale, however, fracture geometry has less influence on overall ground water movement than has the configuration of the land surface.

Flow Near Streams and Lakes

Ground water movement in the vicinity of a stream flowing through an area blanketed by unconsolidated material is shown in Figure 12. The water table intersects the stream at its surface and rises away from the stream. Ground water

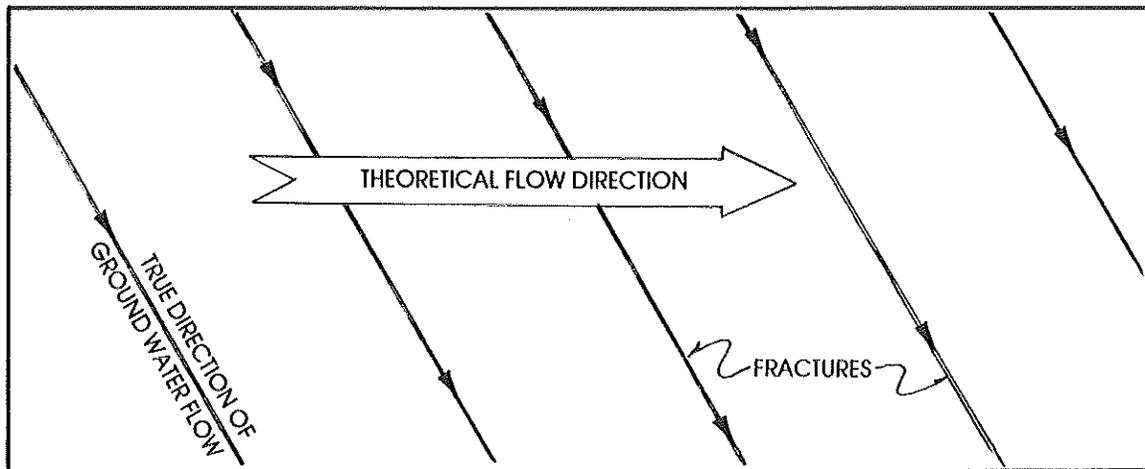


Figure 11. Plan view of ground water movement along available water-bearing fractures where theoretical flow gradient is from left to right.

discharges across a seepage face from the stream banks and directly into the stream itself. Thus ground water becomes surface water. This condition is called a gaining stream and is the normal situation in Maine, whether the stream crosses consolidated or unconsolidated materials. Under drought conditions surface water seeps downward through the stream bottom to become ground water. This condition is called a losing stream.

Lakes, like streams, tend to receive ground water inflow through at least some of their shore and bottom. As shown in Figure 13, ground water inflow is in addition to surface water inflow. Water loss occurs as normal outflow and evaporation. Figure 13 shows a typical lake in a bedrock depression where unconsolidated sediments cover most of the shore and lake bottom. Ground water flow occurs both in these unconsolidated sediments and in the adjacent bedrock.

A kettle pond is quite a different type of lake, as it usually occurs entirely within a permeable sand and gravel deposit (Figure 14). Such a pond typically has a very limited watershed area from which surface water flows into it. Its water level is representative of the local water table elevation, and most water flowing into the pond is ground water. A kettle pond may lose water by ground water outflow, as indicated in Figure 14. Other kinds of lakes also may contribute to ground water flow over some or all of their shore and bottom.

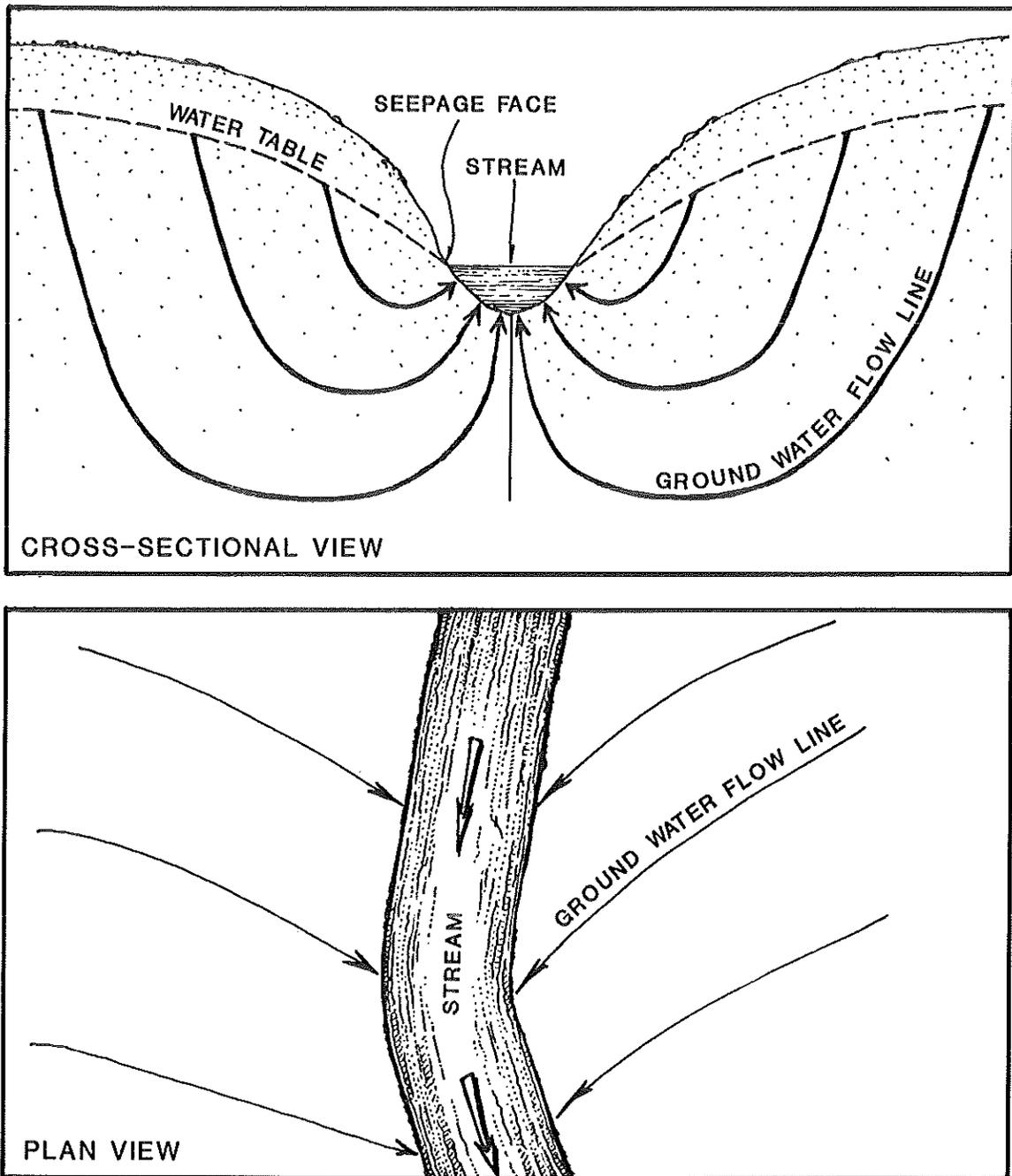


Figure 12. Ideal ground water flow adjacent to a gaining stream (typical of New England).

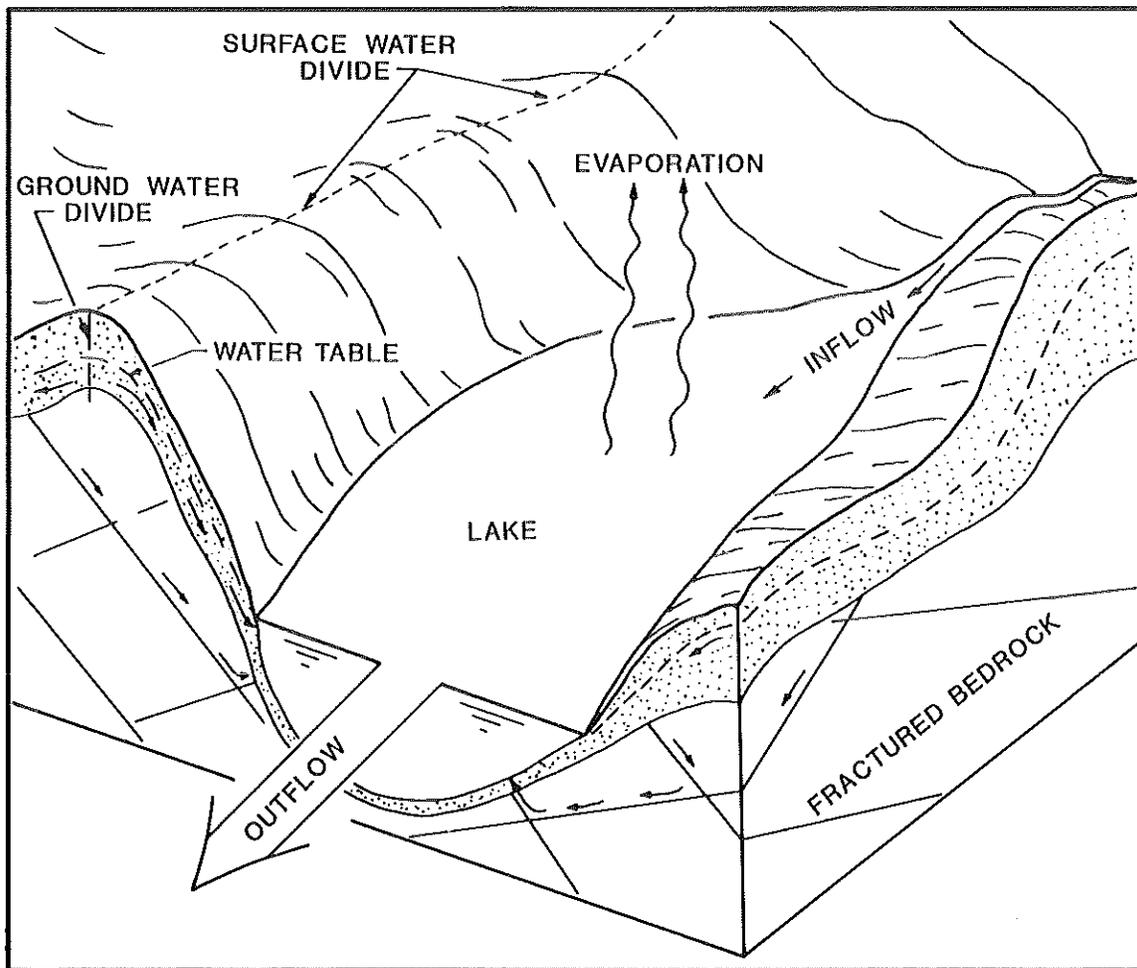


Figure 13. Surface and ground water flow in a lake basin.⁹

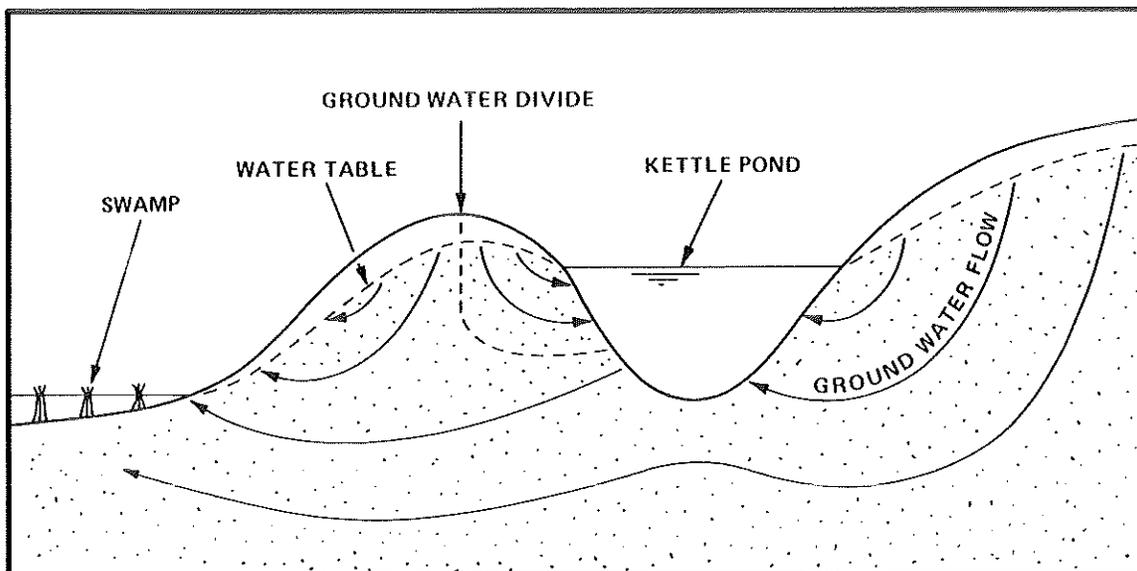


Figure 14. Ground water flow in overburden with kettle pond.¹⁰

Flow Rates and Quantities

Speed of ground water flow through a porous substance is related to the hydraulic conductivity of the material through which it passes, the hydraulic gradient, and the effective porosity of the material as in the following relationship:

$$\bar{v} = \frac{K i}{n_e}$$

where: \bar{v} = average seepage velocity (length/time),
K = hydraulic conductivity or permeability (length/time),
i = hydraulic gradient (length/length), and
 n_e = effective porosity (dimensionless).

In general, the higher the permeability and gradient, the more rapid the rate of flow. At the same hydraulic gradient, flow through a coarse clean sand is more rapid than through a less permeable clayey fine sand. Similarly, flow along a zone of fracturing is more rapid than through poorly fractured bedrock that is much less permeable. At a given permeability, flow is most rapid where the gradient is steepest such as near points of ground water discharge that include streams, springs, and pumping wells. Hydraulic gradient, however, is not only indicative of flow velocity, but is also indicative of the potential expended in moving ground water from one point to another. Clay is so poorly permeable that a steep gradient must develop before water flows through it. A coarse gravel deposit commonly has a very flat gradient, indicating that little potential is expended in moving water from one place to another. Of the two, permeability and gradient, permeability is usually the more important factor for determining the speed of ground water movement. Typical ground water flow rates in Maine within marine clay deposits are 0.02 to 0.8 feet per year, within glacial till deposits 5 to 11 feet per year, and within sand and gravel deposits 40 to 100 feet per year.

Quantity of ground water flow through a porous substance is related to the hydraulic conductivity, hydraulic gradient, and cross-sectional area of the material as in the following relationship:

$$Q = K i A,$$

where: Q = quantity of flow (length³/time),
K = hydraulic conductivity (length/time),
i = hydraulic gradient (length/length), and
A = cross-sectional area (length²).

In terms of ground flow through porous materials, their saturated thickness and breadth are just as important as the permeability and gradient. Under the same conditions of permeability and gradient, a broad sand and gravel deposit conducts a greater volume of ground water than does a narrow bedrock fracture zone.

MORE PRACTICAL ASPECTS OF GROUND WATER HYDROGEOLOGY

GROUND WATER DEMANDS

The volume of ground water required for households in Maine, that is, the minimum acceptable yield of a water well, depends largely on the lifestyle of the users. Homes with no running water or limited indoor plumbing might get by with a few tens of gallons per day. Well yield of a few pints per hour is sufficient as long as there is adequate storage in the well, which can be achieved in a deep, 6-inch diameter bedrock well, or in a shallow but large diameter dug well.

Homes with one or more bathrooms, dishwasher, clothes washer, cars to wash, and lawns and gardens to water require a well yield of about 5 gpm. Homes that do not utilize water for extensive outside uses, especially watering gardens, can operate on about 2 gpm.

The above well yields assume the average depth of drilled wells to be about 150 feet. A six-inch diameter drilled well can store about 1 1/2 gallons per foot of saturated depth. A 200-ft well with a static water level (the water level when the well is not being pumped) at 25 feet below ground surface stores about 262 gallons of water (175 ft of water x 1 1/2 gal/ft of well = 262 gallons). Two hundred sixty-two gallons of water fulfill the needs of a typical home for about one day (five persons using 55 gallons/day/person). Of course, domestic water use varies from hour to hour and day to day, and one does not wish to run the well dry. Generally, a well is not used at its maximum capacity. It is important also to realize that water needs in homes are greatest during daylight hours. If the well can supply the home during the day and then recover (refill) during the night, the instantaneous yield of the well can be surprisingly low.

Water use per household has increased over the last decades throughout the country, most likely because of the greater use of clothes washers, dishwashers, and indoor plumbing in general. As suggested by Table 2, the volume of water people actually drink has little to do with increases in demand. Table 3 suggests that people with individual water systems (wells) tend to use less water than those on municipal systems, but that by the year 2020, municipal and private users will require about the same quantity of water. It is felt that due to higher treatment, pumping, and distribution costs, and to possible water scarcity, all municipal taps will be metered, and that the water needs of these users will become more conservative.

Table 2. Domestic water consumption of typical home in Akron, Ohio, during the 1960's.¹¹

Water Use	Percent of Total
Flushing wastes	41%
Bathing	37%
Kitchen	6%
Drinking	5%
Washing clothes	4%
House cleaning	3%
Watering lawns	3%
Washing cars	1%

Table 3 . Domestic water withdrawals for municipal and individual systems. Based on 1968 estimates for the U.S.A.¹¹

Year	Municipal Systems	Individual Systems
1965	73 gal/day/person	51 gal/day/person
1980	77	58
2000	81	71
2020	83	83

AQUIFERS

An aquifer is a geologic deposit that yields useful quantities of ground water to wells and springs. The term has meaning only in relation to the demands and expectations of the people using the aquifer; in fact, what we think of as an aquifer in Maine might be considered an aquiclude, a poorly permeable geologic deposit, in other parts of the country.

Both hydraulic conductivity and saturated thickness are important to the water-bearing characteristics of aquifers. Transmissivity of an aquifer is its hydraulic conductivity multiplied by its saturated thickness, and is a measure of the amount of water that can be transmitted horizontally by the full saturated thickness of the aquifer under a hydraulic gradient of 1. For comparison, good sand and gravel aquifers in Maine have transmissivities ranging from 50,000 to 100,000 gal/day/ft (length²/time), and good fractured bedrock aquifers have values ranging from 2,000 to 7,000 gal/day/ft.

Gravel Aquifers

Gravel aquifers differ greatly in water yield depending on the texture, permeability, saturated thickness, and recharge potential of the geologic formation. The highest yielding gravel aquifers in Maine are typically glacial eskers (locally called horsebacks or whalebacks) and deltas, glacial outwash deposits, and alluvial deposits associated with modern rivers. Household water supplies are available from a great variety of sand and gravel deposits. Aquifers suitable for municipal or industrial use typically have at least 10 feet of very permeable water-bearing sand and gravel, at least 20 feet of overall saturated thickness, and potential for recharge from precipitation and from a nearby surface water body. Under these favorable conditions, yields of 100 to over 1000 gallons per minute are obtainable from gravel aquifers.

Bedrock Aquifers

Bedrock aquifers occur wherever the crystalline rock is fractured, sufficiently saturated, and can be recharged by precipitation that percolates through overlying sediments. A typical household well is at least 100 feet deep in order to intersect sufficient saturated thickness and number of fractures. Variations in well yield are substantial from one place to another, ranging from essentially dry to very high yields of 300 to 500 gallons per minute. The difference in yield is primarily due to the intensity of fracturing, but also to the permeability and saturated thickness of overlying unconsolidated sediments from which recharge is derived. In Maine and northern New England, rock type generally does not significantly influence the yields of bedrock wells. Granite, for example, may be well fractured and water bearing in one area, and incapable of furnishing anything but a small domestic supply in another area. Important water-bearing fractures appear to be associated with faults. These features are detected through study of aerial photographs, geophysical exploration, and geologic evaluation of bedrock outcrops. Investigated in detail by test drilling and pumping, fractured bedrock aquifers are typically local zones of intensive fracturing that have definable strike, dip, and thickness over distances of a few hundred feet to as much as a mile. Significant bedrock aquifers in crystalline rocks are best thought of as high-yield zones within the bedrock.

Water Table and Artesian Aquifers

There are two principal kinds of aquifers: (1) those with a free surface at the water table and known as water-table aquifers and (2) those associated with confined ground water and known as artesian aquifers. The chief difference between these aquifers is the manner in which ground water is released from storage within them. This difference is important to the way in which water wells in these aquifers function and relates to the susceptibility of aquifers to contamination.

The water table has been described as the upper surface of the saturated zone, above which the interconnected openings in the soil or rock are partly filled with air. If the water table falls, the depth of the overlying zone of aeration expands as air is drawn into the interconnected openings. If the water table rises, air is expelled into the atmosphere. Thus, the water table remains at atmospheric pressure at all times. At any depth below the water table, the hydrostatic pressure will be that caused by the weight of the overlying column of water plus the atmospheric pressure.

Ground water that is confined by a poorly permeable layer does not have free access to the atmosphere as does the water table. A confining layer must have at least 1/10 the permeability of the underlying water-bearing layer. Recharge to a confined aquifer cannot cause a rise in water level, but causes a rise in water pressure. The pressure at the upper surface of a confined aquifer is greater than that of the atmosphere.

Artesian ground water conditions occur in both consolidated and unconsolidated materials. In Maine's glacial deposits, the most common situation is gravel overlain by clay as illustrated in Figure 15. The gravel is the aquifer and the clay and silt are the confining layer.

In bedrock, the situation is somewhat different in that the aquifer is the fractured bedrock, and the confining layer is either relatively unfractured rock or overlying glacial clay and silt. Figure 16a is the most typical artesian system in crystalline bedrock in which solid rock confines water within a fracture zone. A more complex geologic situation is depicted in Figure 16b where the confining layer over the fractured bedrock aquifer is marine clay. Rain falling on the recharge area at some distance away and at higher elevation infiltrates the fractured bedrock and migrates down gradient to a discharge point at the flowing well. When the drill intersects this confined fracture at depth, the water in the well rises above the fracture, occasionally overflowing at the ground surface.

Because the water from the recharge area is restricted in its upward flow, it exists under hydrostatic pressure. This pressure, or head, is indicated in Figure 16 by a dashed line sloping from the recharge area to the well. This line

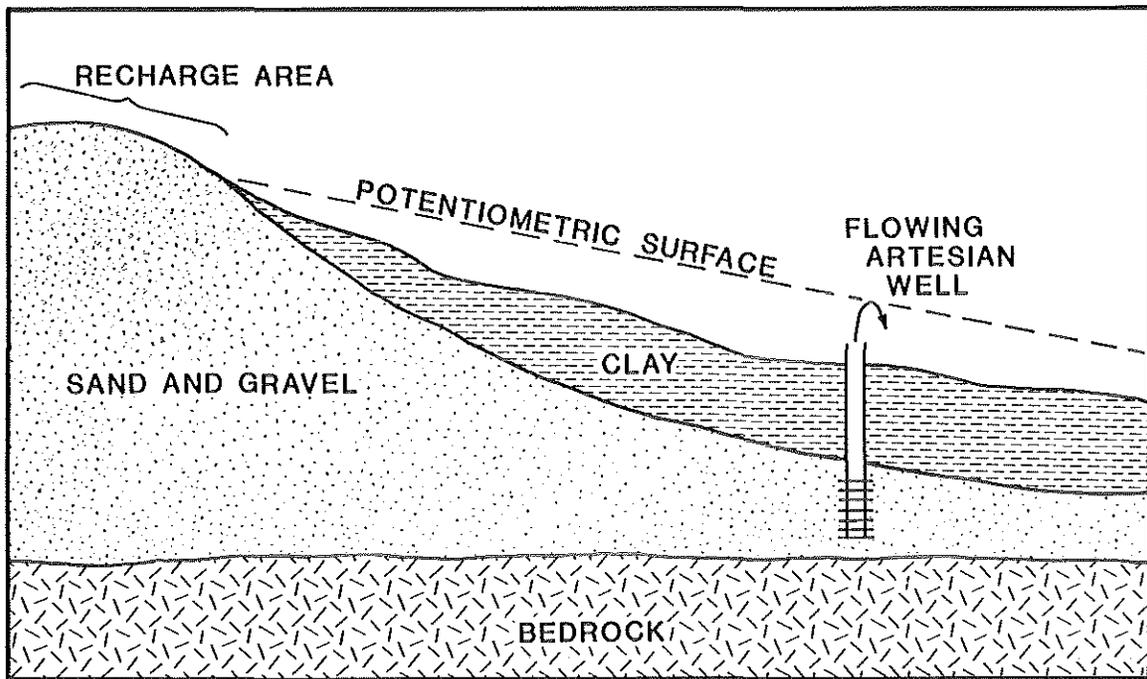


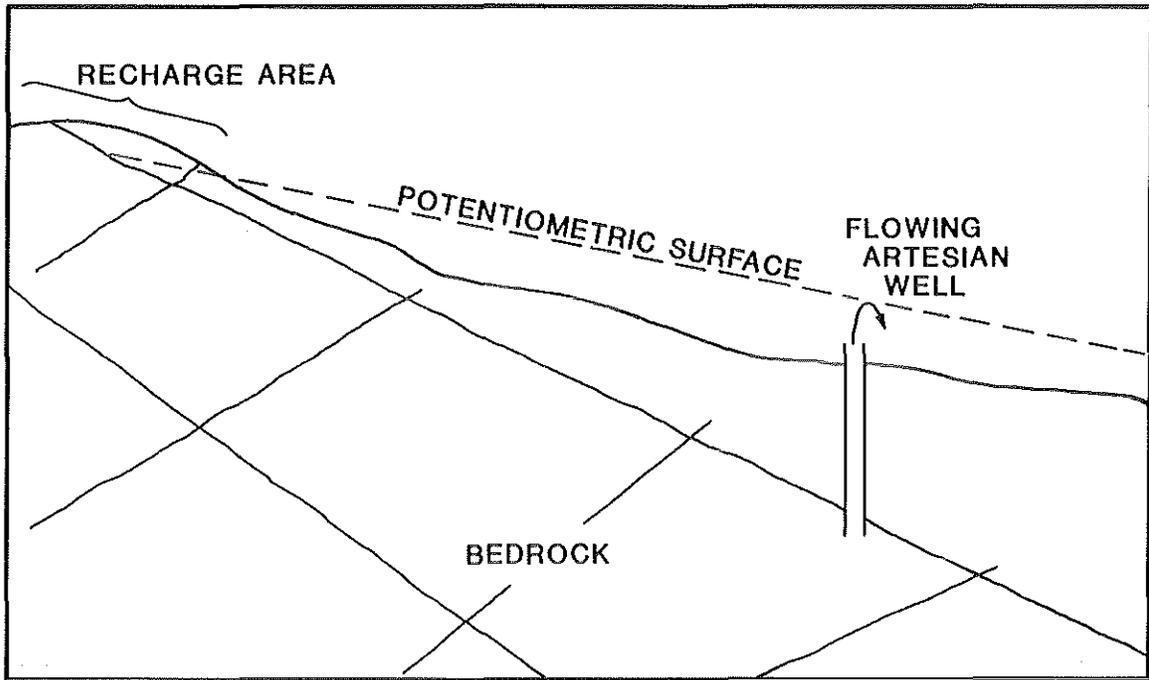
Figure 15. Cross section through artesian sand and gravel aquifer.

represents the potentiometric surface, which would be the natural elevation of the ground water if a well were drilled through the confining silt and clay layer and down into a fracture zone. The slope of the potentiometric surface is caused by frictional losses, called transmission head loss, as the water flows through the fractured bedrock aquifer. The slope of the potentiometric surface is the flow gradient of the artesian system, just as the water table is the flow gradient of a water-table system. Water will flow from points where this surface is high to points where it is low.

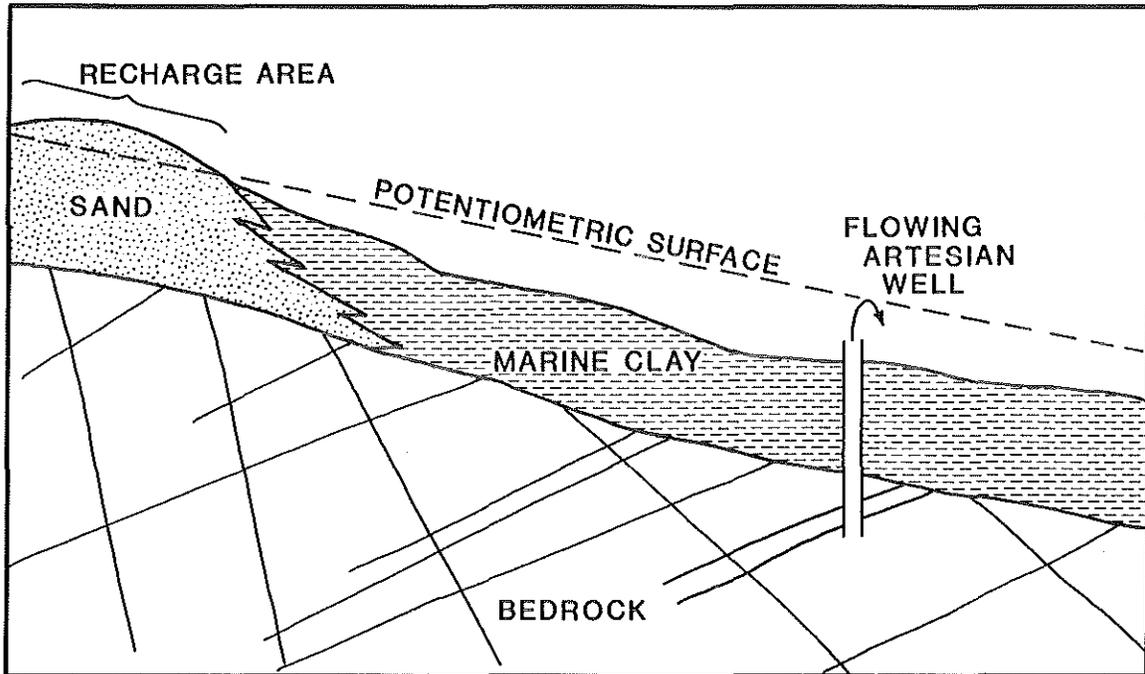
SPRINGS

In the natural movement of ground water, discharge occurs in numerous places, especially into streams. As much as 40% of Maine's streamflow is thought to be derived from ground water discharge.¹² Besides discharge into streams and other bodies of water, ground water comes to the surface at many other points. Wet areas of diffuse ground water discharge are termed seeps, while areas of more obvious flow are termed springs.

Spring water has had a certain mystique in the minds of people from ancient times to the present. Water that "magically" flows at the earth's surface and sometimes bubbles or boils out of the ground is reason enough for feelings of wonderment. Bottled spring water brings a premium price because of its presumed special qualities. Warm springs and mineral springs, some very high in odoriferous sulfur



A. Flowing artesian well where confining layer is unfractured bedrock overlying a water-bearing fracture.



B. Flowing artesian well where confining layer is less permeable overburden.

Figure 16. Bedrock artesian systems typical in Maine.¹⁰

compounds, have been bathed in for therapeutic effects for centuries. All of these kinds of ground water could be and are obtained by wells, yet bottled well water, if it were marketed as such, would find few buyers, and a household bath in sulfurous well water would find few takers.

Regardless of whether springs are magical and wells mundane, the source of both spring and well water is ground water. A spring is a natural point of noticeable ground water discharge; whereas a well is a man-made opening into the subsurface from which ground water can be extracted. Springs and wells occur in bedrock, as well as in unconsolidated sediments, and are influenced by the same differences in permeability, flow gradients, flow divides, and other hydrologic aspects. The flow rate of springs in Maine ranges up to several hundred gallons per minute.

Water-Table Springs

The typical spring in unconsolidated sediments results from the intersection of the water table and the ground surface where there is a significant contrast in permeabilities of strata. Figure 17 shows a water table in a gravel deposit overlying a less permeable till layer. Ground water cannot pass readily downward through the poorly permeable layer, but tends to spread laterally until discharge occurs at the gravel-till contact on the hillside. This is one example of a contact spring, where water is discharged at the contact between an overlying water-bearing layer and an underlying aquiclude.

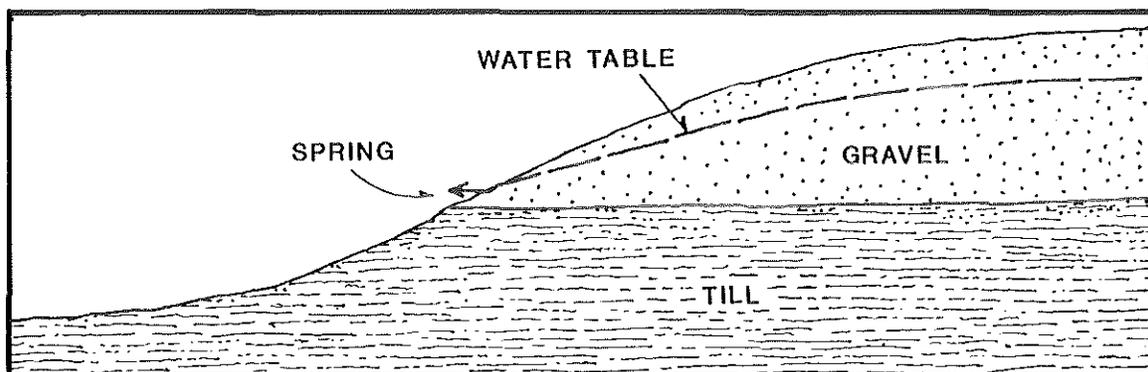


Figure 17. Contact spring in unconsolidated deposits at gravel/till interface.

Another common kind of spring is found where the water table meets the ground surface because of a cut or depression (Figure 18). A depression spring does not need a contrast in permeabilities, but only a gulley or pit entrenched to a depth below the local water table.

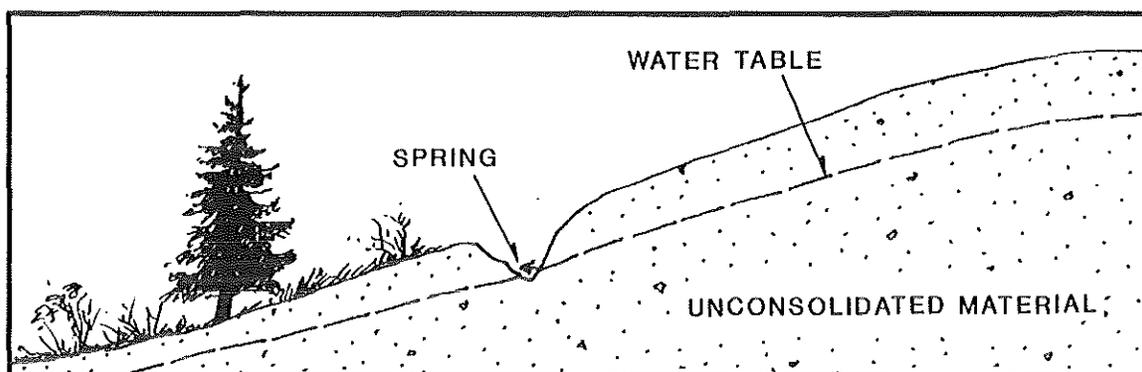


Figure 18. Depression spring in unconsolidated material cut by gully.

There are many variations of these kinds of springs that are associated with either perched or permanent water tables. Although these water tables occur most typically in unconsolidated sediments, they can also occur in bedrock where the fractures are numerous and open to the immediate ground surface. In such a situation a plumbing-system spring may occur in the bedrock (Figure 19).

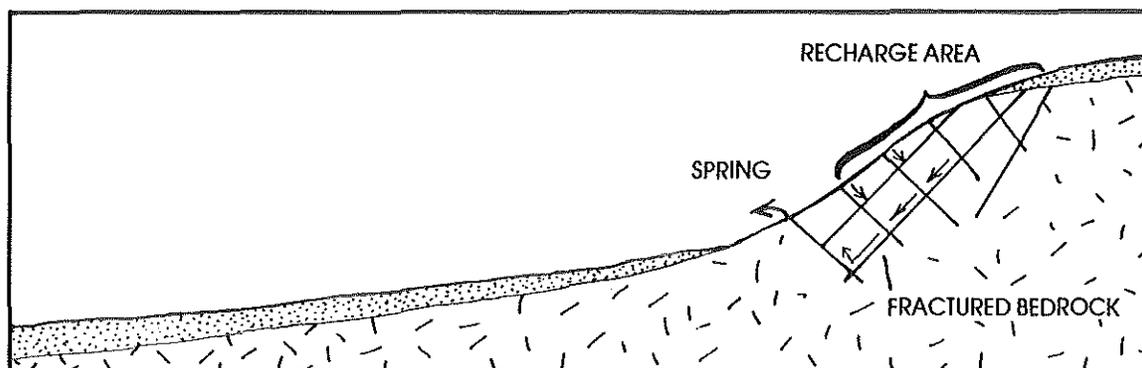


Figure 19. Plumbing-system spring occurring at base of fractured bedrock zone.

Artesian Springs

Artesian springs occur where confined ground water leaks to the surface through the overlying less permeable layer. They are found in sand and gravel and in bedrock.

A typical artesian spring occurs where clay overlies gravel. The clay layer confines the ground water under pressure, but where this confining layer is breached by an erosion channel or depression, is penetrated by roots that have decayed, or is otherwise absent, ground water will flow out to the ground surface (Figure 20).

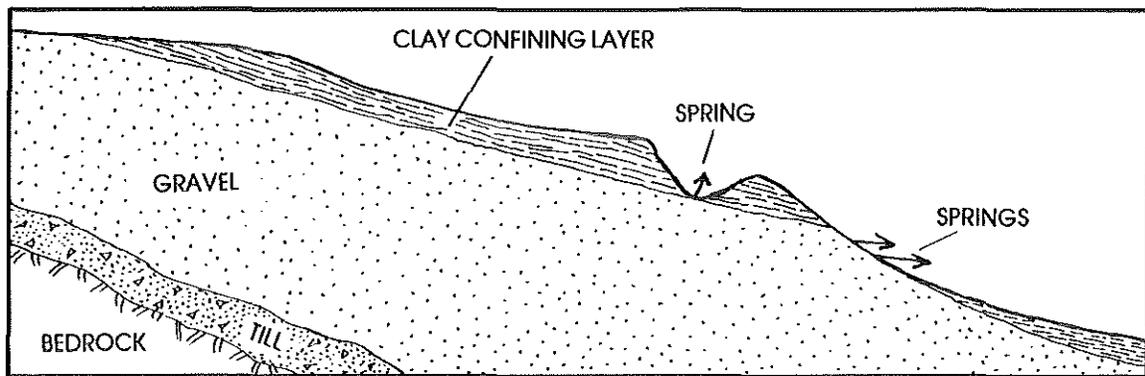


Figure 20. Artesian springs in unconsolidated materials.

An artesian spring in bedrock occurs where ground water, in a series of interconnected fractures recharged at higher elevation, finds its way to the surface through some fracture at a lower elevation than the recharge area. Some apparent water-table springs derived from unconsolidated sediments may be the result of springs in the underlying bedrock. Bedrock artesian springs probably are common, but go unrecognized.

WELLS: WATER TABLE AND ARTESIAN

Water-Table Wells

One kind of well is the water-table well. Drilled or dug down through the saturated zone, this well fills with water to the level of the surrounding water table. As the water table changes position due to pumping or seasonal variation, the water level in the well changes accordingly. The static (non-pumping) water level in such a well can be considered equivalent to the local water-table level. A water-table well is essentially nothing more than an enlarged pore in the porous medium from which water can be withdrawn.

When water is pumped out of a water-table well, the water table immediately surrounding the well begins to slope inward as the water is removed. In a homogeneous and isotropic, or "ideal", material, pumping causes a true cone of depression to form as illustrated in Figure 21. Flow potential, as indicated by equipotential lines inside this cone, is lower than in the surrounding aquifer; thus, ground water flows into the well by gravity. The water-table gradient is steepest near the base of the cone, where ground water flow concentrates and moves rapidly into the well.

As the well is pumped, the water level in the well lowers, and the cone of depression enlarges. Initially, the level drops quickly, and the cone spreads rapidly. But as the cone increases in volume, more and more water flows into the well. At some point, the discharge from the well is nearly equal to

the release of water from storage within the interstices of the aquifer, and the size of the cone becomes relatively stabilized.

Water released from the aquifer flows into the pumping well leaving the interconnected voids within the cone of depression drained to approximately the specific yield. In the vicinity of the pumping well the unsaturated zone has expanded at the expense of the water table. The form of this change is ideally an inverted cone, but is typically elongated in a down-gradient direction because of a sloping regional water table. In fractured bedrock, the cone of depression is often considerably elongated, as pictured in Figure 22. In all water-table situations, however, a "cone" of depression of whatever form defines a region of the aquifer that has been drained of water. When pumping of the well is ended, the drained region is refilled by water moving from other parts of the aquifer. If there is no additional recharge, the regional water table is slightly lowered. The water level in the well returns to the same elevation as the surrounding water table.

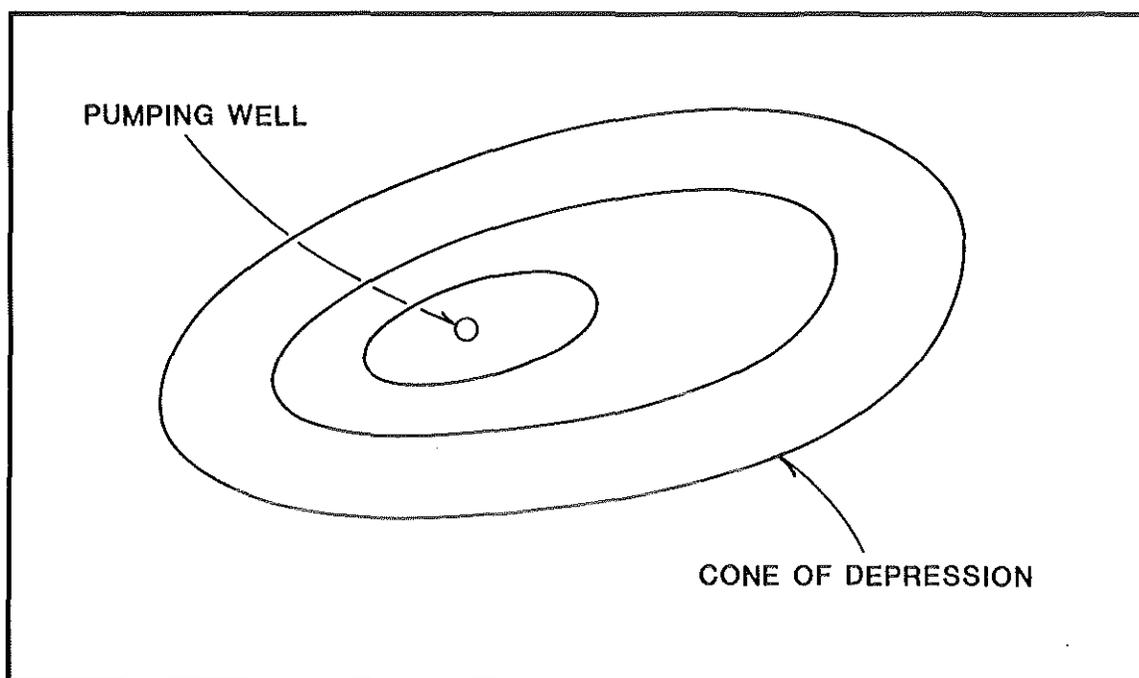


Figure 22. Map view of a cone of depression surrounding a well pumping in a fractured bedrock aquifer.

Artesian Wells

Artesian wells are a second kind of well. When such a well is dug or drilled through the confining layer of an artesian aquifer, water rises up the well to the level of the local potentiometric surface. In some cases this level is

higher than the ground surface, and the well flows naturally, without pumping. Otherwise, the water rises to some point higher than the lower surface of the confining layer.

Pumping an artesian well lowers the pressure in the well relative to that in the surrounding aquifer. The potentiometric surface around the pumping artesian well is lowered under ideal conditions in the form of an inverted cone. The cone of pressure relief is similar to the cone of depression, except that it represents a decrease in water pressure rather than a lowering of a water table (Figure 23). Whereas in a water-table aquifer the materials surrounding a pumping well are drained, in an artesian aquifer only the pressure on the water is decreased. Water is released from storage by expansion of the compressed water and by compaction and settling of the aquifer materials. This process releases only a very small amount of water per cubic foot of aquifer.

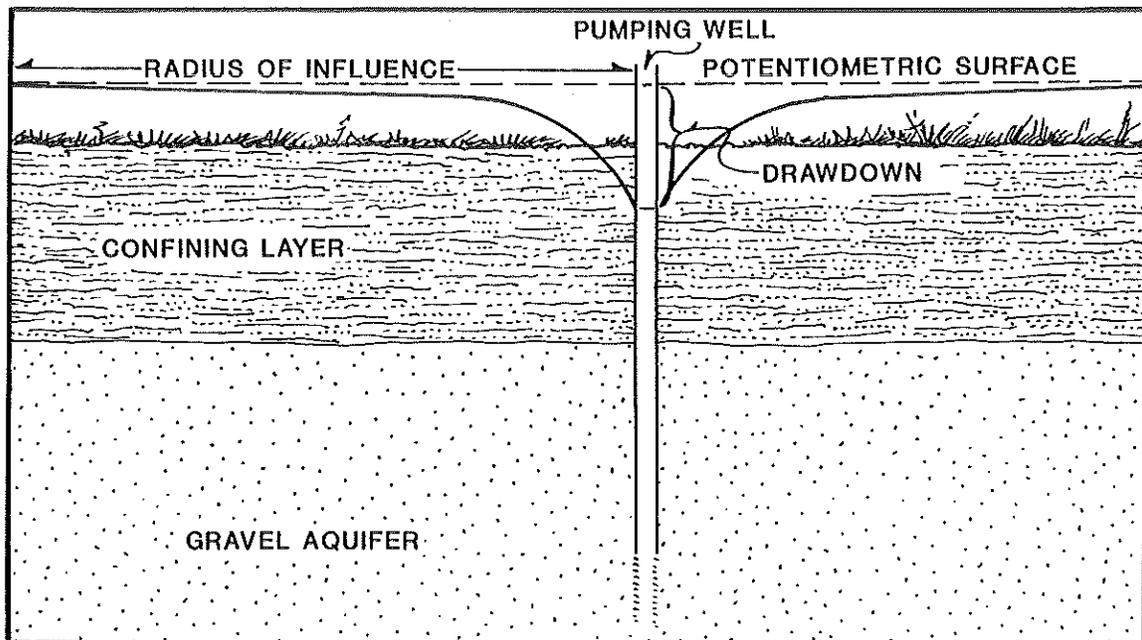


Figure 23. Cross-sectional view of a cone of pressure relief surrounding a pumping well in a homogeneous and isotropic artesian (confined) aquifer. The radius of influence of the artesian well is much greater than that of the water-table well shown in Figure 21.

The volume of water released from storage in an artesian aquifer is indicated by its storativity, which in simplified mathematical terms is the total volume of water pumped, divided by the volume of the cone of pressure relief. Storativity is a dimensionless value. In water-table aquifers the storativity is the same as the specific yield and is usually in the range of 0.100 to 0.400. For artesian aquifers, storativity is much lower, commonly in the range of 0.00005 to 0.005.

In artesian aquifers, because so little water is released from storage per cubic foot of aquifer, the cone of pressure relief is far larger than a corresponding cone of depression would be under unconfined conditions. The result is that an artesian well affects a much larger area than does a water-table well when both are being pumped at the same rate of discharge. The size of a cone of depression in unconsolidated gravel might be in the range of 20 to 500 feet for a domestic well, and 200 to 3000 feet for a municipal/commercial well. Cones of pressure relief in a similar but confined gravel aquifer might be 5 to 10 times the above figures. Within the crystalline bedrock of Maine, the area of influence of domestic wells is in the range of 100 to 1000 feet, while that of the higher yielding municipal and industrial wells is a mile or more.

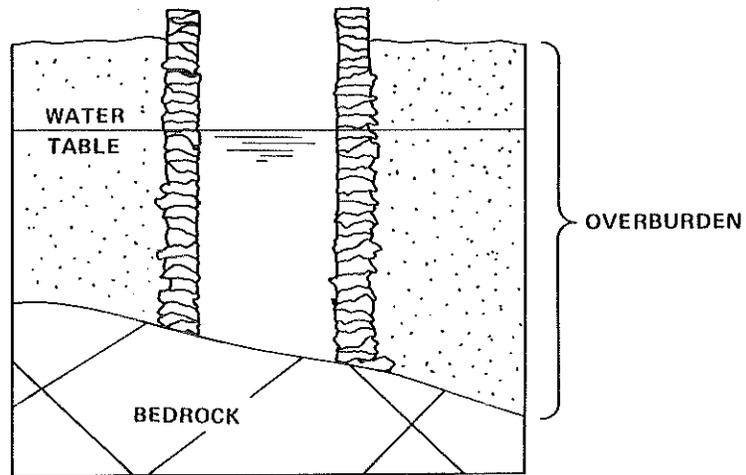
In some cases, aquifers are neither water-table nor artesian, but are a mixture of the two. These semi-artesian, or leaky-artesian, aquifers may be in overburden or bedrock. In bedrock semi-artesian aquifers, wells yield water from unconfined fractures or fractures in the upper part of the wells which drain by gravity flow as the water level in the well is pumped down. In overburden semi-artesian aquifers, the confining layer leaks a significant volume of water into the aquifer as the well is pumped.

WELLS: CONSTRUCTION

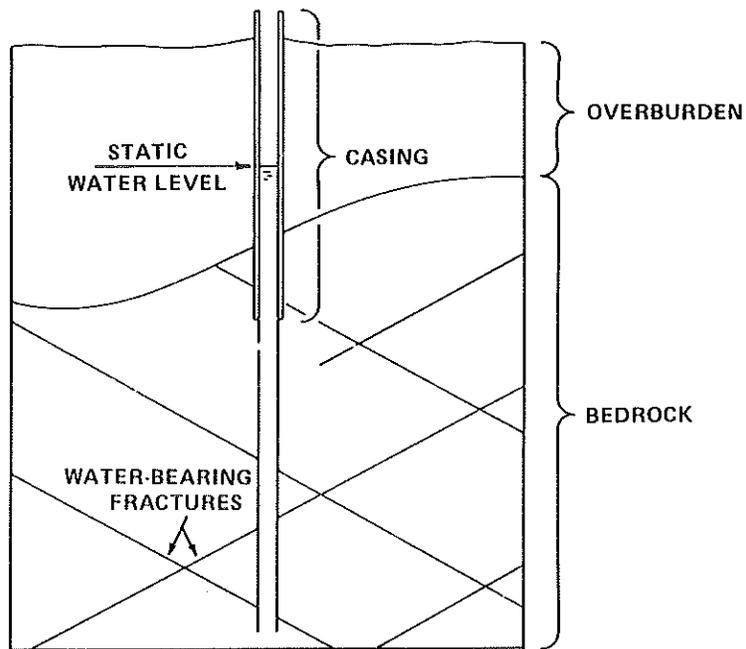
There are many kinds of well construction, most of which require a pump or some bailing device to lift the water to the ground surface. Occasionally, ground water will flow naturally from a well to the ground surface in sufficient volumes to be used as is.

Dug and Drilled Wells

Two basic kinds of wells, dug and drilled, are illustrated in Figure 24. A dug well is a large opening made into unconsolidated sediments and occasionally bedrock by hand, backhoe, or auger. It must be deep enough to go a few feet below the water table. The hole is kept from caving in by installing a lining that may be stone, tile, cement blocks, or some other material. A drilled well in bedrock is of much smaller diameter and made with a drilling rig. It is deep enough to encounter one or more water-bearing fractures. The hole is lined with casing, usually steel but occasionally plastic, which penetrates through the overburden and terminates at some depth in the bedrock depending on local conditions (typically 3 to 5 feet). The remainder of the bedrock hole is left open in order to allow ground water to flow into the borehole through fractures in the bedrock.



A. DUG WELL



B. DRILLED WELL

Figure 24. Cross-sections of a typical dug well and drilled well.

Often wells are drilled into gravel deposits when substantial yields are required for municipal, industrial, or commercial use. Such wells are generally between 6 and 16 inches in diameter. They are cased from top to bottom except for a cylindrical well screen at the lower end. Screen length and size opening are selected to fit the water needs, textural characteristics, and saturated thickness of the particular gravel aquifer. A 20-ft screen might be required for a well yielding 500 gallons per minute, while a 3-ft screen might suffice for a 20 to 50-gpm yield. Occasionally, to increase the yield, and to decrease the energy required to pump a given yield, a gravel well is drilled to a much larger diameter than the final casing of 6 to 16 inches diameter. The oversized space around the well screen is filled with selected gravel that increases the permeability of the aquifer in the immediate vicinity of the well, and thereby greatly increases the pumping efficiency of the well. Such gravel-packed wells are the norm in the case of municipal service (Figure 25).

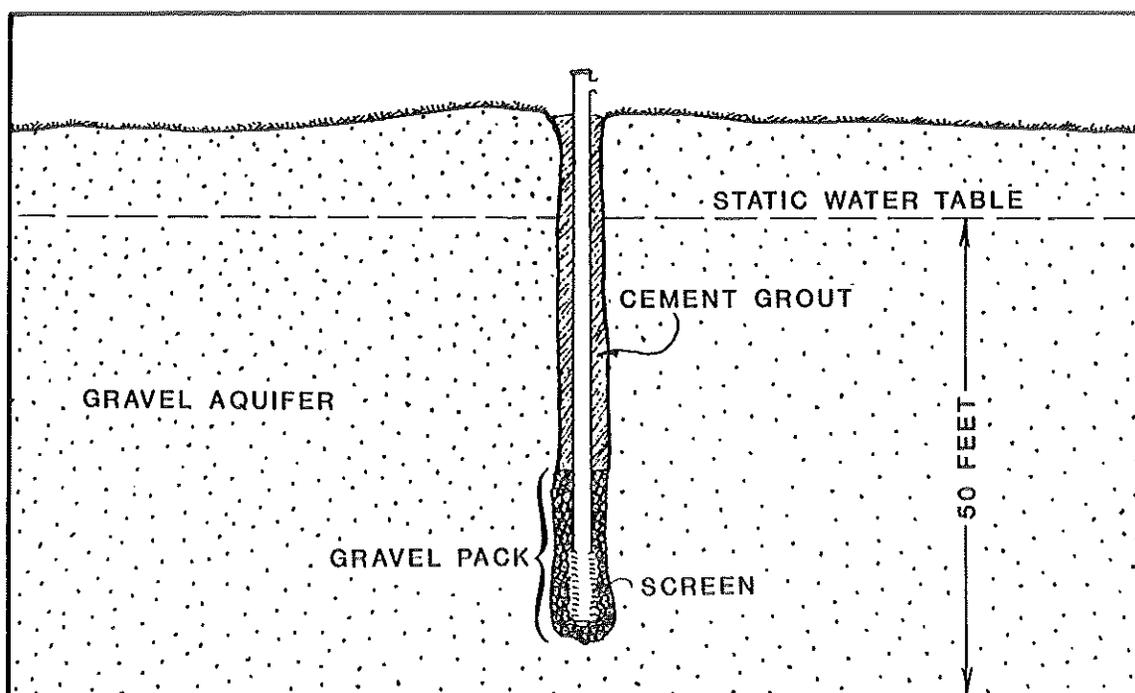


Figure 25. Gravel-packed well.

Driven and Jetted Wells (Point Wells)

Some gravel deposits, where the water table is within about 20 feet of the ground surface, can be tapped by driving a 2 to 3 inch diameter pipe down to the appropriate depth. This pipe acts as a casing and water conductor, and is equipped with a well screen (or "point") at its lower end (Figure 26). Similar to this driven well is the jetted well, in which the water conductor/casing pipe is fitted with a special type of

screen, and is washed down into a water-bearing layer by pumping water down the pipe as it is lowered into the ground. Sometimes the enlarged hole that is created by jetting is filled with a very permeable sand of a particular size that allows free movement of water into the well, but does not pass through the openings in the well screen (Figure 27).

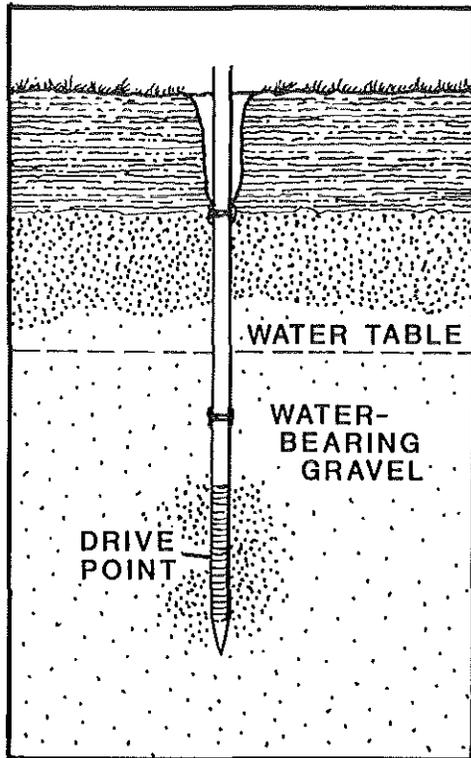


Figure 26. Driven well.¹³

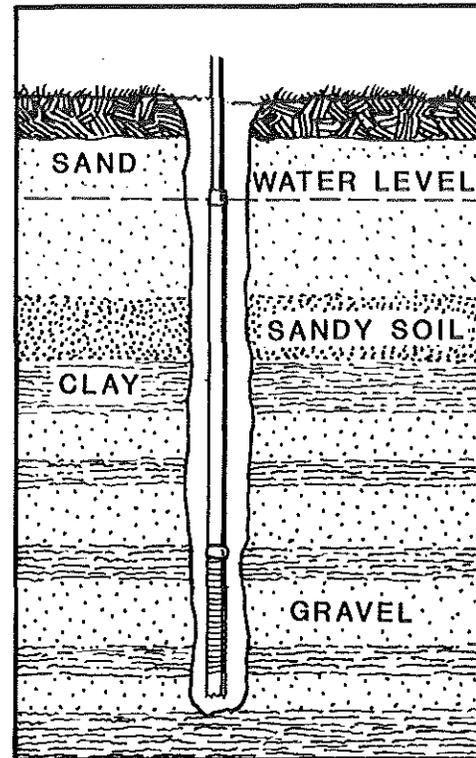


Figure 27. Jetted well.¹³

WELLS: PUMPING TESTS

The hydraulic characteristics of wells and aquifers are determined by measuring changes in water levels in pumping and observation wells. Analysis of these data will define the long-term, or sustainable, yield of the well and the radius that it will influence at various pumping rates and over different periods of time. A complete pumping test includes a variable discharge rate test (step test) of about one day duration, followed by a constant rate discharge test of three, five, or more days duration. Also included is sampling of the pumped water to determine its chemical quality characteristics.

Pumping tests for municipal and other high-yield wells usually include an array of observation wells at different distances and in different directions from the pumping wells as suggested by Figure 28. Data collected during the test include well discharge, drawdown (difference between pumping level and static level), time of a particular drawdown, and radial

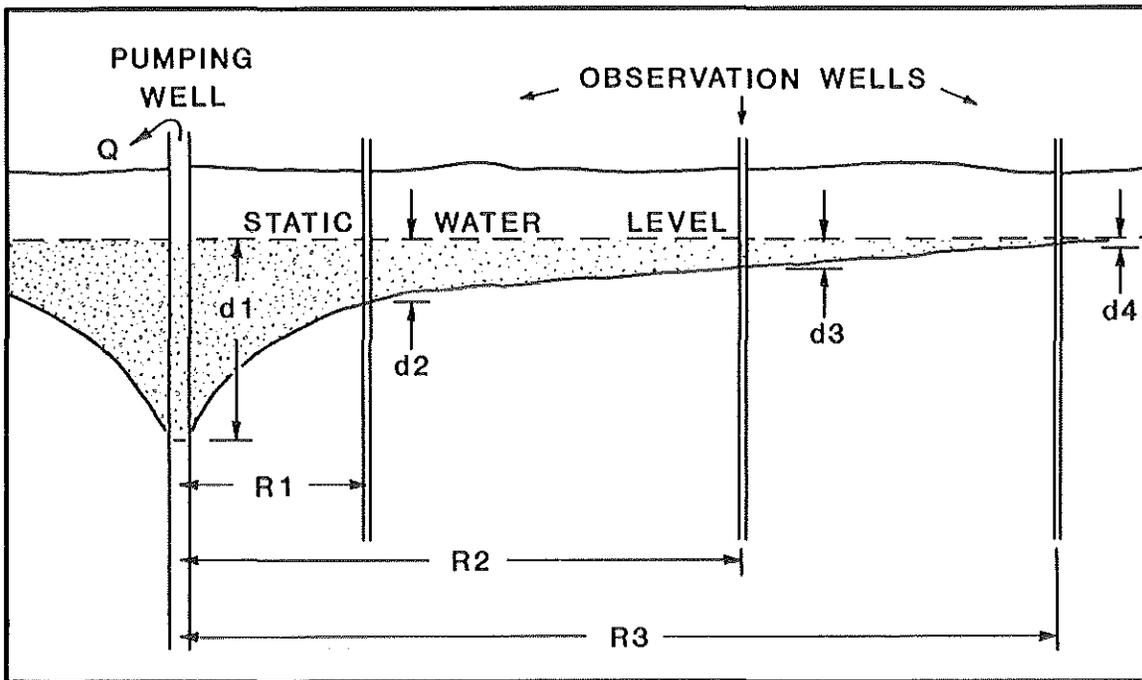


Figure 28. Pumping well and observation well used for aquifer test. Q is the rate of pumping; R is the distance between wells; and d is the feet of drawdown in each of the wells.

direction and distance from the pumping well to the observation wells. In a variable discharge rate test, the well is pumped for short intervals of time (say 100 minutes) at increasingly greater rates (steps), while drawdown is measured in the pumping and observation wells. This information defines the operating characteristics of the well under different pumping rates and provides an early indication of the well's efficiency and sustainable pumping rate.

Following the completion of the step test and recovery of the local ground water levels (typically 24 hours), a constant-rate pumping test is run at a fixed discharge that is continuously maintained for three or more days. A typical arithmetic plot of drawdown in the pumping well (or in any one observation well) against time is illustrated in Figure 29. Just as important as the drawdown measurements during the pumping period are recovery measurements after the pump is shut down. These data are free of any irregularities caused by variations in pump operation. The recovery mirrors the drawdown because the aquifer releases water from storage at nearly the same rate it takes water into storage. These "time-drawdown" data are analyzed by a variety of techniques to define the hydraulic characteristics of the aquifer, such as transmissivity and storativity, and to define how the well and aquifer will respond in the future to various pumping rates that may be imposed by the operator.

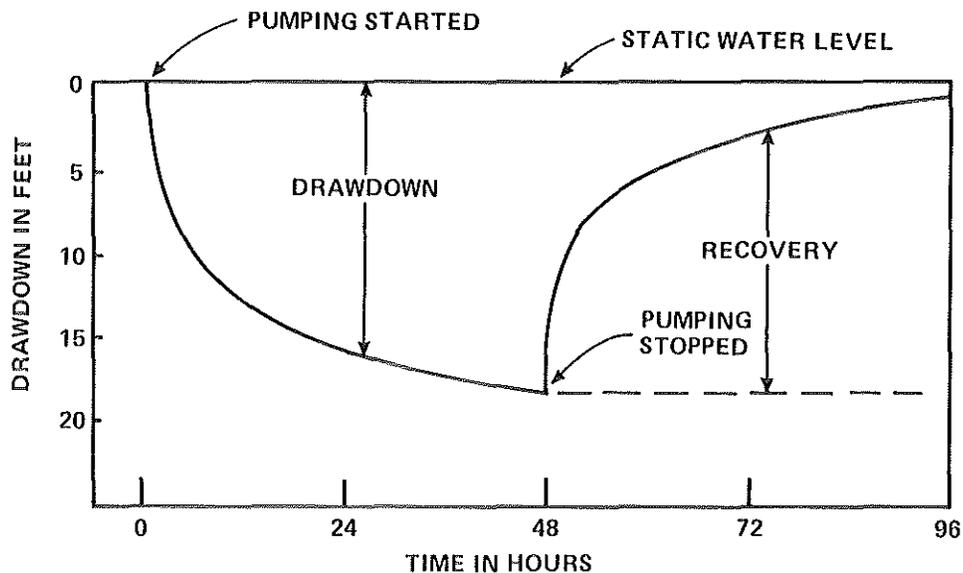


Figure 29. Drawdown and recovery curves for a well pumped 48 hours at a constant rate of 500 gpm. Well recovery was observed for an additional 48-hour period.¹⁴

Also very useful are the maximum drawdowns in the observation wells at different distances from the pumping well. These so-called "distance-drawdown" data also are used to define aquifer hydraulic characteristics, but more importantly are used to define the radius of influence of the well and the magnitude of aquifer drawdown under different pumping rates and at different future times.

A common value determined from a pumping test is the specific capacity of the well, which is its yield in gallons per minute per foot of drawdown. A good bedrock well in Maine will yield 10 gal/minute/foot of drawdown, while a good gravel well will yield 100 gal/minute/foot of drawdown. For comparison, the typical domestic bedrock well in Maine produces only around 0.1 gal/minute/foot of drawdown.

It is beyond the scope of this handbook to describe the various methods of analyzing pump-test data. For additional information, the reader is referred to Chapter 9 of Ground Water and Wells, (Second Edition) S. G. Driscoll; E. E. Johnson Company, 1986, and to other references listed under "Theory of Well Hydraulics" in the bibliography of this handbook.

WELLS: EXPLORATION

Whereas the typical domestic well is located as a matter of convenience without any detailed hydrogeologic exploration and definition of most favorable drilling site, municipal and other large yielding wells are most often constructed at sites selected on the basis of technical investigation. Methods of

investigation for sand and gravel wells are different from those used for fractured bedrock wells because of the major differences in geologic nature of the two types of aquifer.

Sand and Gravel Aquifers

Available surficial geologic and overburden aquifer maps and reports are first consulted to determine what is known about sand and gravel aquifers present in a given area. This work is followed by interpretation of land forms on aerial photographs, and by on-site inspection of geologic features, particularly those evident in sand and gravel pits. Areas that appear favorable for well construction may then be further analyzed by geophysical techniques (seismic refraction profiling and electrical resistivity sounding) to determine depth to water table, saturated thickness, and general stratigraphy. Sites that are shallow to bedrock, for example, are easily eliminated by geophysical evaluation. The ideal test drilling site has a significant thickness of saturated and very permeable sand and gravel, good potential for recharge from precipitation and possibly by inducement from a hydraulically coupled stream or lake, and isolation from potential sources of contamination.

Once favorable test drilling sites are selected, 2 1/2 inch diameter wells are installed by driving and washing casing into the aquifer to depths that are typically 30 to 150 feet. Occasionally, very bouldery deposits require test drilling by rotary or percussion machines. Each test well is pumped for a few minutes or more to determine the potential yield. If a suitable well site is found, an observation well usually 2-feet distant from the previous test well is installed and a 4-hour pump test is completed. Water samples are collected for chemical quality analysis. Where results are favorable, an 8-inch diameter test well is constructed at the same site and test pumped for a minimum of five days.

Finally, if all the test drilling and test pumping results are favorable, a permanent production well is installed with a length and diameter of screen that provides the most suitable well in the given aquifer. This permanent well is also fully test pumped and analyzed before it is put into use.

Fractured Bedrock Wells

Exploration for high yielding fractured bedrock wells includes initial consultation of available bedrock and surficial geology maps and reports, but requires more extensive use of remotely sensed data than is usually employed to locate a sand and gravel well site. Water-bearing fracture zones that are not readily apparent to a ground observer are mapped in detail using aerial photographs, satellite imagery, side-scanning radar, and various geophysical techniques. Field study of bedrock outcrops and regional landforms is also done in the final selection of favorable test drilling sites. The

ideal site is underlain by highly fractured bedrock that stores and transmits ground water readily, is covered by thick and permeable materials that provide recharge to the fractures, and is sufficiently isolated from potential sources of contamination.

Initial test drilling is completed using 6-inch diameter wells. Air-percussion ("down-the-hole-hammer") methods are typically used to reach depths of between 200 and 700 feet. Each test well is evaluated by air-lifting water out of the hole using the same compressed air system that is used in the drilling process. If the results are favorable, and a yield of more than 100 gpm is desired, an 8-inch diameter test well is drilled at the most favorable site. This well is equipped with a submersible pump and is tested for several days. Drawdown measurements are taken in the previously completed 6-inch wells, and water samples are withdrawn for analysis of chemical quality.

Where yields from the bedrock aquifer in the range of 300 to 600 gpm are needed, a 10 or 12-inch diameter permanent production well is constructed in the same favorable area. This well accommodates the required large submersible pump and provides greater hydraulic efficiency for more reliable and economical long-term operation. A full scale pumping test is also completed for the production well.

GROUND-WATER QUANTITY AND QUALITY: NATURAL FACTORS

Ground water fluctuates considerably, both in regard to water level and water quality. Many of these changes are natural and occur continuously. Most of the changes are either small or temporary, although some events, for example a significant climatic change, can have a considerable effect on ground water availability and movement.

Seasonal Variations

The most obvious change in ground water levels is related to day-to-day and seasonal variations in precipitation. Levels are usually highest in spring and lowest in summer, but both the level and the timing of ground water highs and lows can vary from year to year as shown in Figure 30. Over several decades, minor changes in climate can cause noticeable variations in typical ground water levels. There are droughts of several years' duration, and longer periods of more, or less, precipitation.

Water wells respond to rainfall by showing a higher static water level. The degree to which a given rainstorm affects a particular well depends on numerous variables, especially those related to infiltration rate. However, the basic nature of the well, gravel or rock, water-table or artesian, also causes significant variation in the degree and rate of response of a well.

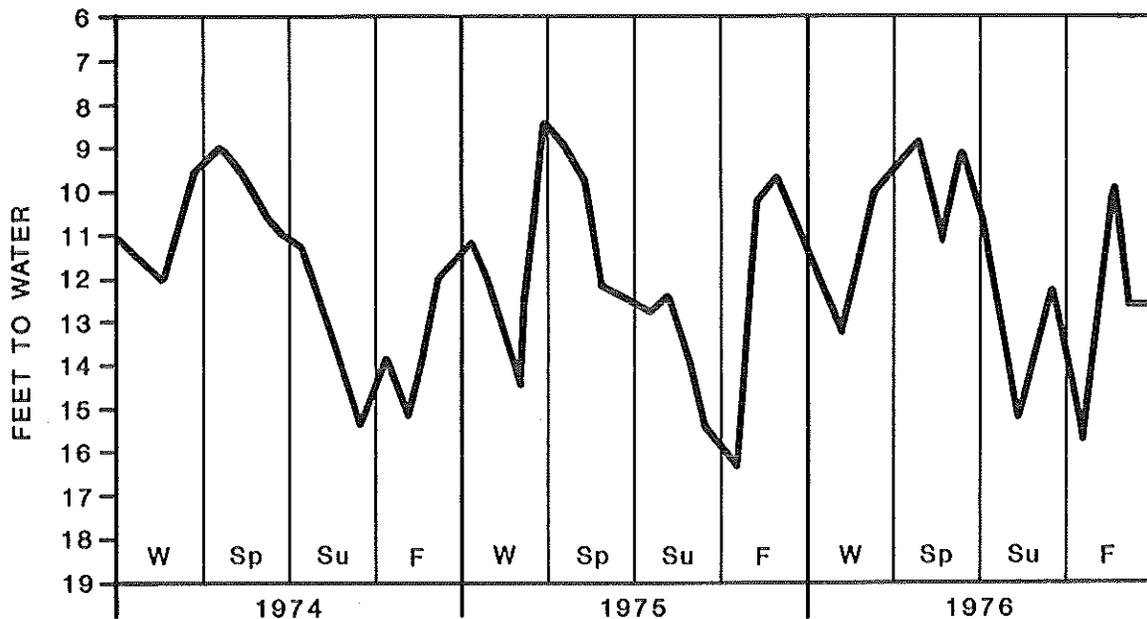


Figure 30. Water-level changes in a U.S. Geological Survey observation well in Cornish, Maine. The well is a water-table type, 24 feet deep.¹⁵

Most wells constructed in unconsolidated overburden respond to rainfall within hours of the onset of the storm, assuming the storm is large enough to satisfy local soil moisture deficits. These wells are typically water-table wells in which the downward-moving recharge water has direct access to the water-bearing zone. Shortly after a rainstorm, the water table rises, and dug wells show a positive response (Figure 31). Artesian wells constructed in unconsolidated sediments tend to respond more slowly to rainfall, possibly several days or weeks later, because of the poor permeability of the confining layer.

Rock wells usually respond to rainfall within several days or weeks, similar to a confined aquifer in unconsolidated materials. The exception occurs where rock wells penetrate an extensively fractured material in an area of thin overburden. The numerous fractures are more likely to be open to the surface and to carry recharge water directly down to the saturated zone. Even though drilled into bedrock, such wells are of the water-table type and respond to rainfall much as do water-table wells in unconsolidated sediments (Figure 32).

Ground water quality varies seasonally, and often with each rainstorm. During the periods of significant recharge, ground water tends to be less mineralized; that is, it is diluted by the fresher recharge. Soluble constituents in overburden could, however, cause recharge to be highly mineralized. Recharge raises water levels and increases flow rates, thereby reducing travel time within a porous material.

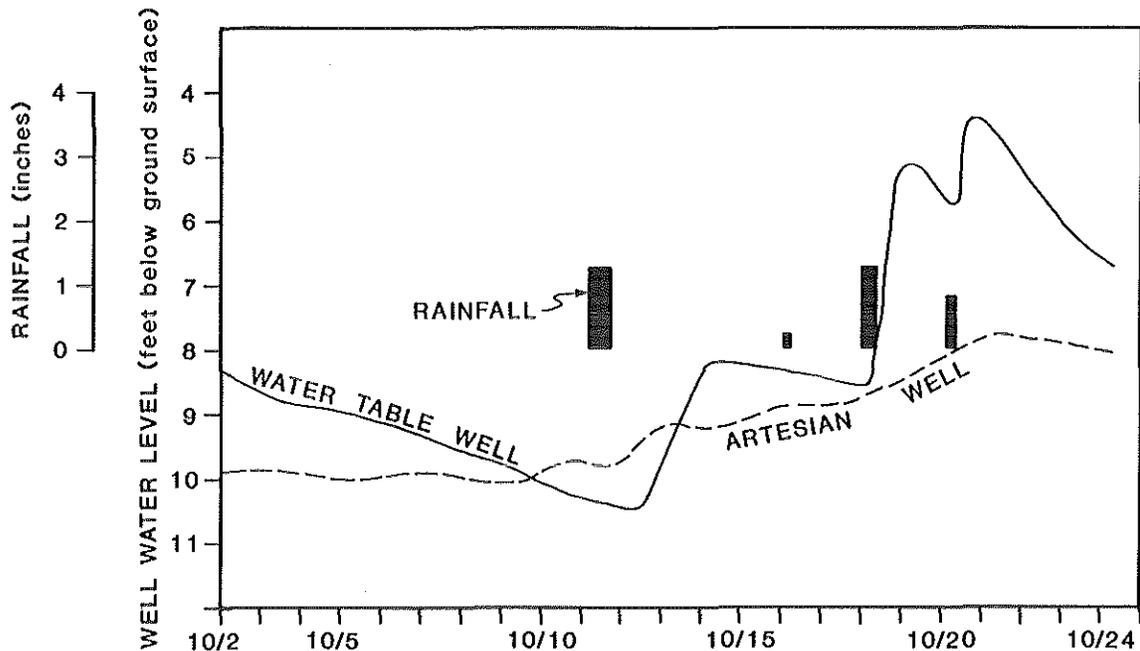


Figure 31. Response of water-table well and artesian well to rainfall. Both are drilled bedrock wells.

Late summer, when water tables (and potentiometric surfaces) are at their lowest seasonal level, is the period when ground water is most mineralized. Coastal wells are also likely to be highest in chlorides during this period because the water table is at its lowest level, and the salt-water interface has migrated significantly landward. Increased recharge following a rainstorm often freshens a ground water supply. For example, not only does a spring increase in discharge after a rainfall, but its water quality responds in a variety of ways to the recharge, as indicated in Figure 33.

Aquifer Composition and Length of Flow Path

Water stored in and moving through earth materials dissolves many substances from the surfaces of the interstices and fractures. The length of time a given volume of water is in contact with certain soil or rock types, the degree of consolidation of the water-bearing material, and the mineral makeup of the porous materials affect the quality of water obtainable from the subsurface.

Shallow and deep ground water flow systems have significantly different flow-path lengths that affect water quality. Shallow flow passes into and out of the subsurface in a much shorter distance than deeper flow. Even assuming rates of flow in a shallow and deep system are similar, ground water in the deeper system is in contact with the rock strata for much longer periods than water in the shallower system. In fact, ground water in the deeper system is likely to flow more slowly than that in the shallower system. As a general rule,

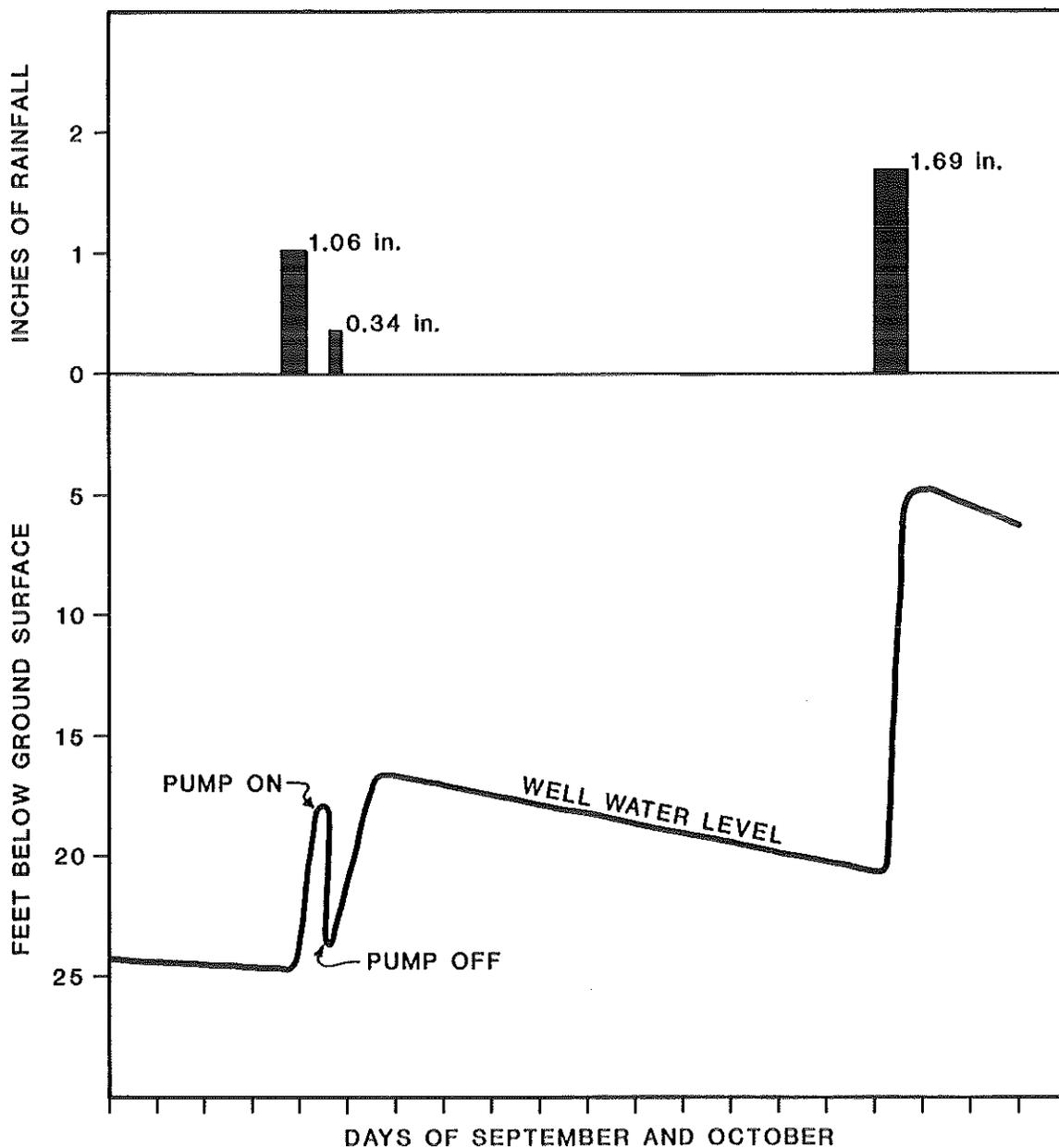


Figure 32. Response of high-yield bedrock well to rainfall. This well is drilled 100 feet into bedrock, but functions as a water-table well. It yields 60 gpm. A similar well approximately 300 feet distant was pumped for a short period and affected this well as shown.

ground water derived from greater depths tends to be more highly mineralized than water derived from near-surface sources. Water recovered from a recharge zone (where ground water is moving downward) is usually less mineralized than water recovered from a discharge zone (where ground water is returning to the surface). Residence time refers to the period of time that a given droplet of ground water is in contact with

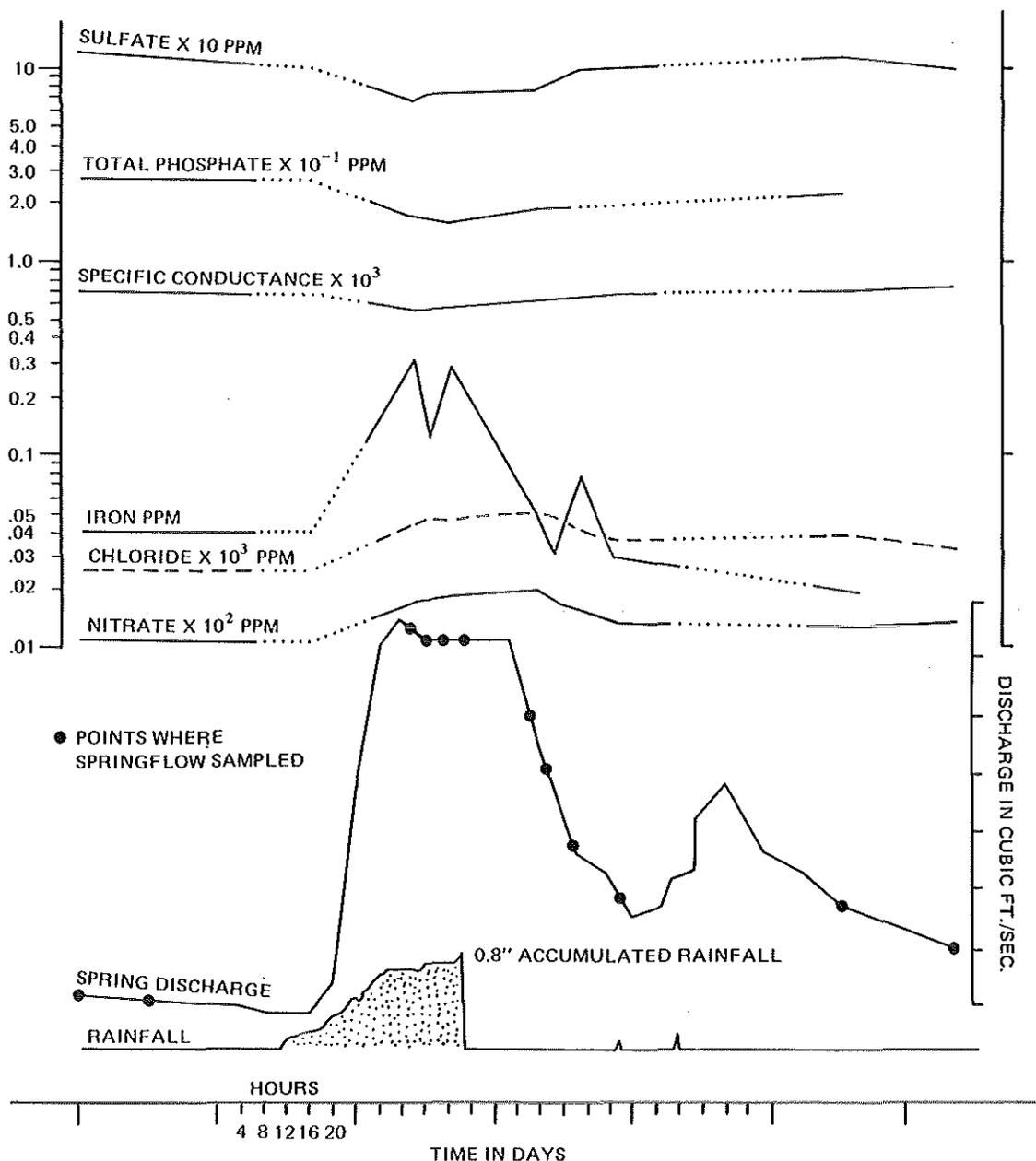


Figure 33. Changes in discharge and water chemistry measured at a spring after a rainfall.⁵

rock and soil from which it dissolves various chemical constituents. The longer the residence time, whether caused by distance traversed, slow rate of movement, or both, the greater the degree of mineralization of ground water obtained from a particular rock or soil type.

The amount of consolidation of water-bearing materials plays an important part in ground water quality. The more surface area to which ground water is exposed, the greater the opportunity for chemical and physical reactions to take place.

In unconsolidated material this surface area is proportional to the porosity of the material; thus, a highly porous clay material exposes more surface area to ground water held within it than does a more permeable, but less porous, gravel. Crystalline rocks have very low porosity; thus, little surface area is exposed to ground water contained in rock fractures.

Ground water chemistry often varies according to chemical composition of the soil and rock through which it flows. Limey soils and rocks release calcium ions to ground water. Materials bearing iron sulfide release iron, and possibly manganese and sulfur compounds, to ground water. Granites may contribute constituents, including fluoride and radon gas, to ground water.

Hardness refers to the ability of water to form suds with a soap. Hard water causes difficulty in making suds, leaves a ring in the bathtub, forms soap curds in clothing, and builds up scale in boilers and tea kettles. It is caused mostly by calcium and magnesium carbonates dissolved from soil and rocks, most especially those composed of, or containing, limestone.

The ability of water to conduct an electric current is called specific conductance. The more mineralized a water, the lower is its resistance to the flow of an electric current, and thus, the higher its specific conductance. The parameter is measured very quickly and easily with an electronic instrument that is used in a laboratory or lowered down a well.

The hydrogen ion concentration in water is indicated by its pH. Seven is neutral pH, greater than seven is alkaline, and lower than seven is acidic. Most ground water tends to be acidic, some to the extent that it attacks copper plumbing, as well as the rocks containing it.

Alkalinity is a measure of the ability to neutralize acid. It is related to the presence in the water of certain salts and carbonate and bicarbonate ions.

Excess chlorides in ground water cause it to taste "salty". Sea spray, salt water intrusion, de-icing salts for highways, and animal wastes contribute chlorides to ground water.

Iron and manganese are dissolved from soils and rocks containing various minerals, commonly iron and manganese sulfides. Such rock types are common in Maine, causing much of our ground water to be high in these two substances. They are chemically similar, thus generally occur together. Iron and manganese are not toxic, but impart objectionable taste to water and may leave brown stains on porcelain and in clothing.

Nitrogenous compounds are usually derived from animal and plant materials, but are contributed also by fertilizers in agricultural and urban areas. Nitrate is the most common form

of these compounds to occur in ground water. Human and other animal wastes are the cause of serious nitrate pollution in various parts of the world.

Many rocks in Maine contain uranium. As uranium decays, one of the products is radon, a radioactive gas. This gas can diffuse into ground water and is found in many bedrock wells, sometimes in very high concentrations. Radon gas in a domestic water supply will, in turn, diffuse into air of a home. High radon levels in homes is considered to be a cause of cancers of the respiratory system.

Air Pressure and Tides

In addition to rainfall, changes in atmospheric pressure and variations in ocean tides in the coastal region affect artesian wells. Some respond even to minute changes in the shape of the earth, known as earth tides and caused by gravitational attraction of the sun and moon.

Ground water in an artesian aquifer is in direct contact with the atmosphere only where a well is drilled. A change in air pressure acts only on the water surface exposed in the well. A rise in air pressure (more weight of air) causes the water level in the well to go down. A drop in air pressure causes a corresponding rise in the water level in the well (Figure 34). The ratio of air-pressure change to change in

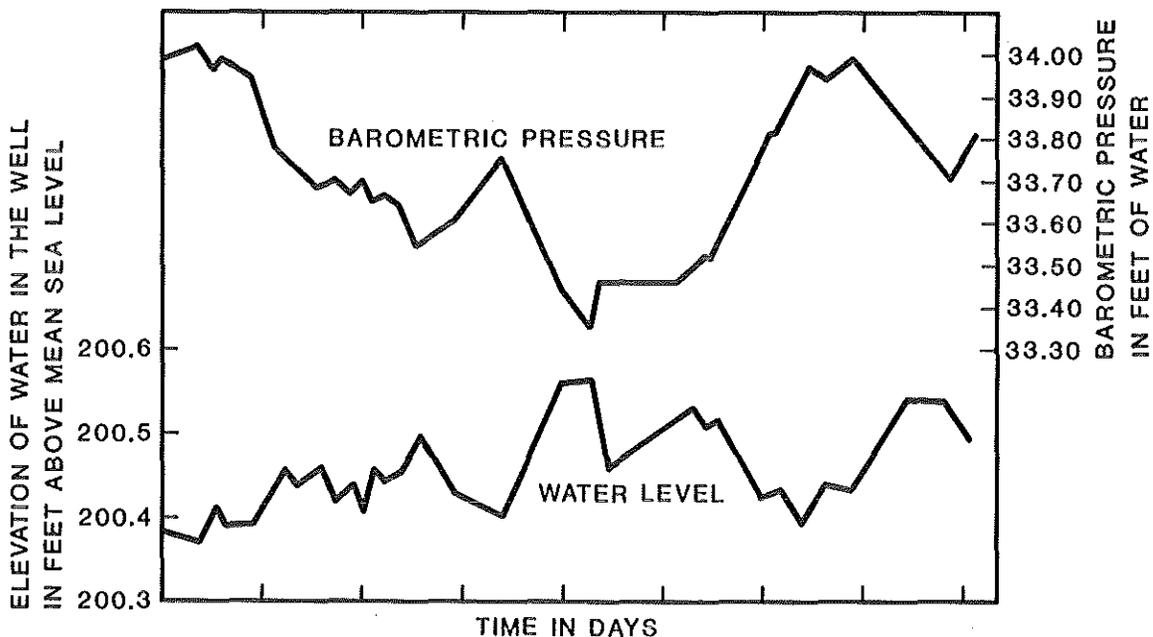


Figure 34. Water-level fluctuations in an artesian well that correspond to barometric pressure fluctuations. The barometric efficiency of this well is 52%.⁵

well water level is called the barometric efficiency of the artesian aquifer. It is most often given as a percent. If air pressure changes an equivalent of six feet of water, and the well's water level changes three feet, the barometric efficiency of the aquifer is 50%.

Barometric efficiency is a measure of the rigidity of the confining layer. The more this confining layer is able to resist change due to variation in air pressure, the greater the effect of the air pressure on the water in a well penetrating the aquifer. Thirty feet of shale overlying an artesian aquifer would be more rigid than three feet of clay, and a well in an aquifer underlying the shale would have a higher barometric efficiency.

Artesian wells within several miles of the coast respond to the changing tides because of the load of seawater placed, and then removed, on the confining strata, and because of the decrease in the ground water discharge to the ocean basin at high tide. Tidal efficiency is the ratio of feet of tidal change to feet of change in well-water level, and is usually given as a percent. If a nine foot tide causes a three foot change in water level, the aquifer tapped by that particular well has a tidal efficiency of 33%. The weight of the tide acts on the aquifer, rather than on the level of water in the well, just the opposite of the atmospheric pressure (Figure 35). Tidal efficiency is a measure of the flexibility of the confining layer. In theory, the barometric and tidal efficiencies of a particular aquifer should together equal 100%, or 1.

These two kinds of aquifer efficiencies are useful for measuring the degree of confinement of a particular aquifer. The reaction of three coastal bedrock wells to the same tidal forces (the three wells are approximately equidistant from the coast), shown in Figure 36, suggests large differences in the nature of the water-bearing fractures intersected by each well. Comparison of water-level changes in these three wells to rainstorms indicates that the rock fractures must be more open to the land surface and recharge in the two wells showing the least tidal efficiency.

Proximity to the Ocean

Fresh water occurs beneath the continent and moves slowly in the direction of the ocean, where it comes into contact with salt water that saturates the intergranular spaces and rock fractures of the ocean basin. The line of contact is called the fresh-water/salt-water interface. Its location is determined by two factors: (1) the difference in density between fresh and salt water and (2) the flow potential of the fresh ground water.

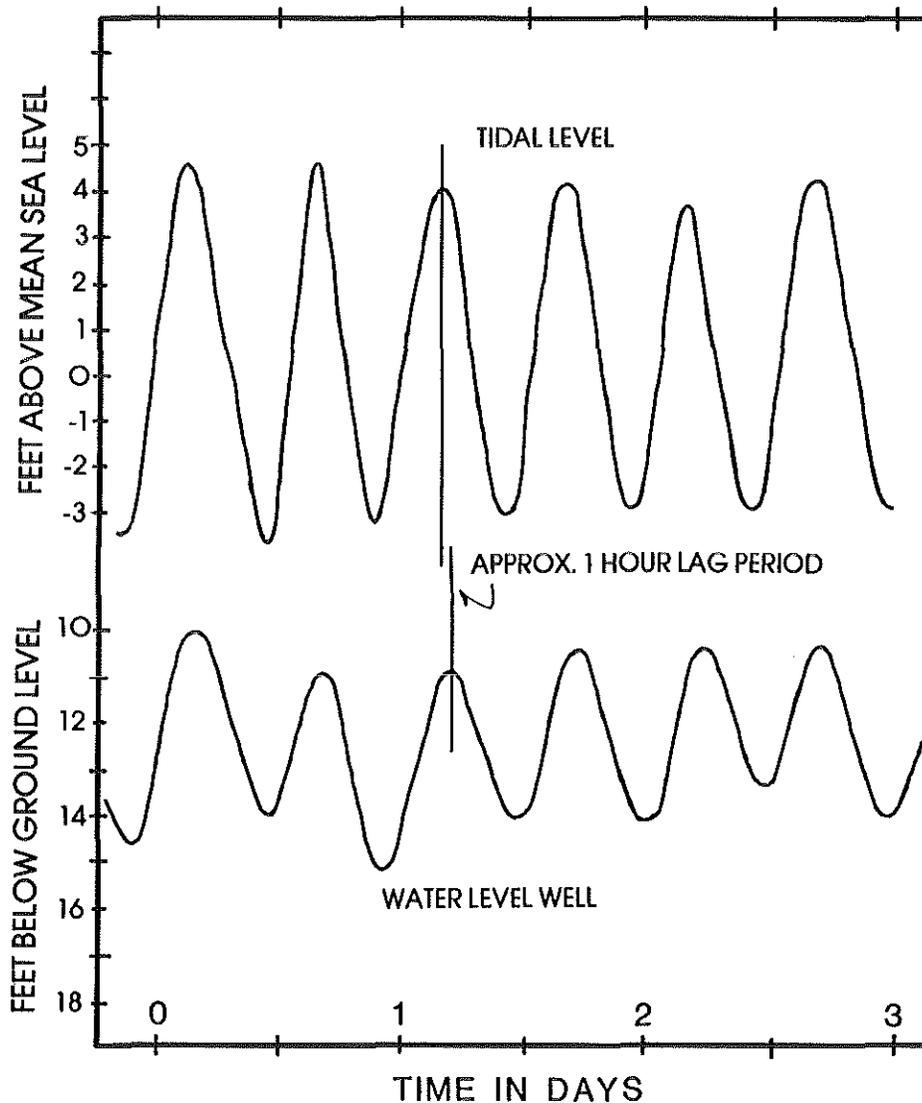


Figure 35. Comparison of water-level fluctuations in a coastal artesian well to tidal cycle.

Fresh water is less dense than salt water. Where both occur in a saturated material, the fresh water tends to float as a lens on top of the salt water. The situation is analogous to an iceberg that floats in the sea with about 75% of its bulk below ocean level. Figure 37 is a simplified illustration of an oceanic island where ground water derived from and continuously replenished by rainfall saturates the subsurface. The water table is typically higher under the center of the island and slopes downward to where it intersects the sea. The height of the water-table mound above sea level determines the thickness of the fresh water lens under the island. The higher the water table, the deeper the lens of fresh water. Thus, the greater the elevation of the land above sea level, and the greater the amount of precipitation falling on the land, the larger the volume of fresh water available on the island.

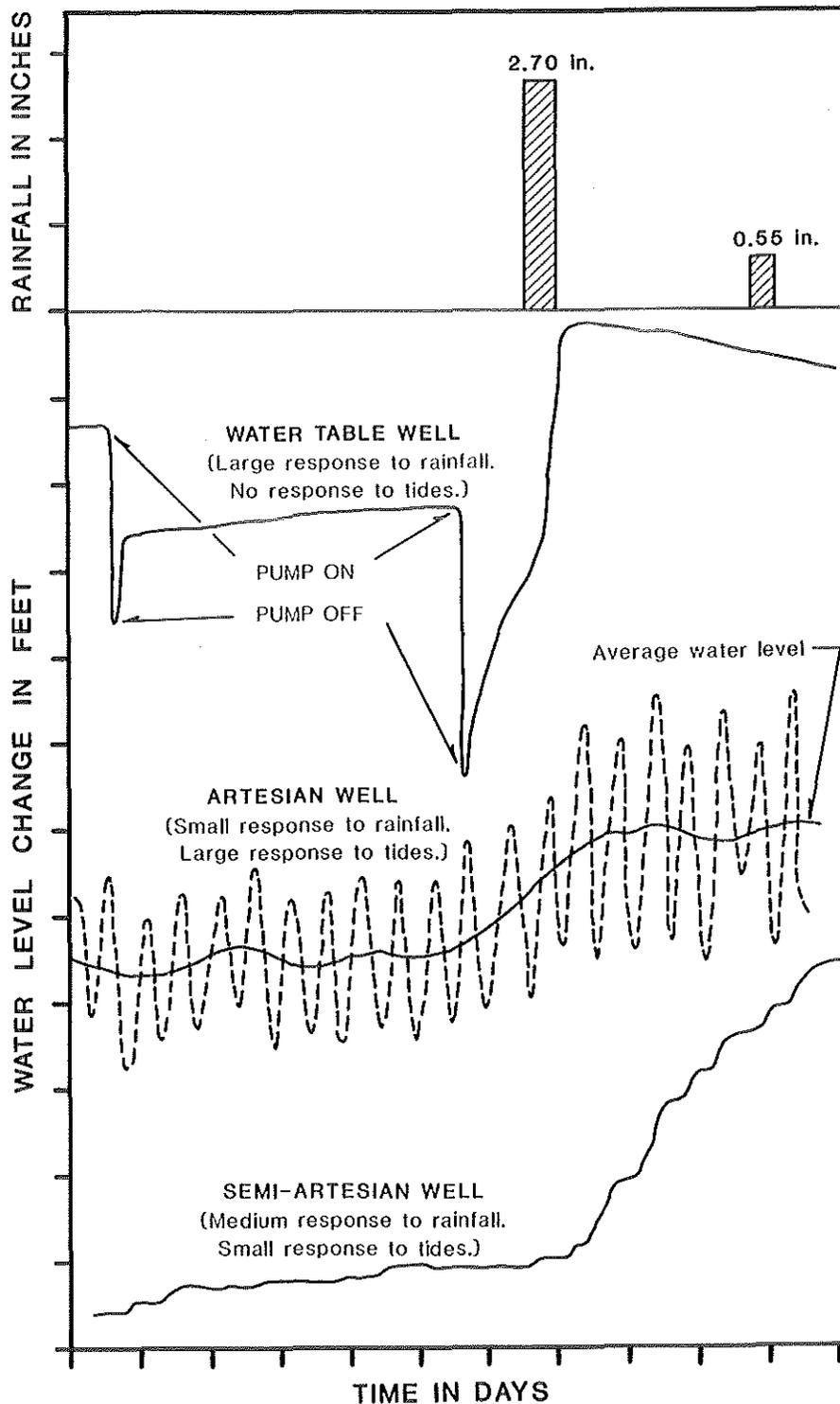


Figure 36. Water-level records showing the very different response of three coastal bedrock wells to the same rainfall and the same tidal influence. The water-level rise in the artesian well starting a few hours before the major rain storm is caused by the decrease in atmospheric pressure, rather than the rain associated with the storm.

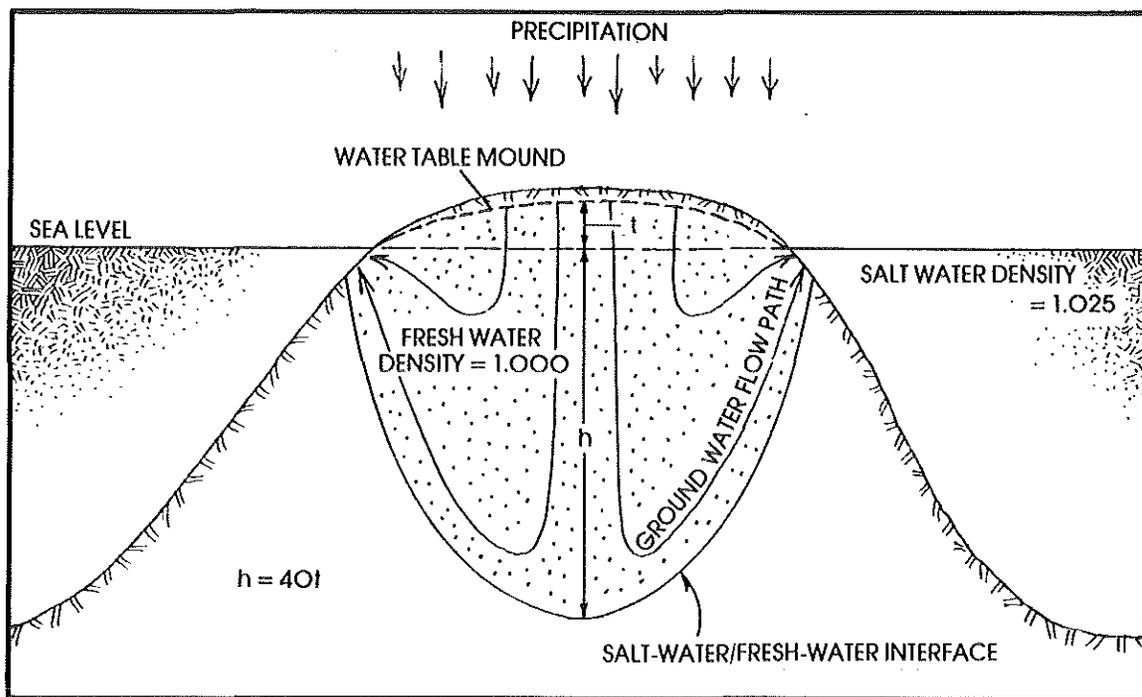


Figure 37. Schematic cross-section of oceanic island showing lens of fresh water. The depth of fresh water below sea level (h) is 40 times greater than the height of fresh water above sea level (t). The water table mound is maintained by precipitation.

The relationship known as the Ghyben-Herzberg Ratio is a calculation of the static (non-flowing) relationship between the column of fresh water and the column of salt water pictured in Figure 37. These two columns are equal in weight. Their difference in height is caused by the difference in density between salt water and fresh.

If " t " is the height of the water table above sea level (in Figure 37), and " h " is the thickness of the fresh water lens below sea level, the following relationship can be derived where the density of sea water is 1.025 and fresh water is 1.000:

$$\begin{aligned}
 (h + t) \times 1.000 &= (h) \times 1.025 \\
 \text{weight of fresh-water column} &= \text{weight of salt-water column} \\
 h + t &= 1.025 \times h / 1.000 = 1.025 \times h \\
 t &= (1.025 \times h) - h = .025h \\
 h &= \frac{1}{.025} t = 40t
 \end{aligned}$$

A more detailed view of the fresh-water/salt-water relationship is illustrated in Figure 38. The interface is on

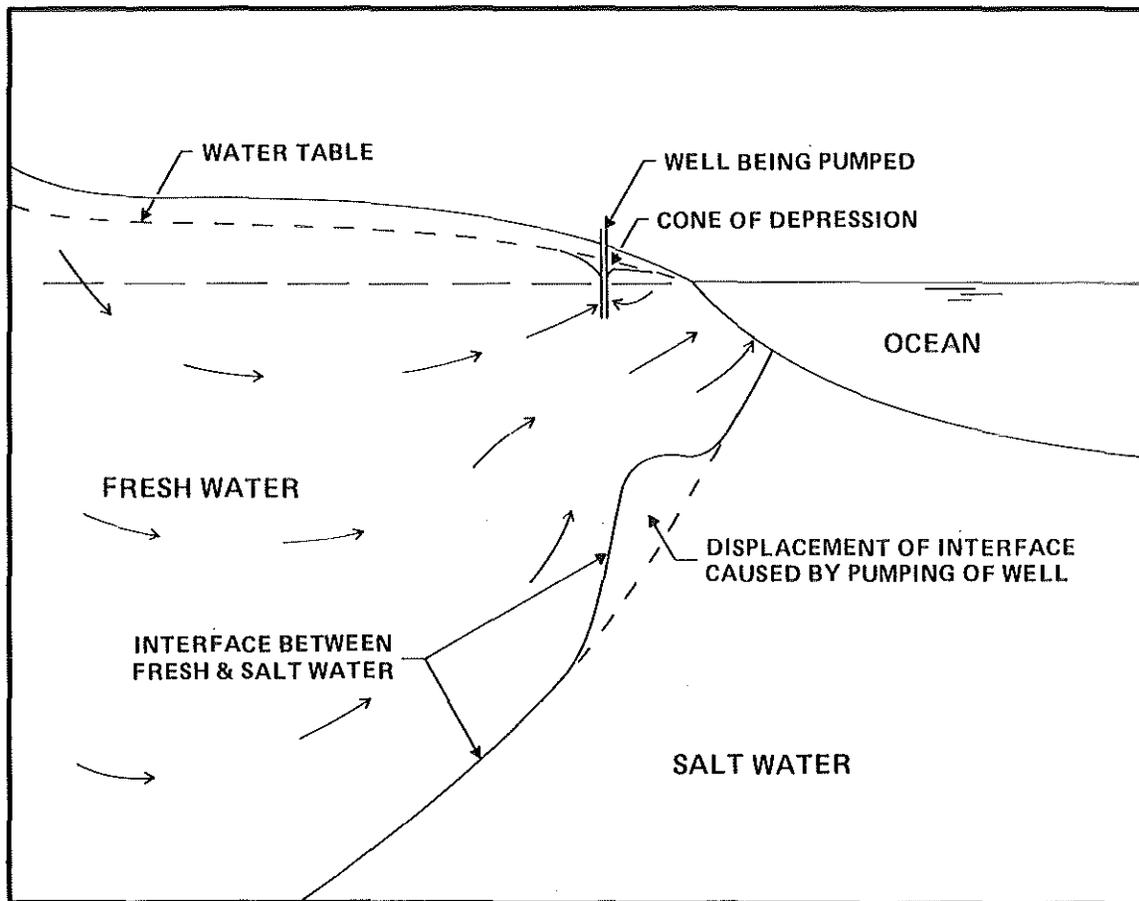


Figure 38. Idealized ground water flow near the fresh-water/salt-water interface.³

the seaward side of the coastline. Under static conditions, the interface would be at the shore. However, in reality, ground water is not static, but flows towards and continually discharges into the sea, as indicated by the arrows in the figure. It is this flow that causes the seaward displacement of the fresh-water/salt-water interface and permits the drilling of fresh water wells in Maine within a few feet of the coastline.

Because the interface position is very dependent upon the height of the water table above sea level, seasonal changes in water-table level and daily changes in sea level cause the interface to change position. With each tidal cycle, the interface migrates inward and outward. A nine foot tidal change should cause a 40×9 ($h=40t$), or 360 foot variation in the interface position. Similarly, a seasonal water-table change of five feet should cause a seasonal interface change of 200 feet. Thus the lens of fresh water that exists below sea level shrinks slightly with each high tide, and shrinks significantly in late summer when the water table is lowest.

Air Temperature

Temperature of ground water is ordinarily within a few degrees of the mean annual air temperature prevailing in a given locale. Ground water temperatures in Maine tend to be a relatively constant 40° to 50°F, a property useful to some commercial operations, for example the raising of fish in hatcheries. In summer, ground water is cooler than the air and feels cool (Figure 39). Streams receiving much ground water are cool, and typically good sources for trout and other cold-water fishes. Buildings and industrial boilers are often cooled using the relatively low temperature of ground water. In winter, however, ground water is warmer than the air, so that it seems warm (Figure 40). Streams receiving much ground water are warmer and tend not to freeze over so rapidly. The same buildings that are cooled in summer using ground water can be heated in winter using heat pumps to concentrate the caloric content of ground water.

GROUND WATER QUANTITY AND QUALITY: HUMAN EFFECTS

Man, too, affects water level and quality, although it is impossible to clearly separate human factors from natural ones. Pumping wells, for example, can steepen or reverse local flow gradients and draw in contaminants. Pumping wells also affect other pumping wells, but are in turn affected by such natural factors as aquifer boundaries and the presence of surface-water bodies.

Well Interference and Aquifer Boundaries

If two or more wells obtain ground water from the same aquifer, their cones of depression (or pressure relief) will interact if the wells are close enough to one another or are pumped at a great enough rate of discharge. Where cones of depression contact each other, the wells cause mutual interference, as pictured in Figure 41. The drawdown in one well causes some drawdown in the adjacent well and vice versa, so that the pumping levels in both wells are lower than they otherwise would be. Well interference is most typical in gravel aquifers in Maine, but occurs occasionally in domestic bedrock wells. It is very possible that well interference is more common in rock wells than expected, but goes unnoticed. Where two rock wells interfere, it shows that the water-bearing fractures supplying both wells are hydraulically connected. If the interconnection is direct, the interference effect can be very significant, as shown in Figure 42. This figure is drawn from the records of a well on High Head Peninsula, Harpswell, Maine. Of 27 observation wells monitored, only four show certain interference from a nearby pumping well. Three of the four are in the same area of the peninsula where the wells tend to yield more than the local average yield. The interference suggests that the higher yields are related to more numerous interconnections among the water-bearing fractures.

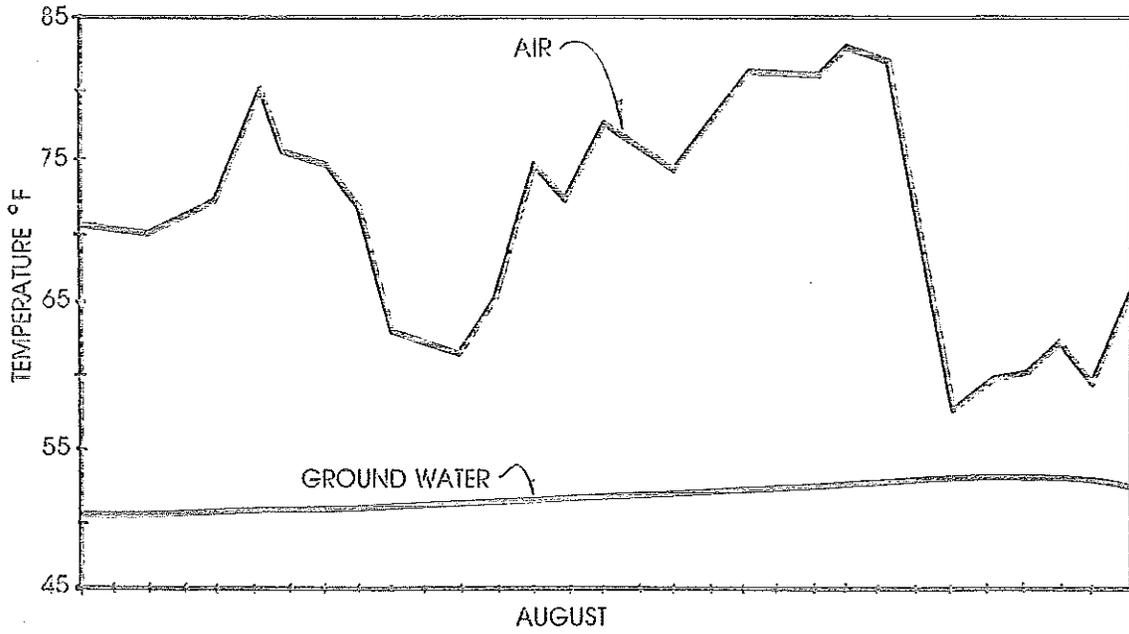


Figure 39. Comparison of air and ground water temperatures in August.⁵

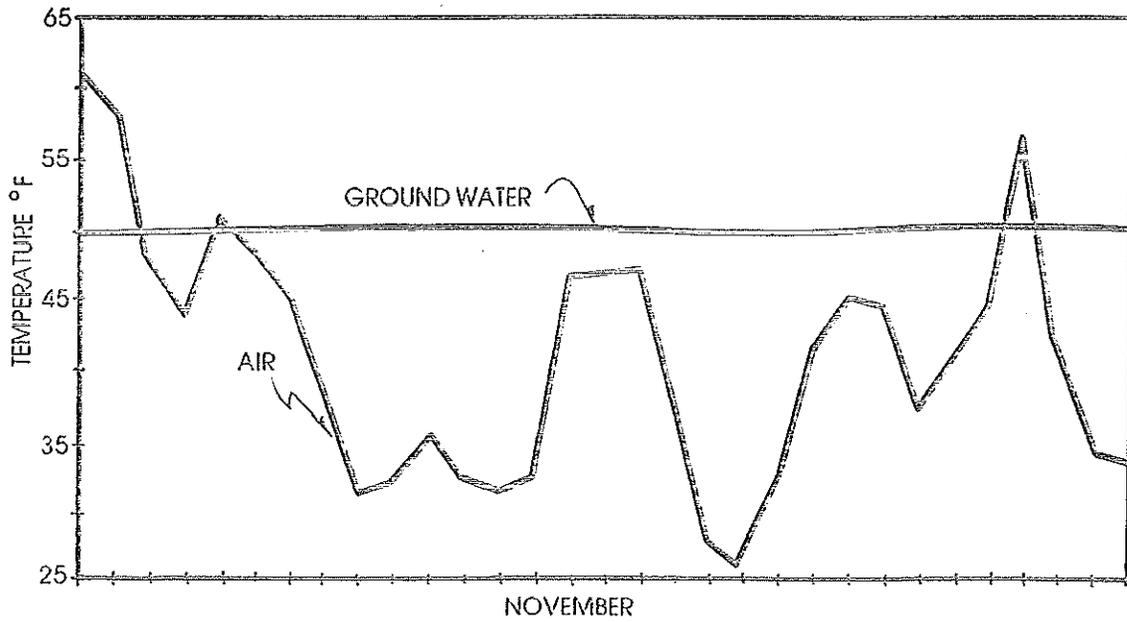


Figure 40. Comparison of air and ground water temperatures in November.⁵

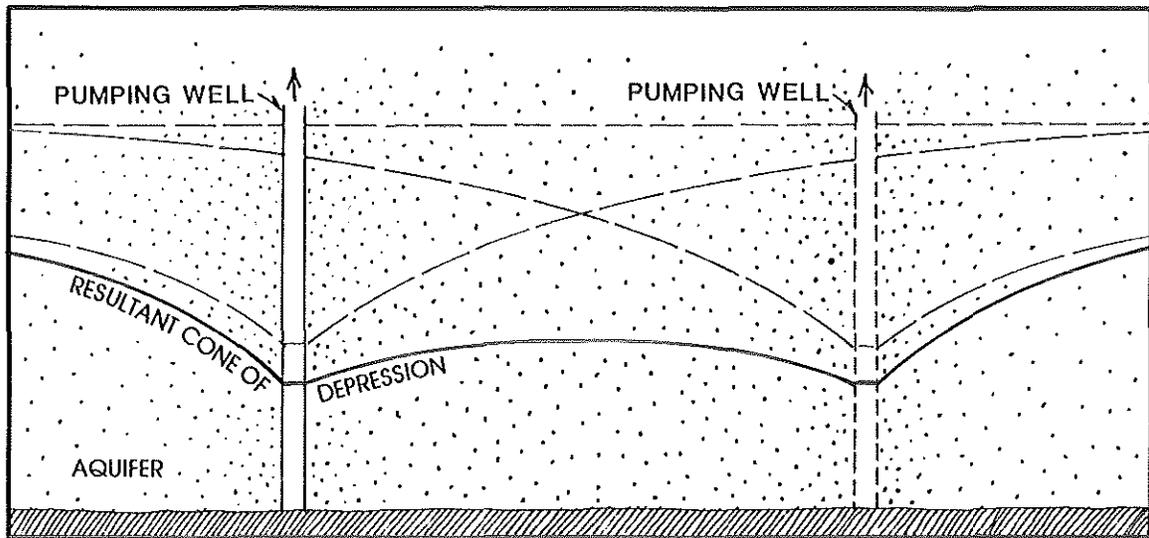


Figure 41. Interference of two pumping wells causes a lower resultant cone of depression.¹⁶

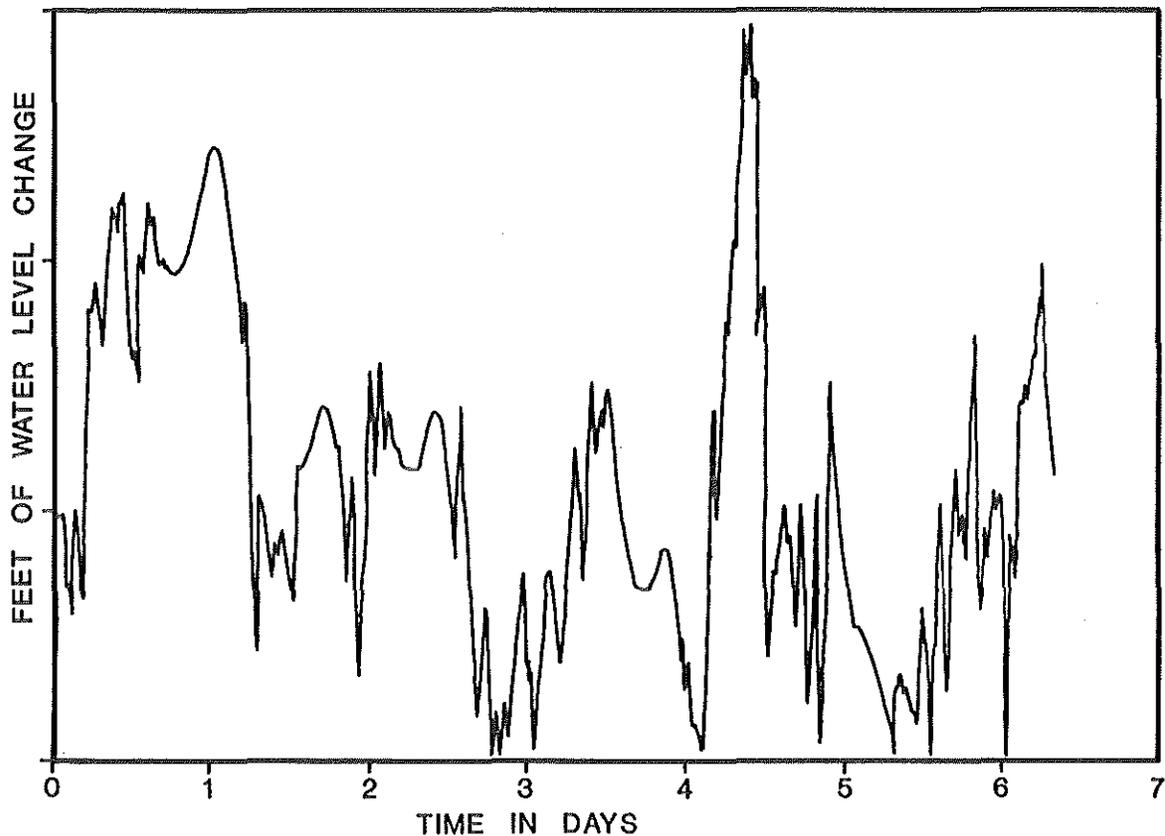


Figure 42. Water-level changes in a coastal bedrock well that show well interference superimposed on daily tidal fluctuations (compare with Figure 35). This well is located over 100 feet from the pumping well that affects it.

Significant problems with well interference in Maine's bedrock aquifers have not been documented, however, the number of high yielding municipal and other bedrock wells with significant cones of depression is still small.

As has been discussed, pumping wells affect the surrounding water level in the form of a cone of depression (or cone of pressure relief). The shape of the cone of depression is altered by aquifer boundaries, beyond which a significantly different amount of ground water (more water or less water) is available to the pumping well. Less water is available to a pumping well where an aquifer is bounded by poorly permeable material. Examples of this type of boundary interference would be places where a gravel aquifer is surrounded on its sides by clay and underlain by till. Bedrock may also be a poorly permeable boundary to a gravel aquifer, as depicted in Figure 43. For crystalline bedrock aquifers, such boundaries are fracture walls, or distinctly less fractured rock in the case of a zone of highly sheared material.

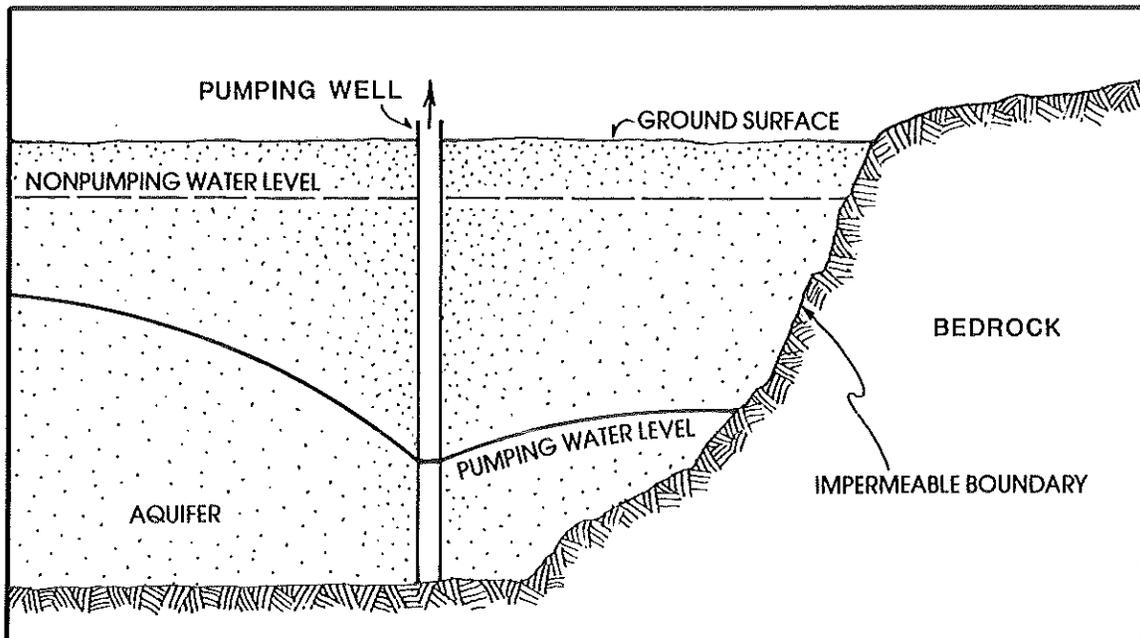


Figure 43. Pumping well adjacent to an impermeable boundary.¹⁶

The opposite type of boundary condition occurs where a well is in close proximity to a surface-water body such as a lake or stream. The lake or stream bottom, in theory, is a boundary of infinitely high permeability. (Fine sediments on the bottom of the lake or stream, however, may make this boundary much less permeable.) Additional water will be drawn from this source if the cone of depression extends to the surface-water body, and if the lake or stream bottom is relatively permeable. Figure 44 illustrates this condition,

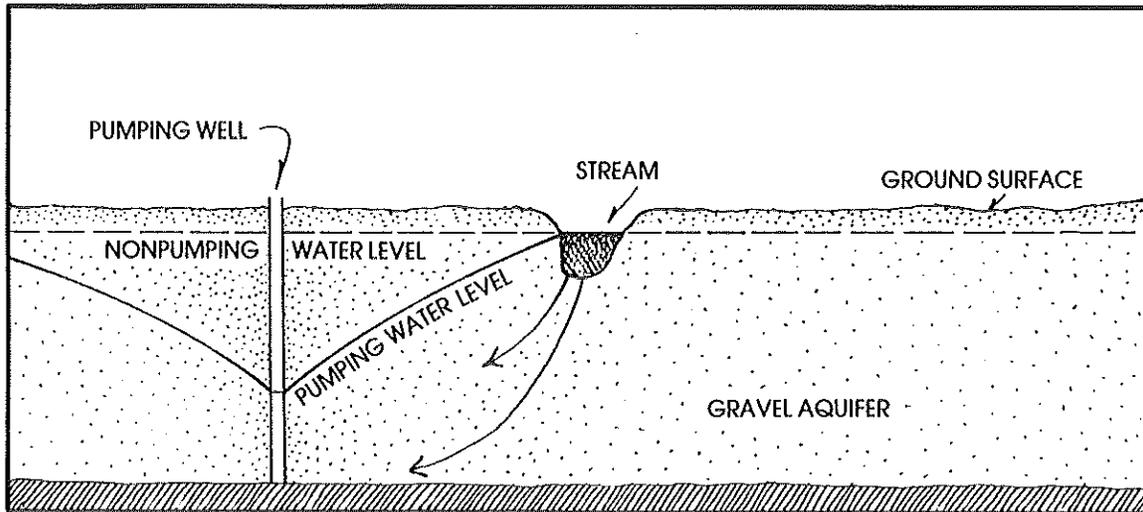


Figure 44. Pumping well adjacent to a stream. Reversal of the ground water flow gradient causes water to flow from the stream to the well.¹⁶

known as induced infiltration, in which the normal discharge of ground water to a stream has been reversed, and the stream itself loses water to the discharging well. The cone of depression in this case extends farther in the direction opposite the stream because of the greater volume of aquifer in that direction required to supply water to the pumping well.

In some cases induced infiltration contaminates well water. The technique of placing wells where they will benefit from induced infiltration, however, is often used to increase their long-term yield.

All of the various hydraulic parameters such as yield, drawdown, interference, and boundary conditions can be predicted through detailed geologic observation and analysis of pumping tests. For example, the area affected by a given well, pumping at a particular rate for a certain time, can be calculated with sufficient accuracy so that potential well-interference problems and contamination problems can be avoided before they occur.

Water level changes in wells being pumped in Maine typically are of short, or at most seasonal, duration because the long-term withdrawal rate is not greater than the long-term recharge rate. Long-term downward trends in water levels caused by pumping are not known in Maine, although some may be occurring. In other parts of the country, a notable example being the High Plains district of Texas, ground water withdrawals for agricultural purposes have far surpassed natural recharge for many decades. The ground water has been mined (ground water mining), and local water levels have dropped several hundred feet. Ultimately, the local water

resource will be depleted by virtue of being too expensive to be pumped hundreds of feet to the surface, and the agricultural activities will change. Over many centuries, the High Plains water table could rise again if most pumping ended.

In Maine, lowered water levels could become bothersome in coastal regions subject to salt-water intrusion, in some of the larger gravel aquifers utilized by several municipalities and commercial firms, and in agricultural areas where there is a large-scale shift to irrigation of field crops. Such situations can be prevented by regulating the annual withdrawal to match the annual recharge.

Ground Water Contamination

Man has an effect on water quality as well as water quantity. Contaminants released to air, water, or land, for example, can find their way into ground water supplies, as suggested by Figure 45. Raindrops form on airborne dust particles and bring them to the ground surface. Compounds are leached out of the particulate matter into the droplets before they reach the surface. Gases are also absorbed by water droplets, and are carried to the ground by rain. Chloride-enriched precipitation is common in the coastal areas, where salt-water spray is blown aloft. Some rain downwind of industrial areas has a low pH, and is referred to as acid rain. A number of lakes in Maine and the Northeast are reported to be decreasing in pH because of acid rain.¹⁷ The source of some of this contamination may be as distant as the Midwest region. Actual, or potential, effects of acid rain on ground water in Maine are not well known.

Water from polluted streams is sometimes drawn into the ground water system by reversed flow gradients caused by pumping a well adjacent to the polluted stream. At other times, flooding streams carry contaminants onto the floodplains, where they are leached downward into the ground water after the flood has passed.

Leachate from solid and liquid wastes placed on or under the ground surface migrates downward into ground water. Spilled substances such as petroleum products commonly pollute subsurface water.

The opportunity for ground water pollution is present nearly everywhere, not just in the vicinity of populated places. Yet most ground water remains of good quality because of natural cleansing properties of the unsaturated porous substances which may overlies the water table. The presence of air with oxygen to react with biologic and organic pollutants is one of the most significant of natural cleansing factors. Ion-exchange capacity of clay soils and sediments is also very important in the removal of such things as metals from recharge water. Absorption of contaminants by soil particles, and adsorption (physical attraction) onto the particles remove many

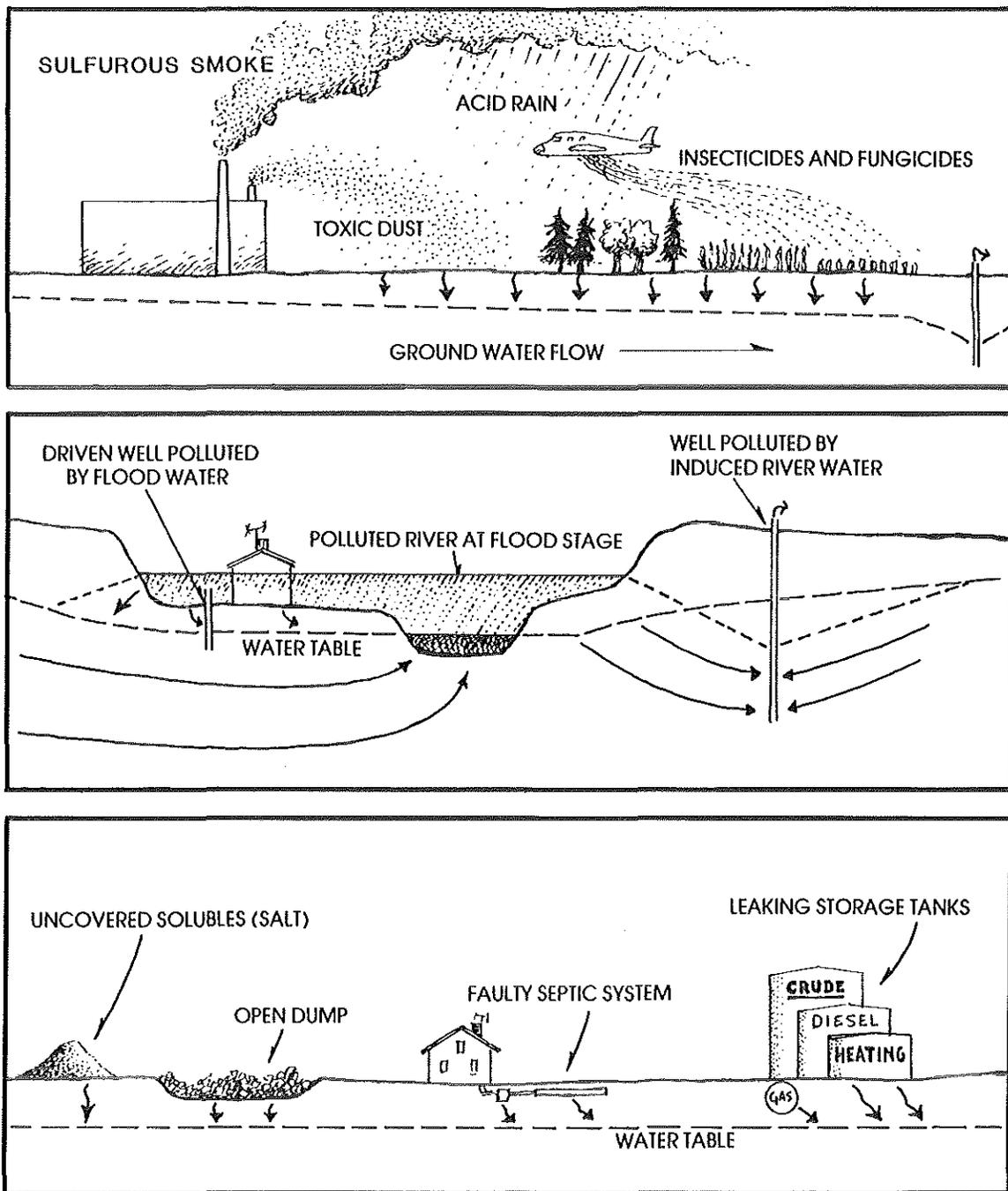


Figure 45. Mechanisms of ground water contamination from air, water, and land sources.¹⁰

contaminants as well. Microbes are involved with the breakdown and retention of organic pollutants moving through the soil. All in all, porous materials are superior water-reclamation media and generally maintain ground water in a potable state. Man, however, often overwhelms the natural processes available at a given site and contaminates ground water.

Once in the ground water system, contaminants travel the various paths followed by ground water and are sometimes able to migrate considerable distances. Different contaminants travel at different rates and to different distances from the source of introduction to the system. A single large discharge of a particular contaminant may react differently from a small, but continuous discharge of the same waste, and the distance a certain pollutant can migrate through a particular geologic deposit is subject to a variety of chemical, physical, and geological factors.

A critical factor in contaminant travel is the biological and chemical nature of the pollutant. Most pathogenic organisms, for example, are attenuated within 100 feet of their source, but viruses apparently can migrate much farther. Some chemicals, such as nitrate-nitrogen, chlorides, and numerous household and industrial organic chemical compounds (generally, hazardous wastes) are not broken down by physical, biological, or chemical processes that naturally occur in geologic formations and aquifers. Their concentrations are decreased almost entirely by dilution. Thus these materials can migrate great distances in a ground water system at ever decreasing, but still undesirable, concentrations. Other substances, such as lead and various metals adhere to soil particles and generally travel only short distances.

In a general way, less permeable substances, especially those containing clays with available ion-exchange sites (a water softener, for example, exchanges sodium ions for calcium and magnesium ions), are better suited to waste attenuation, while gravel soils are least suited. Furthermore, the thickness of the unsaturated material through which recharge water must pass before becoming part of the ground water body is an important factor. Aquifers underlying a thick, unsaturated soil cover are better protected than those with little or no overburden.

GROUND WATER QUANTITY AND QUALITY: SITE ASSESSMENTS

Investigations to determine ground water quantity and quality are undertaken at various sites in Maine to define potential ground water supplies, to disclose the areal extent and severity of existing contamination, and to predict changes in ground water quantity and quality that might come about as a result of some proposed development. Exploration techniques for ground water supplies were discussed previously under "Wells: Exploration". Site assessments more specifically aimed at defining existing or possible ground water contamination often utilize the same basic investigative techniques as used in water supply studies, but with different emphasis on details. The most often used technical approaches for these site assessments are discussed below.

Site Reconnaissance and Aerial-Photograph Interpretation

After study of existing data, such as that described later in this handbook under "Available Hydrogeologic Data", aerial-photograph interpretation and on-site hydrogeologic reconnaissance are typically undertaken to identify major geologic features such as glacial deposits and bedrock fracture structures which may affect ground water availability and movement. Cultural features, such as homes and existing wells, as well as many other items of importance to a site assessment can be identified and plotted on maps.

Geophysical Investigations

Geophysical investigations use some physical property of porous media and the fluids in them to identify subsurface characteristics such as the depth to the water table, presence of contaminants, and the depth to bedrock. Commonly used methods are seismic refraction profiling, electrical resistivity soundings and profiles, and terrain conductivity profiles, all of which are run across the ground surface of the site. Seismic refraction uses the acoustical properties of geologic strata to generally define their thickness, depth, texture, and saturation. Electrical resistivity uses the electrical properties of these formations and the fluids in them (ground water and contaminants) to determine similar properties, but more often to determine the presence and areal extent of certain contaminants. Terrain conductivity is similar to electrical resistivity, but best used to map plumes of ground water contaminants. Geophysical investigations are often a prelude and guide to subsequent detailed test boring investigations.

Test Borings and Monitoring Wells

Test borings are made using a variety of techniques including auger, drive casing, and air percussion, to sample and explore glacial overburden and underlying bedrock. Samples of overburden are often collected by a split spoon device that is driven into the material, while bedrock is typically sampled by cutting a continuous core with a diamond bit. These methods provide a log of the composition, thickness, and texture of subsurface materials. Visual logs are sometimes augmented by subjecting the collected samples to laboratory analysis.

Hydraulic conductivity of subsurface materials is measured in test borings at various depths as they are drilled. A typical technique is to drive steel casing to a particular depth, wash out the casing, and fill the casing with water and observe the change in water level with time. The "falling head" of water in the casing will be more rapid in permeable sediments such as sand and gravel, than in poorly permeable sediments such as silt and clay. There are, in addition, other field techniques used to measure hydraulic conductivity in boreholes and in monitoring wells.

Once the drilling, sampling, and permeability measuring in a test boring are completed, a monitoring well is usually installed to observe ground water levels over a period of time and from which to collect ground water samples for chemical analysis. There are numerous materials used for construction of monitoring wells depending on the particular application. Many monitoring wells are built of PVC pipe (polyvinyl chloride plastic), using a slotted section for the well screen and solid pipe for the riser from the top of the screen to above ground surface. Also used for their non-reactive chemical nature are teflon, stainless steel, and polypropylene pipe.

Monitoring wells may be built to measure a water table or to measure ground water flow potential at one or more depths below the water table. Often a "cluster" of closely-spaced wells is constructed with one at the water table depth, a second at some intermediate depth, and the third just above or below the bedrock surface as illustrated by Figure 46. In some cases, two or more wells of a cluster may be in the bedrock aquifer. Water levels measured in these multiple depth wells are used to define the vertical components (vertical hydraulic gradient and direction of flow) of ground water flow. For example, in a recharge area, a well cluster would show a

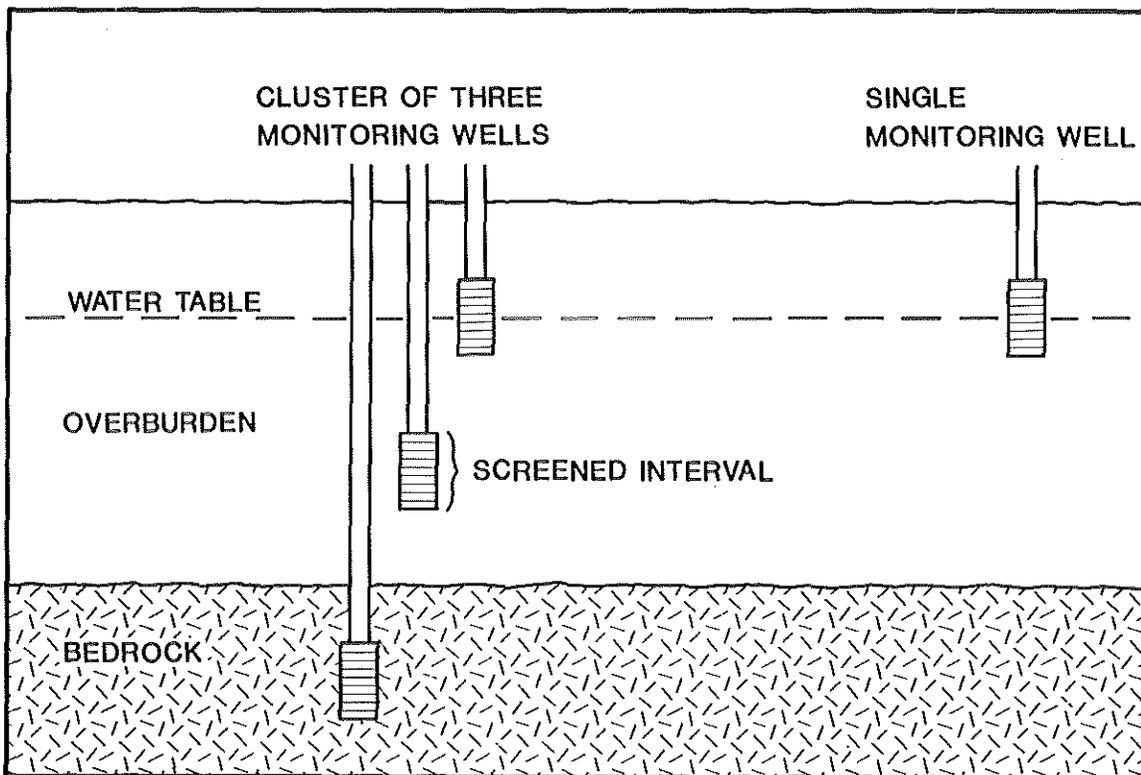


Figure 46. Schematic diagram of a cluster of three monitoring wells used to measure vertical components of ground water flow and single monitoring well (one of at least three) used to measure horizontal components of shallow ground water flow.

downward flow gradient, while in a discharge area an upward flow gradient would be shown. Similar monitoring points across a study area are used to map the horizontal components (horizontal hydraulic gradient and direction of flow) of the water table and of deeper (intermediate and regional) flow systems if they occur beneath the site. In all cases, it is prudent to take several sets of water level measurements spaced by several days or weeks in order to be sure the monitoring wells have equilibrated with the natural ground water systems. Furthermore, where detailed water level information is required, elevations of the measuring point at each well (usually the top of the casing) is determined by land survey.

Site assessment data, usually derived from completion of test borings and monitoring wells, include horizontal flow nets (Figure 47) and vertical flow nets (Figure 48). Figure 47 shows contour lines that represent the flow potential of shallow ground water (in this instance these equipotential lines describe the water table), and shows representative flow lines that indicate directions of shallow ground water movement. Figure 48 is a geologic cross section along line A-A' that illustrates the vertical characteristics of the shallow ground water flow system shown in Figure 47. These two flow nets were drawn from test boring and monitoring well data to graphically define the hydrogeologic conditions that controlled the movement of gasoline that leaked from a buried gasoline tank at the point marked in Figure 47. The resulting contaminant plume is discussed later in this handbook under "Specific Problems and Case Studies, Petroleum Products, case 2".

Computer Analysis

Computer study of hydrogeologic problems is used to analyze and assess future conditions or, rarely, to reconstruct some past event such as a contaminant spill. There are a great variety of computer programs developed for different hydrogeologic settings and for different needs. Some programs deal with changes in flow potential and direction, while others can handle both ground water flow and migration of dissolved contaminants. There are three-dimensional programs available, as well as the more commonly used two-dimensional programs. Whatever the particular program, all require input of hydraulic data that are peculiar to the site being assessed. For general analysis, assumed hydraulic values are sometimes used, but for detailed site analysis, field measured values of such things as hydraulic conductivity, hydraulic gradient, and saturated thickness must be used.

The computer program is first constructed to mimic the natural ground water flow conditions that are either assumed or are field measured. Once this "history matching" is completed within an acceptable limit of error, the program is run to evaluate future situations. In water supply work, for example, the interference among several proposed and existing municipal

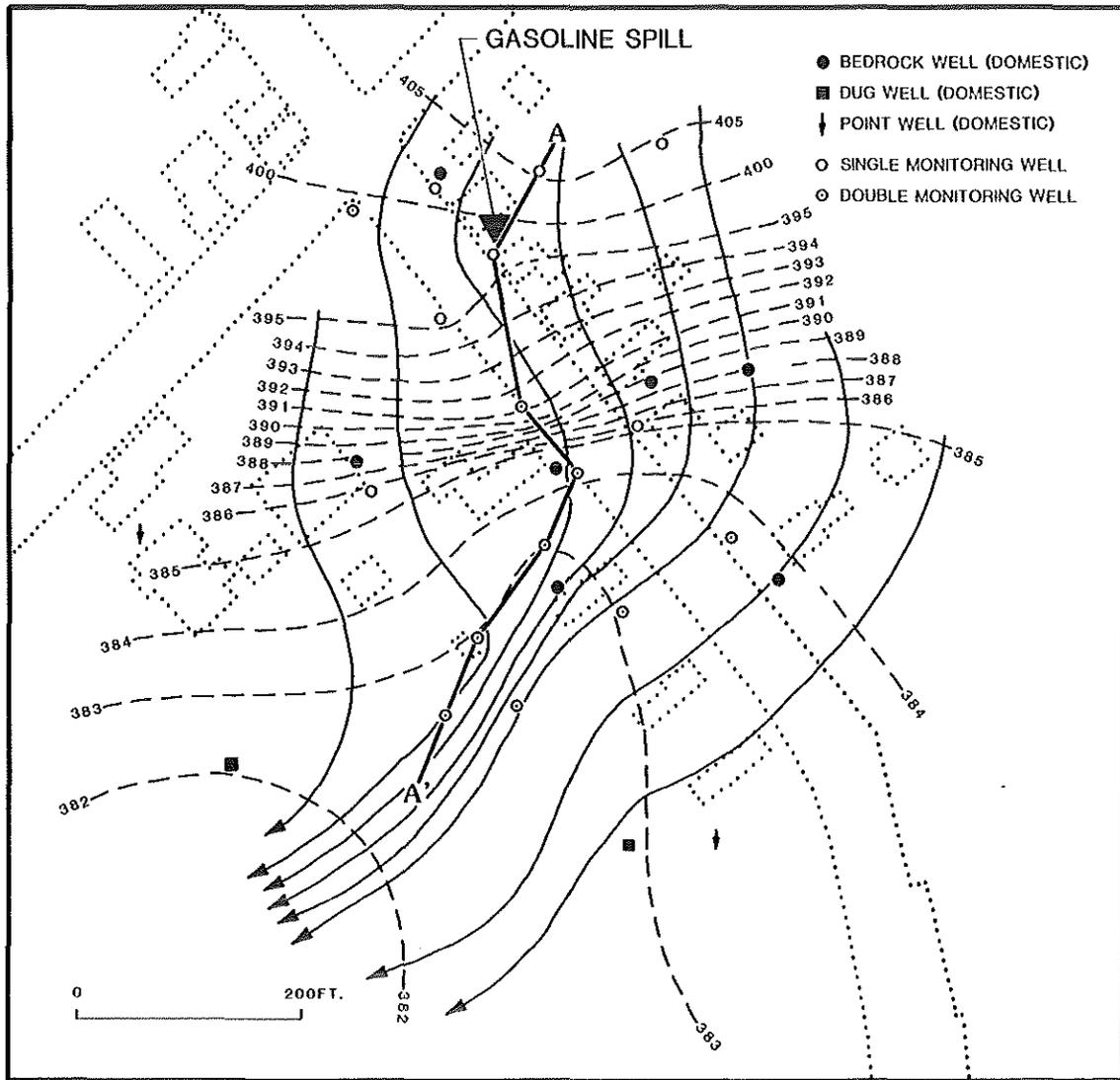


Figure 47. Shallow horizontal flow net drawn in area of a gasoline spill from monitoring well data. Equipotentials (dashed lines) connect points of equal water table elevation. Flow lines (solid lines) show down gradient directions of shallow ground water flow.¹⁸

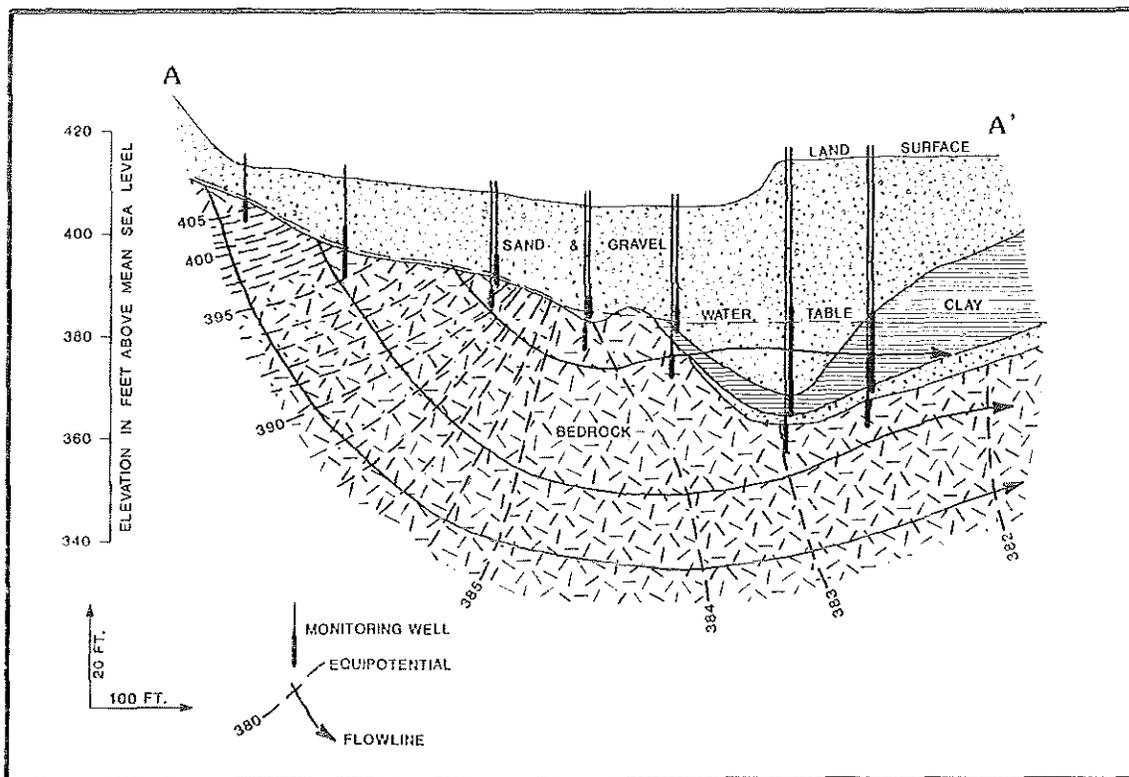


Figure 48. Vertical flow net A - A' drawn approximately parallel to the horizontal direction of ground water flow as shown in Figure 47. Vertical components of flow (vertical hydraulic gradients) were measured in the paired monitoring wells.¹⁸

wells might be studied, while in contaminant assessment work, the future dimensions and extent of a plume might be investigated. In this way, a great variety of pumping rates, waste-disposal methods, contaminant clean-up plans, and many other hydraulic situations are evaluated so that future conditions can be anticipated and the best possible alternatives can be selected for implementation.

In utilizing computer models, it must be remembered that the output is only as good as the field data used in the model. There is always a temptation to use reconnaissance-level data to predict the exact outcome of a land-use decision. Computer analysis is a valuable tool when used in conjunction with a well-designed field investigation program.

CHAPTER 2

MAINE'S WATER SITUATION

Throughout this handbook examples of hydrogeological situations found in Maine are used to illustrate ground water theory. This chapter presents more specific characteristics of Maine's water situation.

RELATIVE USE OF GROUND AND SURFACE WATERS FOR DOMESTIC SUPPLIES

Ground water is widely used in Maine for drinking purposes. Nearly all of the rural population depends on wells and springs for potable water, and approximately 50% of the municipal systems use ground water at least in part. In total, about 57% of Maine's people use ground water for their domestic water supply.¹⁹

INFILTRATION OF PRECIPITATION

As was described earlier, precipitation falling on the earth evaporates back into the atmosphere, runs off to streams and water bodies, and recharges the ground water supply. Numbers representative of conditions in Maine are as follows: 50% of the precipitation runs off as streamflow, 30-40% returns to the atmosphere by evapotranspiration, and 10-20% infiltrates soil and rock and recharges the ground water reservoir.²⁰ Locally, where permeable glacial sand and gravel deposits are exposed at the surface, recharge may be as much as 50% of the total precipitation.²¹

TOTAL GROUND WATER IN STORAGE AND ANNUAL RECHARGE

The total ground water in storage in the soils and rocks of Maine can be calculated only crudely. Using some rough estimates of the specific yield of these porous materials, it is calculated that every square foot of land in Maine to a depth of 1,020 feet has 14.5 cubic feet of ground water. Maine, then, has 100 trillion gallons of ground water, or 20 times the total volume of surface water in storage.

Annual ground water recharge in Maine is dependent upon the average annual rainfall, and the percentage of this that infiltrates the ground surface. Both parameters vary considerably over the State. Using the average annual rainfall figure of 41 inches, and an average recharge of 15% of the total rainfall, the annual recharge to ground water reservoirs is calculated as follows:

average annual rainfall x average recharge of total
rainfall = annual recharge

41 inches of rain x 0.15 = 6.15 inches of annual recharge

Thus, over every square foot of the State there is an annual recharge of about 0.51 cubic feet of water. Annual recharge, then, is only about 3.5% of the volume of ground water available in the upper 1,020 feet of the crust. This is the amount of ground water that is replenished each year; that is, the long term safe yield of Maine's ground water resource, or about 3.5 trillion gallons.

GROUND WATER AVAILABLE IN SURFICIAL AND BEDROCK AQUIFERS

The amount of ground water available from the unconsolidated materials overlying bedrock is highly variable, depending mostly on the texture and saturated thickness of the material. Gravel and sand are permeable, and where saturated serve as good sources of ground water. Tillis yield some water to wells, but clays are poorly permeable, usually making poor water sources even when saturated.

Throughout the State, till is generally present at the surface or underlying younger sediments. Clay of marine origin is extensive in the coastal region and extends up the major river basins for some distance. Farther inland there are small areas of glacial-lake clays. Sand and gravel deposits occur over about 25% of the State. They are most extensive in York, Cumberland, Oxford, Hancock, and Washington Counties. The highest yielding unconsolidated aquifers (500 gallons per minute or more) are the gravel deposits that are saturated, and are in hydraulic contact with a lake or stream.

Quantities of ground water available from the bedrock of Maine are extremely variable locally, but essentially similar

regionally. The underlying crystalline rock, which includes granitic and metamorphic types, shows similar yield characteristics throughout the State.

Average yield from most of the bedrock in Maine is less than 10 gpm, and sufficient only for supplying dwellings and limited agricultural needs. The range of domestic well yields (6-inch diameter wells) is from "dry" to about 100 gpm. The highest yields are found where the bedrock is extensively fractured, possibly by faulting. These fracture zones can be located by a combination of aerial photograph, satellite, geophysical, and other hydrogeologic techniques. Sustainable yields of 100 to 500 gpm are obtainable from major zones of fractured bedrock in Maine.

Numerous homes in Maine have wells yielding less than 1 gpm. Usually these wells are relatively deep, more than 200 feet, sometimes up to 500 feet or more. A guide developed by the Water Well Drillers Association of Maine, and shown as Table 4, illustrates the relationship between available well yield and the depth of well required to provide sufficient water storage. The deeper the well, the less the instantaneous

Table 4. Water Well Drillers Association of Maine recommended minimum depth of well for a given yield to supply a typical home with sufficient water. This guide assumes a standard 6-inch well where the static water level is at ground surface, and a family of 5 using 75 gallons each in one hour. It is very conservative in that 375 gallons of water would rarely be used in a single hour of the day.

Maximum available yield of the drilled well	Minimum well depth needed to supply typical home with sufficient water
5 gal/min	0-50 feet
4	51-100
3	101-150
2	151-200
1	201-300
½	301 and greater

flow need be. (A 6-inch diameter well casing stores 1 1/2 gallons per foot of depth below the static, or non-pumping, water level.) The values given in this table are very conservative in that the per-person use is higher than the national average of about 55 gallons per day per person, and the total daily use is obtained in one hour by all five members of the family.

NECESSARY WELL DEPTHS

Domestic wells dug or driven into the overburden are typically between 5 and 25 feet deep depending on the depth to the water table and the depth to bedrock. They usually are just deep enough to penetrate the water table by several feet, and for this reason may go dry during periods of drought. Higher yielding sand and gravel wells, such as those used by municipalities, are generally at least 30 feet deep, and as much as 150 feet deep depending on the overall thickness of the water-bearing formation. These wells are constructed to fully penetrate the water-bearing zone of a significant sand and gravel aquifer and, thereby, to obtain the maximum volume of ground water available on a continuous basis.

Bedrock wells obtain ground water from water-bearing fractures; thus, a well is drilled to a finished depth at which at least one water-bearing fracture is encountered. Records for domestic wells in the mid-coastal part of Maine suggest that the first such fracture is struck most often before drilling 100 feet, and that there is about a 90% chance of encountering water before drilling 200 feet. If additional flow is required, the second water-bearing fracture is often found before drilling 100 feet more. The majority of domestic bedrock wells obtain sufficient ground water from three or fewer fractures; thus the typical domestic bedrock-well depth, at least in coastal Maine, is in the 100 to 300-foot range.

A common problem for the well driller and homeowner is the decision to continue drilling in a hole that is several hundred feet deep, but yields insufficient ground water. Many Maine drillers consider a depth of around 300 feet a point to stop and start over if no water has been encountered. The greater difficulty of drilling below 300 feet is in part responsible for the choice of this turning point. Figure 49, however, shows that only about 50% of the available fractures occur in the upper 300 feet of rock. It further shows that the decrease in percentage of fractures, the frequency of change, is nearly the same between about 40 to 500 feet into bedrock. Rather than at 300 feet, a decrease in frequency of water-bearing fractures appears to occur at around 500 feet. Drilling between 300 and 500 feet depth seems to give nearly the same chance of success per foot as drilling from 40 to 300 feet. This is a general observation, however. In practice, test

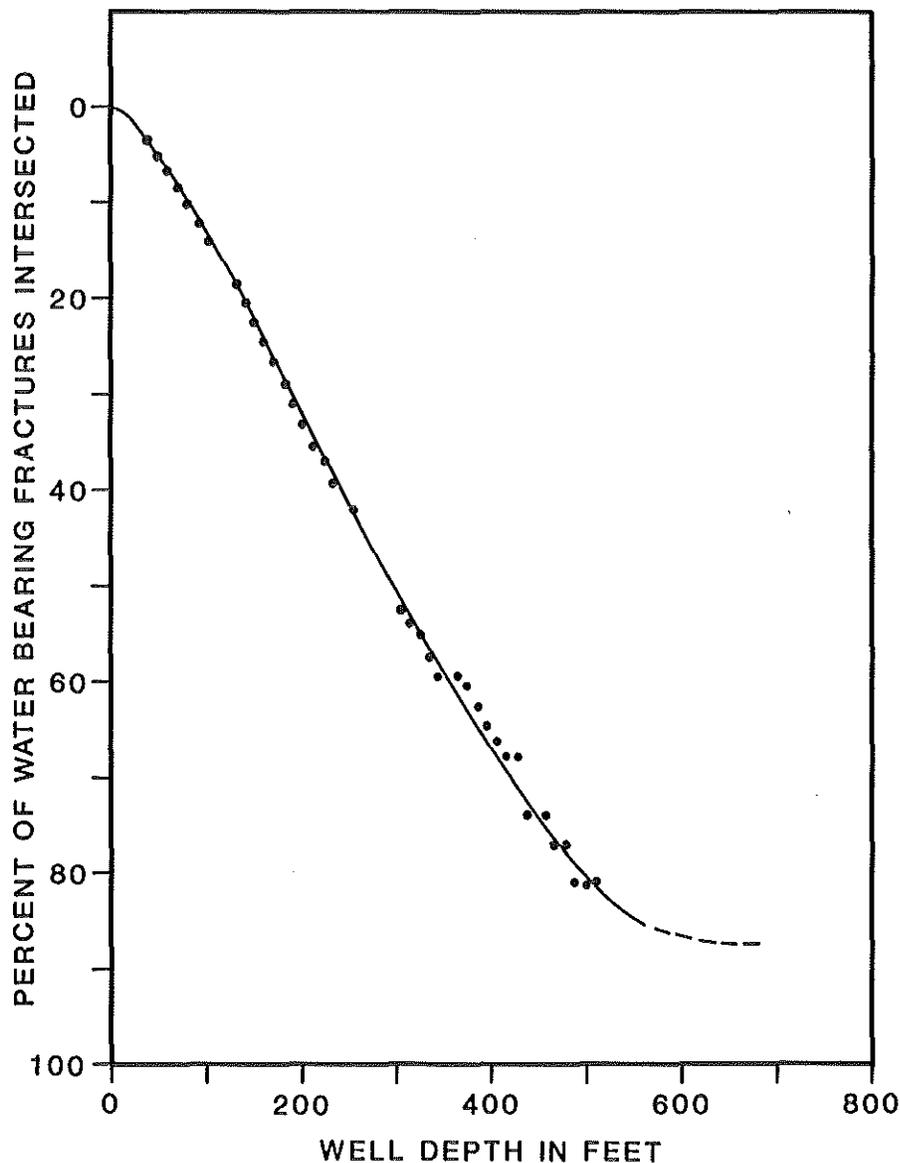


Figure 49. Change in number of water-bearing fractures with depth. Curve is based on data from Cumberland and Sagadahoc Counties, Maine.

drilling in Maine has found areas where the only water-bearing fractures are above a depth of 100 feet, and has found other areas where water-bearing fractures can be found at depths of 700 to 900 feet.

In some instances, a bedrock well that is 200 or more feet deep but is not yielding enough water can be made to yield sufficient water by the technique of hydraulic fracturing. Water is pumped into the sealed well bore under such high pressure that incipient, or possibly plugged, fractures are opened, allowing ground water to more freely flow into the well. Further deepening of the well is then unnecessary.

Bedrock wells located and drilled specifically for municipal, industrial, or commercial uses typically encounter zones of closely spaced fractures at depths between 50 to 700 feet. Often the location of a production bedrock well is selected on the basis of previously drilled 6-inch diameter test wells to intersect the major fracture zones at depths greater than 200 to 300 feet. The reason for this is to permit a large drawdown under pumping conditions without dewatering the major fractures. Thus in contrast to the typical domestic bedrock well, the necessary depth of the municipal or other production bedrock well is a matter of design rather than accident.

Generalized maps are available that show the depth of many existing bedrock wells and some existing gravel wells (see "Available Hydrogeologic Data" in this handbook), and as such are a guide to necessary well depths in a given area.

GROUND WATER QUALITY

The most common natural ground water problem in Maine is excessive iron content. Iron is a nuisance, causing poor taste, staining of fixtures, and encrustation of pipes, pumps, and tanks. It is most common in iron-sulfide-bearing rocks that seem to be very numerous throughout the coastal half of the State. Some gravel aquifers also produce water with excessive iron, probably because of the concentration of iron-bearing mineral particles incorporated into the sand and gravel.

Other natural ground water quality problems include excessive hardness, sulfur, sodium chloride, and radon. Hardness causes soap curd and encrustation of pipes and especially boilers, sulfur results in poor taste, salt makes water unfit for most uses, and radon can be dangerous to one's health.

Regional variations in ground water quality are not well-documented in Maine because little study has been done. However, an obvious difference occurs in areas of limestone, such as eastern Aroostook County. Bedrock ground water in this area is almost always hard, compared to that from the crystalline rocks throughout the southern half of the State. Wells in the thin, patchy limestone formations, such as those found in Knox County and parts of Cumberland, Androscoggin, and Kennebec Counties, usually produce hard water.

High levels of sodium chloride may occur in coastal areas due to salt-water intrusion from the ocean. In addition to areas of salt-water intrusion, inland wells with high levels of sodium chloride occur in several areas of Maine. These salt-water concentrations are the result of sea water trapped in

bedrock valleys under a layer of marine clay since the close of the last glacial episode, 10,000 to 13,000 years ago.²²

Radon, a radioactive gas, is present in some quantity in nearly all Maine ground water. Radon concentrations are highest in rocks such as granite and highly metamorphosed sediments which contain uranium.

Bedrock geologic maps of Maine, available from the Maine Geological Survey (Augusta), show the areal distribution of the rock types mentioned above, and may be useful as a rough guide to the quality of ground water available in different parts of the State.

Man's activities may also result in ground water contamination. These activities are discussed in the section entitled "Specific Problems and Case Studies".

CHAPTER 3

AVAILABLE HYDROGEOLOGIC DATA

From previous discussions, one can see that such factors as the type and thickness of overburden, bedrock elevation, potentiometric surfaces, water-table level, and fault and fracture zones relate to the location of aquifers, as well as to their yield and susceptibility to contamination. The Maine Geological Survey and the U.S. Geological Survey publish maps and reports pertaining to those factors and other data of a more statistical kind relating to ground water supplies.

Figures 50, 51, and 52 are index maps showing published ground water data available from the Maine Geological Survey in 1987. Index maps showing the availability of all kinds of geologic maps and related information are available from the Maine Geological Survey in Augusta. Lists of maps and reports available from the U.S. Geological Survey may be obtained from that agency. The maps and published data specifically for Maine, however, are of such a scale and degree of generality that they are of little help when considering tracts of land smaller than about two acres. The situation of such landowners is discussed in the section on "Specific Problems and Case Studies".

SURFICIAL AQUIFER INFORMATION

All the unconsolidated material overlying bedrock is referred to as overburden. Overburden in Maine is of glacial origin, and consists of till (a heterogeneous mixture of gravel, sand, clay, cobbles, and boulders), sand and gravel, and clay. It is discontinuous, ranging from zero to a few hundred feet in thickness. Overburden cover in much of the

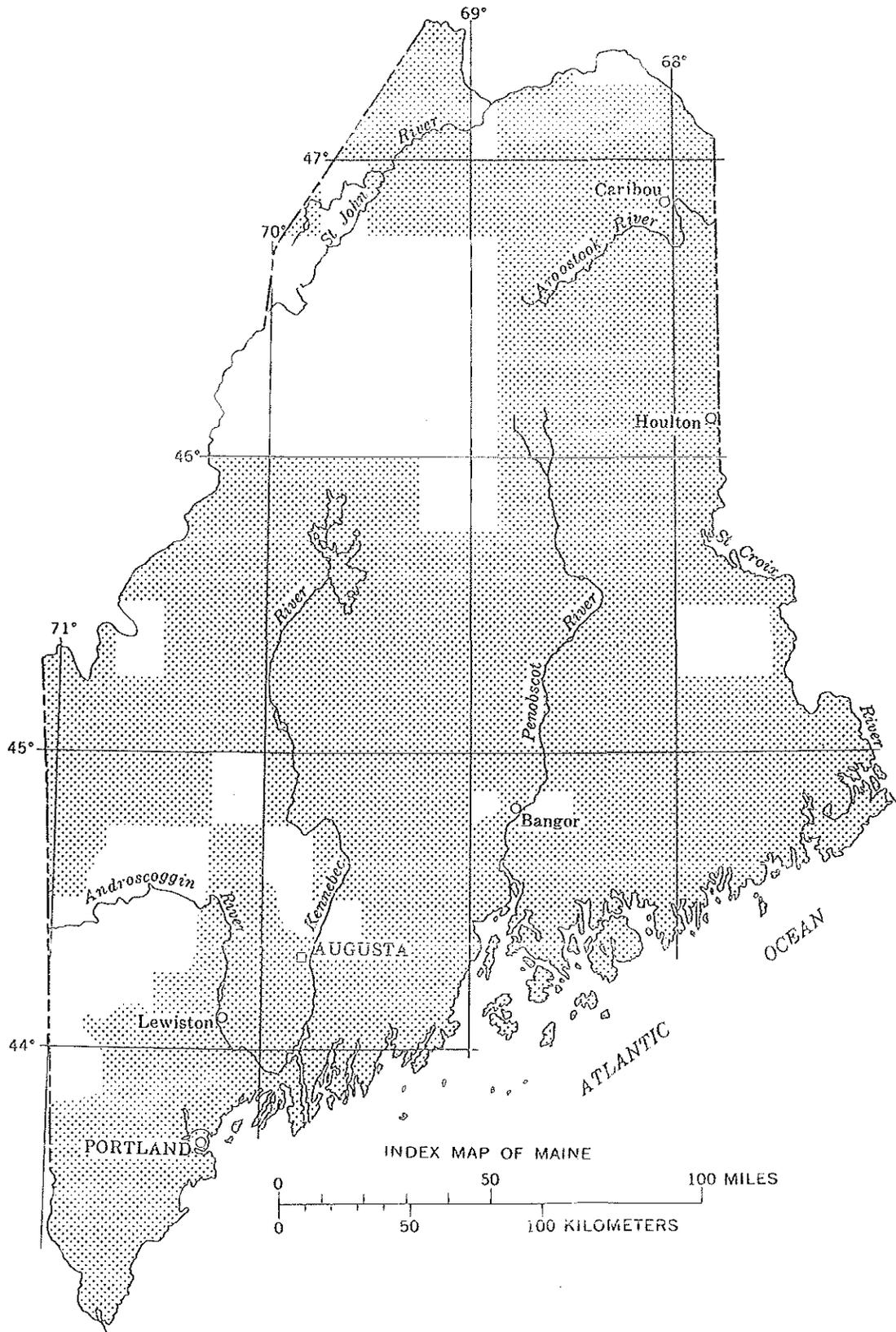


Figure 50. Index of reconnaissance surficial geology maps available from the Maine Geological Survey in 1987.

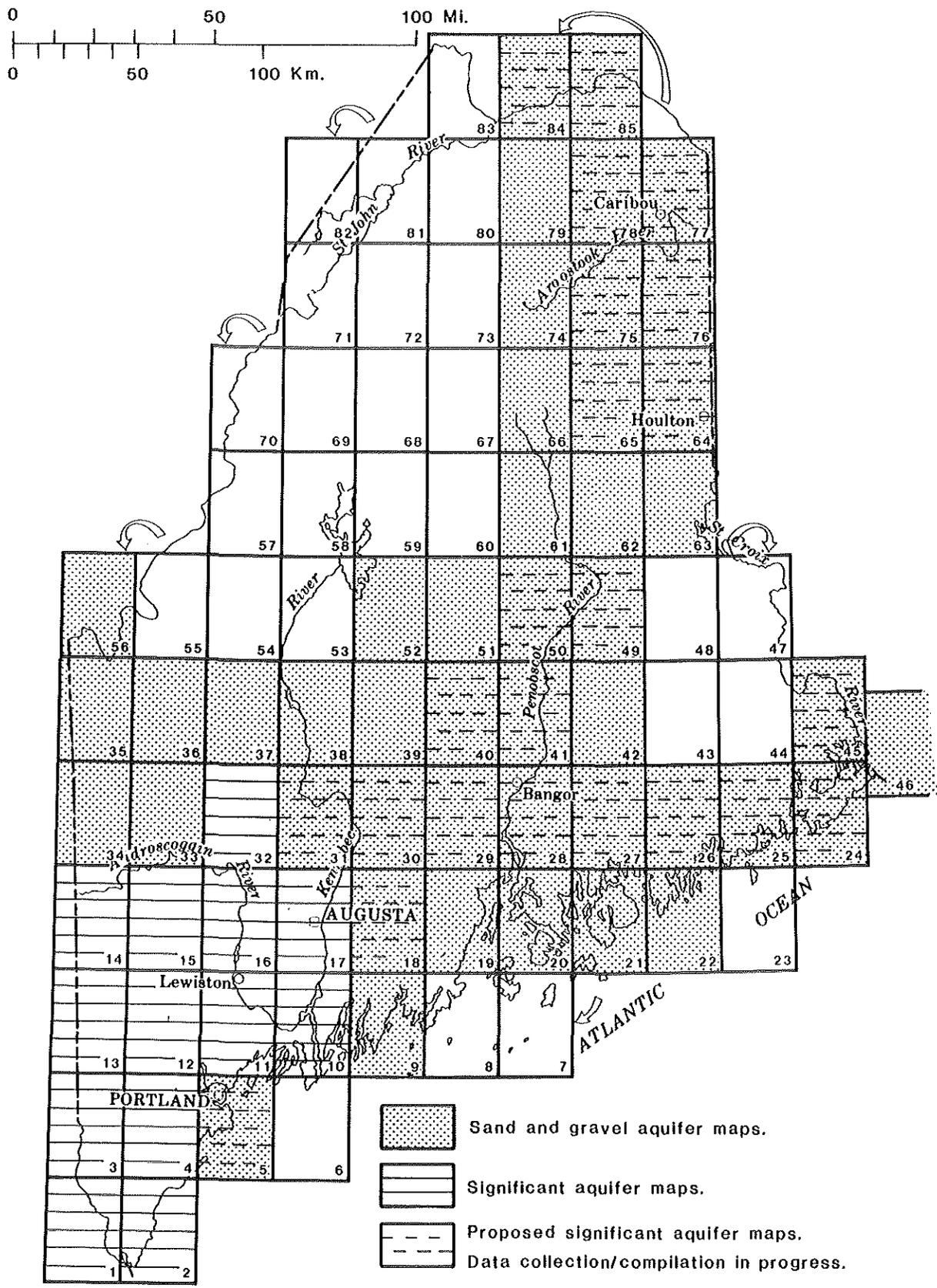


Figure 51. Index of sand and gravel aquifer and significant aquifer maps available from the Maine Geological Survey in 1987.

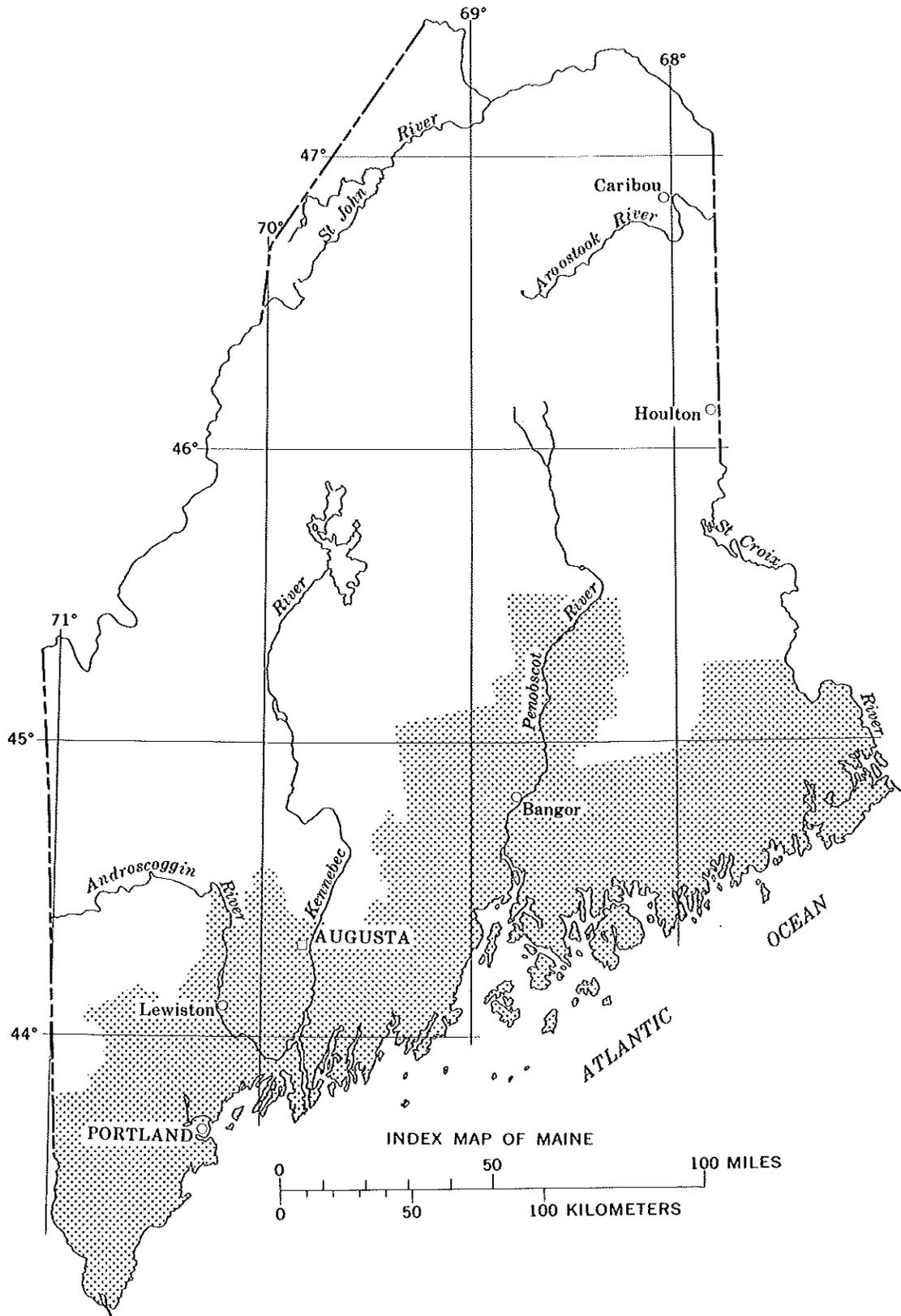


Figure 52. Index of ground water resource maps available from the Maine Geological Survey in 1987.

mid-coastal region is thin and patchy, but there is thicker cover in the southwestern and northeastern coastal regions usually associated with glacial delta and outwash deposits. Although the surficial geology (overburden cover) for most of the area inland of the coastal counties has been mapped, overburden thickness has not been mapped, so there are no generalizations to be made at this time.

Overburden kind and thickness relate to the yield of all types of wells, and to their susceptibility to pollution from human sources. Wells constructed in overburden obtain the most water from thick, saturated deposits of sand and gravel. The general locations and characteristics of these deposits are indicated on Sand and Gravel Aquifer Maps and Significant Aquifer Maps available from the Maine Geological Survey. Additional information on all types of glacial deposits can be found on Surficial Geology Maps available from the Maine Geological Survey.

SURFICIAL GEOLOGY MAPS

Reconnaissance surficial geology maps are available for a large part of Maine as depicted in Figure 50. These maps show the surface distribution of glacial and post-glacial sediments such as till, ice-contact sand and gravel, marine silt and clay, and alluvium. The majority are available at a scale of 1:62,500, while others are available at a scale of 1:24,000. All maps include a discussion of general origin, texture, and stratigraphic nature of the deposits depicted.

SAND AND GRAVEL AQUIFER MAPS

Reconnaissance sand and gravel aquifer maps show the presumed areal extent of coarse-grained surface materials that in all probability can supply useful quantities of ground water to properly constructed and developed wells. These maps depict the boundaries of surficial aquifers where potential well yields are 10-50 gpm or 50 or more gpm. Additional information pertaining to wells, springs, test borings, and test pits is also shown directly on the map (Figure 53). The materials of each aquifer area are described in an accompanying text. The maps are plotted at a scale of 1:50,000 and cover the area shown in Figure 51. These maps may be used to locate general areas that are favorable for development of water supplies from Maine's surface sand and gravel aquifers and, as a corollary, to locate areas that generally are unfavorable for storage or disposal of wastes, toxic substances, or hazardous materials.

SIGNIFICANT AQUIFER MAPS

In many parts of Maine, significant aquifer maps and accompanying reports have replaced or will replace sand and gravel aquifer maps (Figure 51). In these maps more detailed surficial aquifer information is available. This information has been obtained from seismic refraction profiling, well

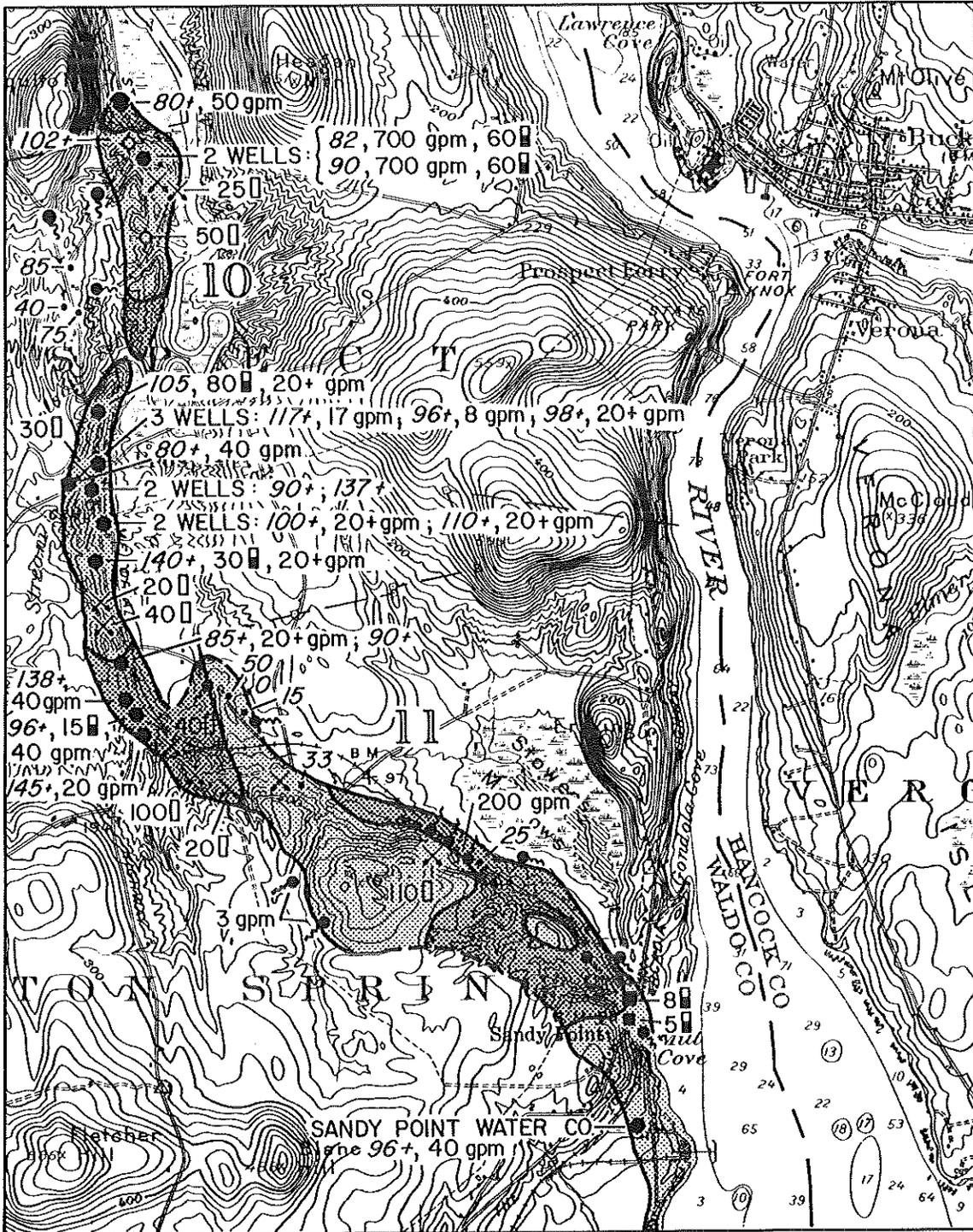


Figure 53. Gravel aquifer map of the Stockton Springs area of eastern Waldo County, Maine.²³ (1:50,000 scale)

inventory, stratigraphic borings, and test wells. The maps, which are at a scale of 1:50,000, better define the boundaries and potential yields of the aquifers present in the area. Reports accompanying the Significant Aquifer Maps include a description of the geologic setting, glacial history, and ground water quality of the mapped region, and include a large number of subsurface profiles drawn from the seismic refraction data.

Both the Sand and Gravel Aquifer Maps and Significant Aquifer Maps provide general hydrogeologic information about Maine's overburden ground water sources that is useful to individuals, governmental agencies, and others. For general aspects of land-use planning, site assessment, and well location, this information may be sufficient. Specific well location and other ground water yield, flow, and quality decisions require additional on-site hydrogeologic investigations.

WATER QUALITY IN SAND AND GRAVEL AQUIFERS REPORTS

These reports are available, or are being prepared, on a county basis for use in conjunction with Significant Aquifer Maps of the same region (see Figure 50). Each report describes regional ground water quality and includes a collection of brief reports on selected potential or known sources of ground water contamination. Sites investigated include road salt storage and distribution facilities, municipal and industrial dumps and landfills, and industrial lagoons. A sketch map and narrative give the layout of the facility and its history of operation, the hydrogeologic setting, the geophysical studies and chemical sampling performed, and an estimate of the nature, extent, and migration directions of contamination. Regional impact of all investigated potential contamination sources is implied by a 1:125,000 scale map that shows site locations, sand and gravel aquifer boundaries, estimated recharge areas for the aquifers, and generalized ground water flow directions near potential ground water contamination sites.

These reports and accompanying maps serve to identify and generally describe many sources of possible contamination that may now, or in the future, detrimentally affect the chemical quality of ground water available from the sand and gravel aquifers, and possibly from the underlying bedrock aquifers. They do not identify and describe all potential sources of ground water contamination in the areas investigated. In most cases, additional hydrogeologic study is recommended.

BEDROCK AQUIFER INFORMATION

General information concerning bedrock aquifers in Maine is available from the Maine Geological Survey in a series of 1:250,000 scale county Ground Water Resource Maps that cover the coastal region of the State as shown in Figure 52. The data sources and suggested uses for each of five different maps included in this series are discussed below. Also available from the Maine Geological Survey are a variety of bedrock geologic and bedrock fracture maps.

THICKNESS OF OVERBURDEN MAPS

Thickness of surficial materials is indicated on maps, as illustrated by Figure 54, that are based on data from water wells, test borings, gravel-pit observations, and bedrock outcrops. These maps are best used at the scale drawn to provide an areawide interpretation of overburden thickness.

Glacial deposits are a source of water not only for overburden wells, but also for bedrock wells. Permeable cover permits a greater rate of infiltration of precipitation and transmits this water downward to the water table. In a thick deposit that is saturated, there is a greater head to move ground water downward into the underlying bedrock. When a well in the bedrock is pumped, and a cone of depression or pressure relief is formed, ground water from the thick, permeable, and saturated overburden moves downward in response to the pumping and maintains the yield of the well.

Surficial geology maps indicate by implication the relative permeability of the overburden (refer to Table 1). Aquifer maps show more specifically the saturated sand and gravel deposits that have the strongest influence on bedrock well yield (Figure 55). At the opposite end of the scale is marine clay, which has a negative influence on bedrock-well yield; the thicker the cover of clay, the lower the well yield.

Overburden thickness and type are related to ground water contamination, as well as to yields. Because most purification processes take place in the unsaturated zone above a water table, and in the unconsolidated sediments overlying bedrock, overburden thickness is indicative of the susceptibility of local bedrock aquifers to pollution from surface sources of contamination. Assuming constant thickness, susceptibility is greatest where the overburden is sand and gravel and least where it is clay. Both surficial geology and overburden thickness maps should be used to locate general areas most acceptable for the disposal of liquid and solid waste.

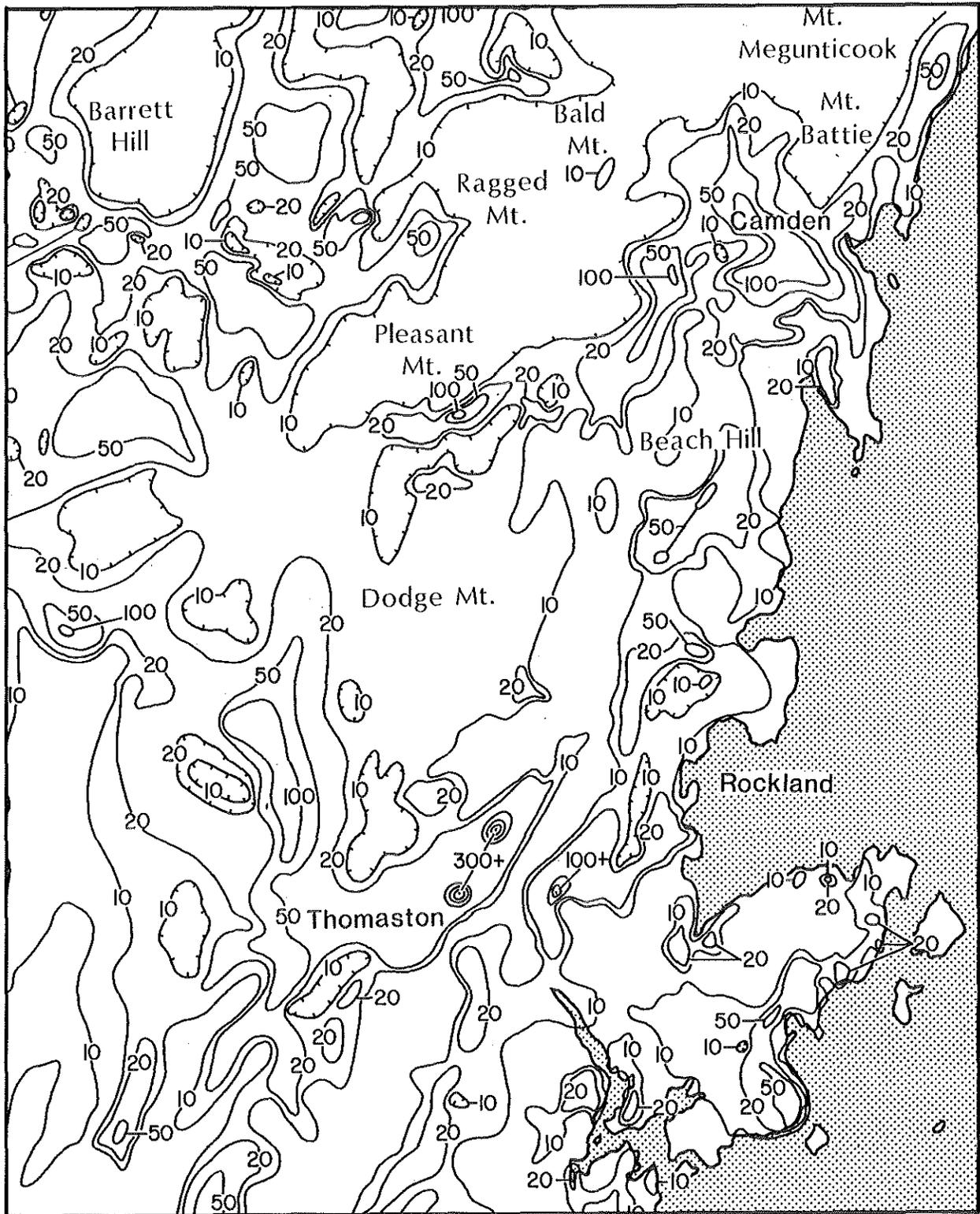


Figure 54. Map of Rockland, Maine, area showing thickness of overburden contours with thickness shown in feet. (1:125,000 scale)

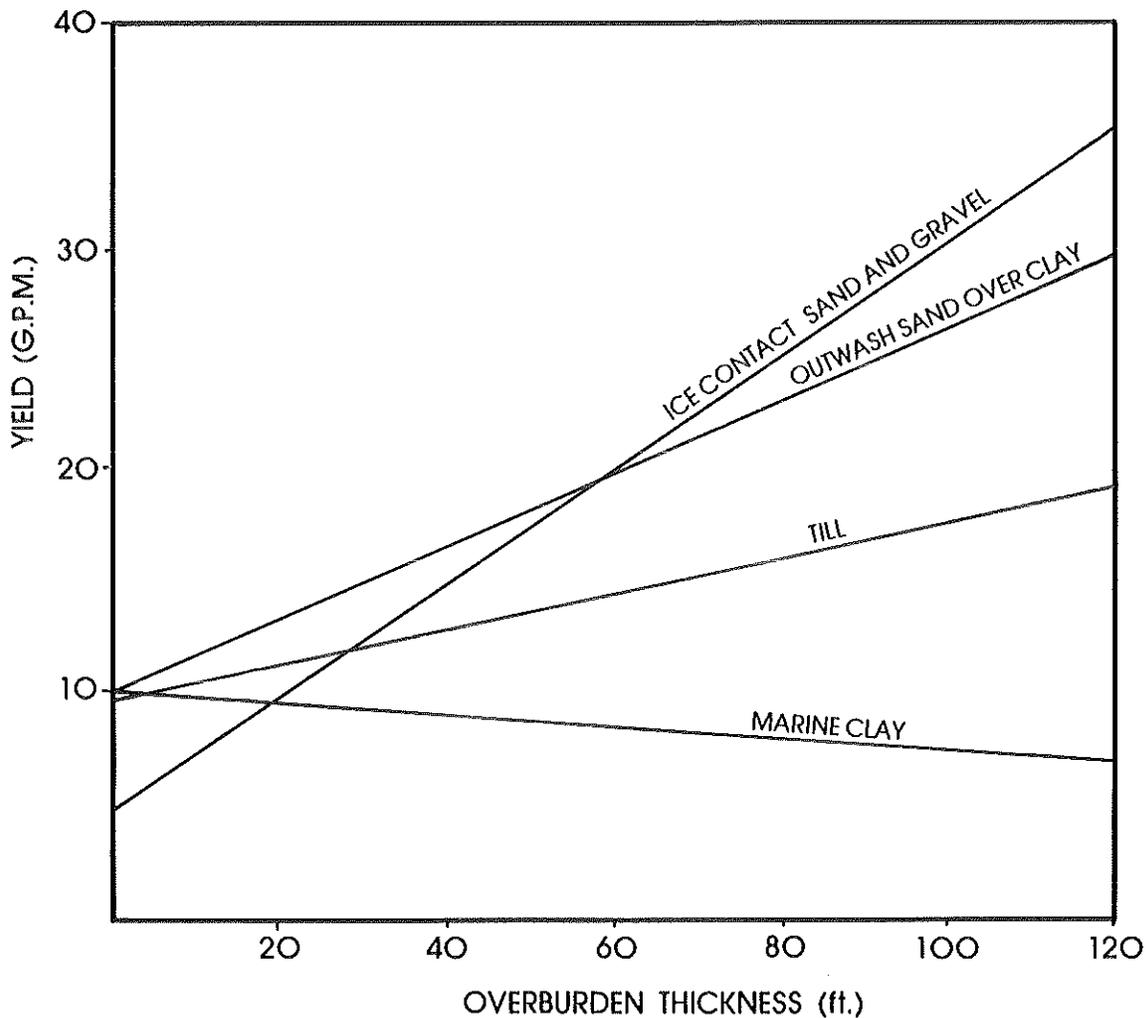


Figure 55. Effect of overburden on the yield of bedrock wells, coastal Maine.³

BEDROCK SURFACE TOPOGRAPHY MAPS

If the overburden were removed, the bedrock surface would be exposed to view. Because overburden tends to soften the landscape, filling valleys and reducing the steepness of slopes, a bedrock surface topography map shows greater relief than the more common topographic map (Figure 56). Both kinds of maps use contour lines that connect points of equal elevation to show surface topography.

The principal use of bedrock surface maps is to determine probable directions of ground water flow in the overburden just above the bedrock surface. Where the overburden is about 10 feet thick, bedrock has a strong control on shallow flow systems. Where more than 10 or 20 feet thick, intermediate flow systems in the overburden probably are controlled to a large extent by the slope of the bedrock surface. Ideally, ground water flow directions in overburden just above the bedrock surface are nearly at right angles to the bedrock surface contours.

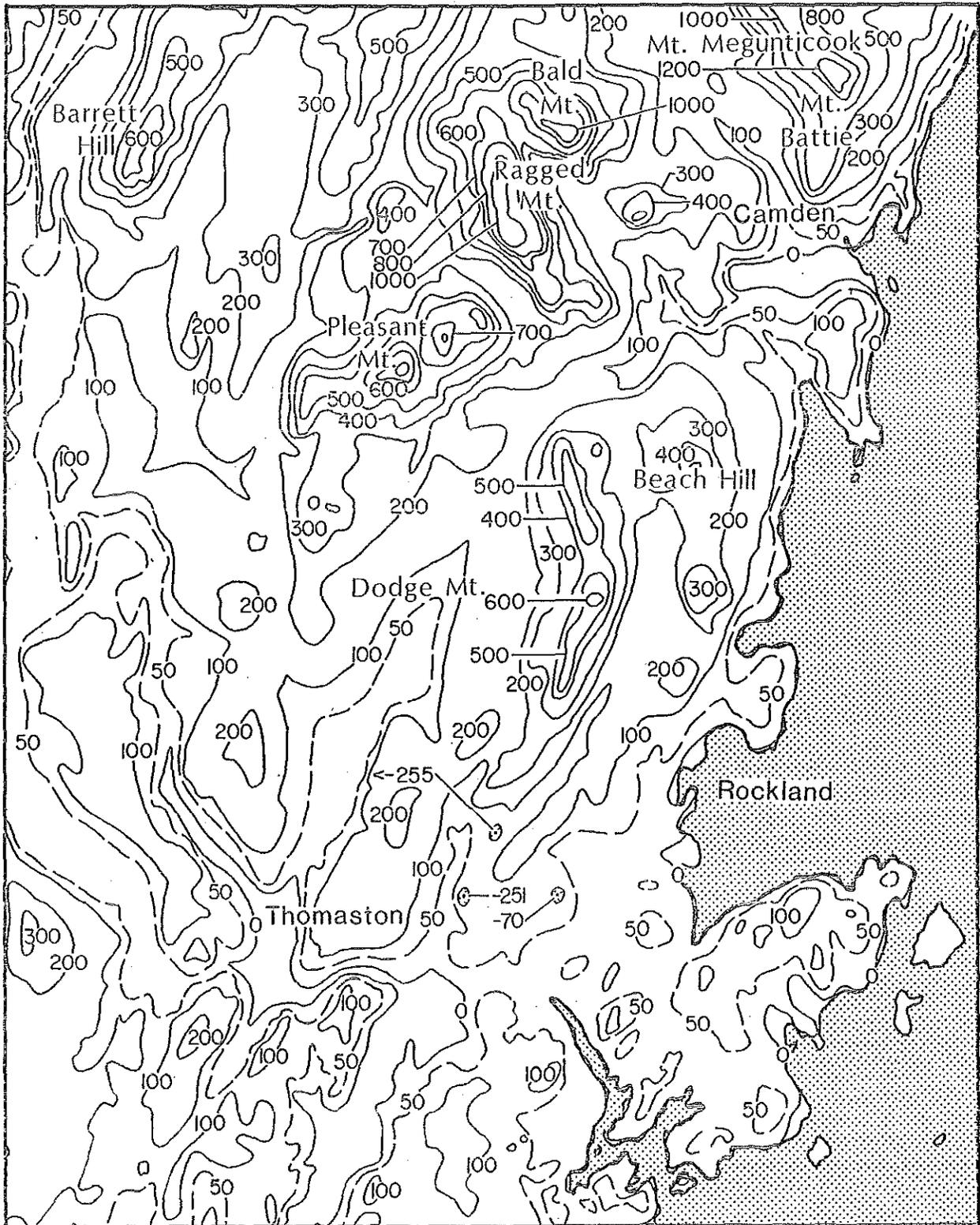


Figure 56. Map of the Rockland, Maine, area showing bedrock surface contours with elevations in feet above mean sea level.²⁵ (1:125,000 scale)

Bedrock elevation data are available from well logs, test-boring logs, and outcrop locations, all of which are used to construct the bedrock topography maps. They are best used at the scale drawn to give an area-wide sense of the bedrock surface topography.

POTENTIOMETRIC AND WATER TABLE SURFACES

Given sufficient points where ground water elevation is known, lines of equal flow potential can be drawn to show in map view the shape of the water table or the potentiometric surface. Such maps are similar in appearance to topographic maps, but the contours denote points of equal flow potential, rather than points of equal land elevation.

Whether based on water table elevation or potentiometric level, these maps appear similar to the topographic maps and are near replicas of the topographic landforms, except in the vicinity of ground water discharge points such as pumping wells and streams. The potentiometric surface map shown as Figure 57 indicates that high flow potentials (water elevations) generally coincide with the topographic highs, and the low flow potentials generally occur in the topographic valleys. The conclusion is that the valleys are essentially the areas of ground water discharge, while the hilltops and slopes are the recharge areas.

Under ideal conditions, flow occurs at right angles to the equipotential contour lines, from areas of high potential to areas of low potential. In fractured crystalline rock, however, flow must follow existing water-bearing fractures, and may at times move parallel to the equipotential lines. In addition, in unconsolidated material there are changes of flow directions, for example, along buried channels of coarser material and around poorly permeable layers of silt or clay.

The potentiometric surface maps are based on static water levels measured in bedrock wells of differing depth, and at the time they were drilled. Wells drilled over a period of 10 or more years are included, even though the static levels are likely to have changed somewhat because of climatic conditions. In all cases, these maps are suggestive only of ideal flow conditions and must not be used for more than a regional indication of ground water flow directions in the bedrock aquifer.

BEDROCK WELL DEPTH MAPS

The total depth of a well refers to its finished, or completed depth. For most domestic wells, it is the depth to which the driller goes in order to obtain the desired flow of ground water and allow a few feet for storage. Total depth includes the thickness of overburden penetrated. Plotting the

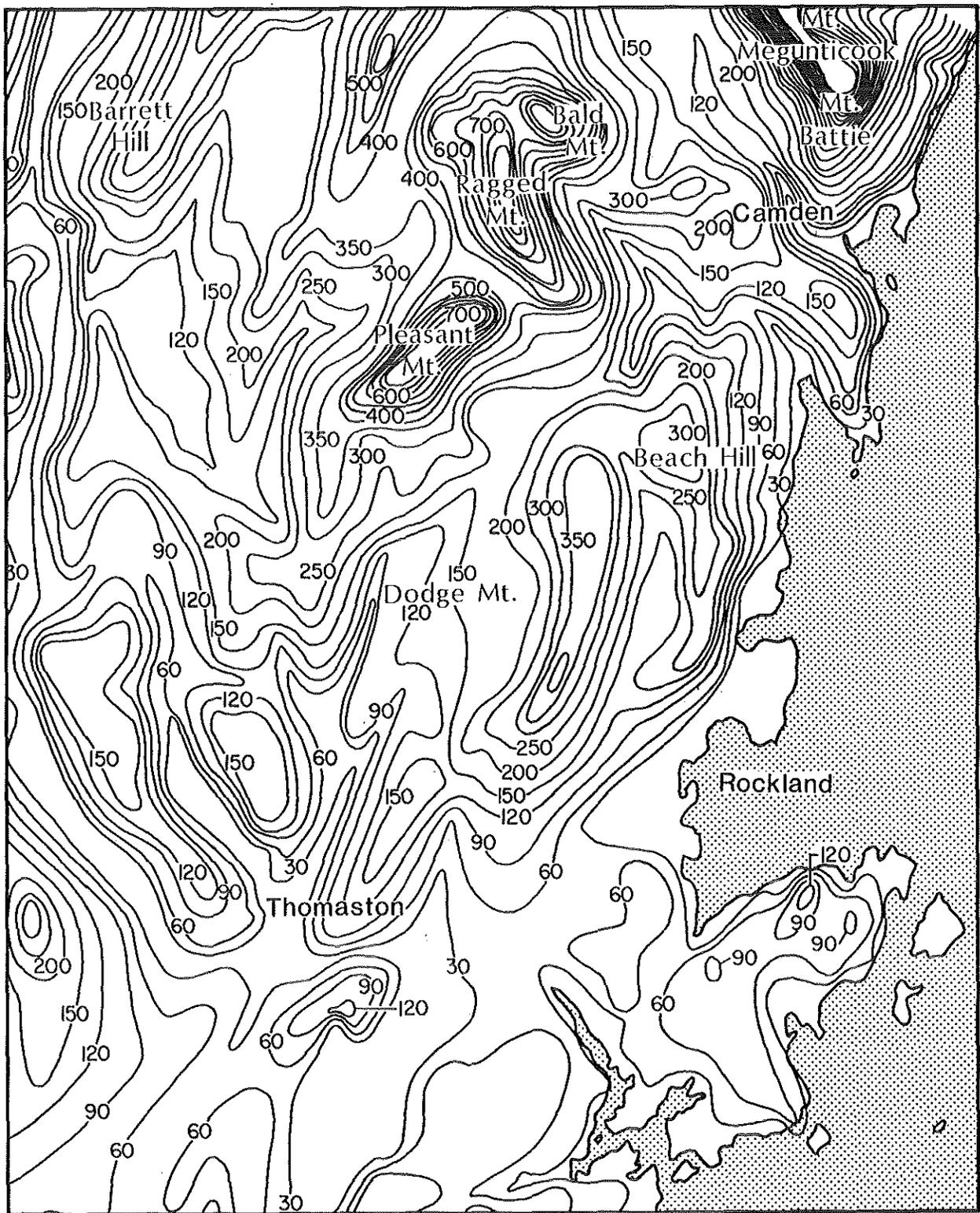


Figure 57. Regional potentiometric surface map of the Rockland, Maine, area showing potentiometric surface contours with elevations in feet above mean sea level. Overall direction of ground water flow in the bedrock aquifer is at right angles to the equipotential lines, as suggested by the several arrows.²⁶

total depth of many water wells in an area shows the typical depth at which sufficient water usually can be obtained (Figure 58). The information is helpful to the well driller and homeowner in assessing the general range of well depth necessary in a given region. It is also suggestive of geologic controls, both bedrock and surficial, that, if understood, can help in the selection of the most favorable well sites in the crystalline bedrock.

HIGH-YIELD BEDROCK ZONE MAPS

Bedrock wells in Maine most often yield small quantities of water; only 30% of the domestic wells drilled in the mid-coastal region yield 10 or more gallons per minute (Figure 59). Those yielding 10 or more gallons per minute are defined here as high-yield bedrock wells.

The occurrence of permeable, high-yield zones in crystalline bedrock is related to geologic structures, such as faults and joints, that are often linear or localized features. Areas of known higher than average yield are mapped by drawing yield contours. Contour lines delineate areas of equal yield, including those of 10, 50, and 100 or more gallons per minute. Each area enclosed by a 10 gpm contour line is potentially more favorable for the development of ground water supplies than surrounding areas. Yield contours, however, are drawn only where data are available. Bedrock yield maps (Figure 60) are best used as a general guide to favorable well location. Much more detailed site-specific investigation is usually necessary to locate and drill a high-yielding bedrock well for municipal, industrial, or commercial purposes.

GENERAL WATER-RESOURCES DATA

The U.S. Geological Survey, Water Resources Division, in Augusta, Maine, maintains a number of stream gauges, observation wells, and water quality stations at which periodic water level and water quality measurements are made. This information is published annually in Water Resources Data for Maine. A monthly publication entitled Current Water Resources Conditions in Maine lists general streamflow and ground water level conditions occurring in Maine in the preceding month. These reports include a large amount of detailed information that is useful in many ways, although not specifically for ground water studies.

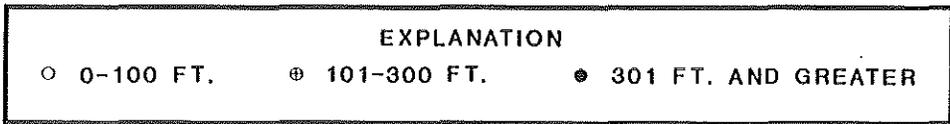
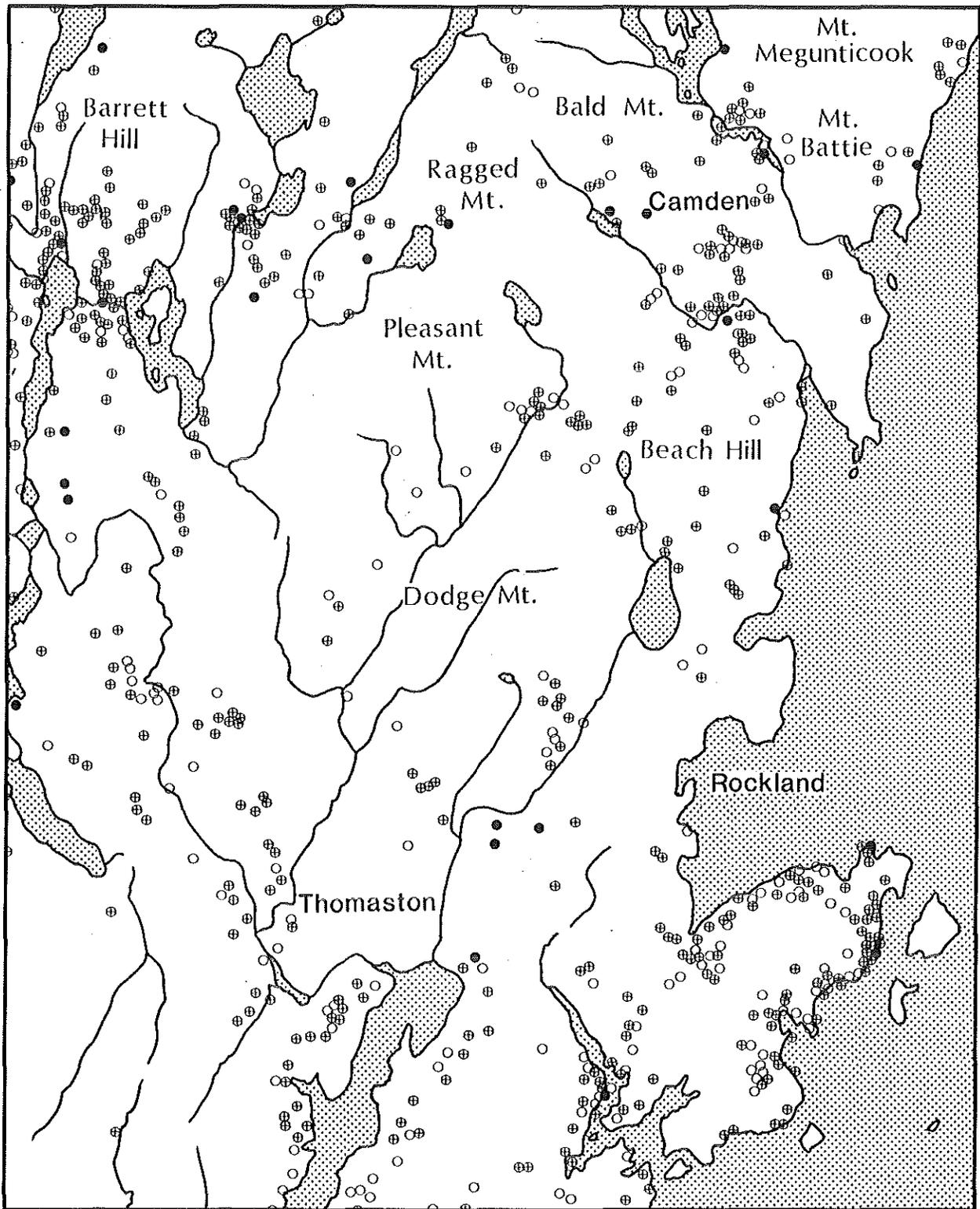


Figure 58. Map of the Rockland, Maine, area showing total depths of domestic bedrock wells in feet.²⁷
(1:125,000 scale)

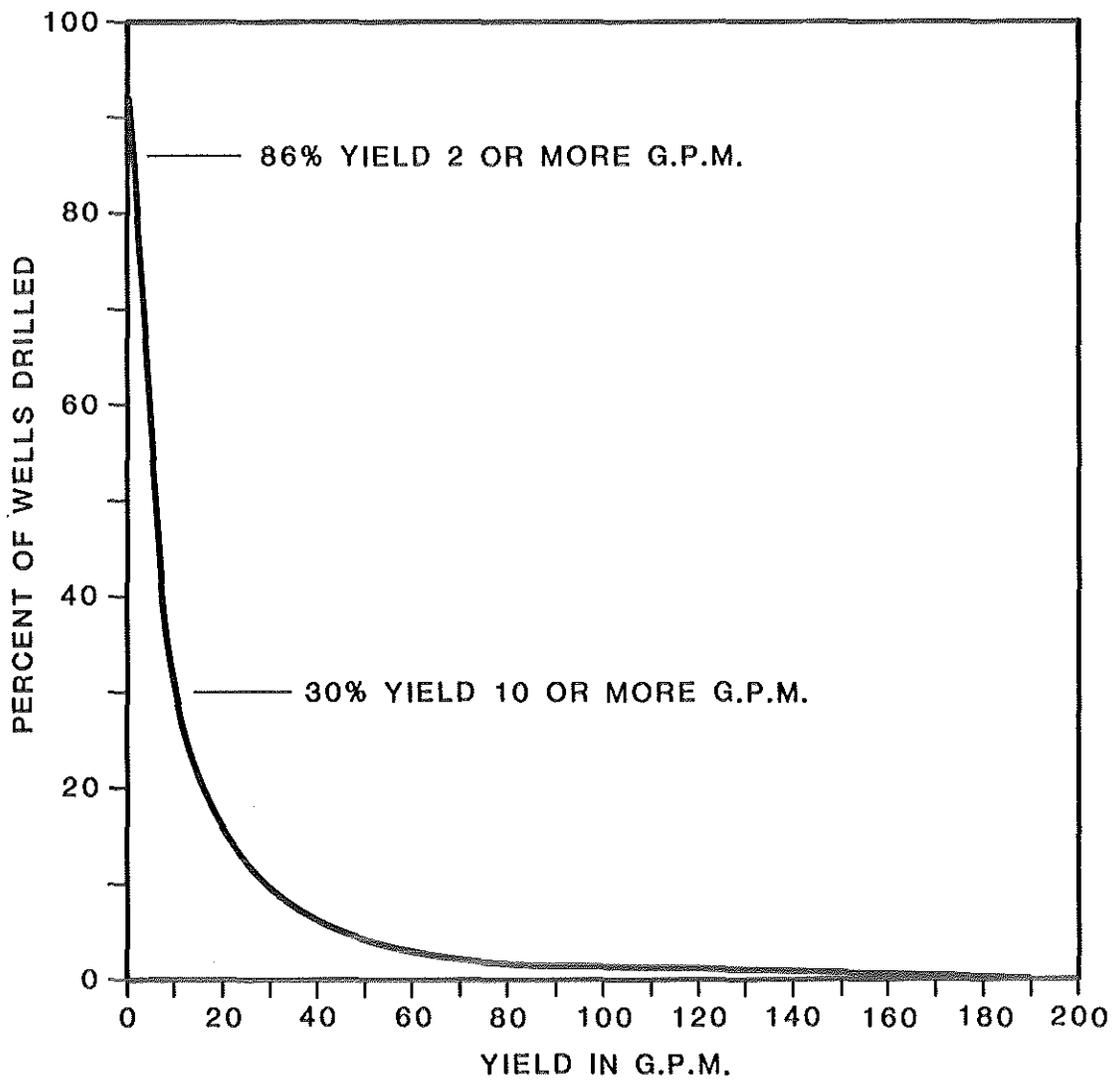


Figure 59. Yield of bedrock wells in coastal Maine. Curve is based on 2,552 wells in the mid-coastal region of Maine.

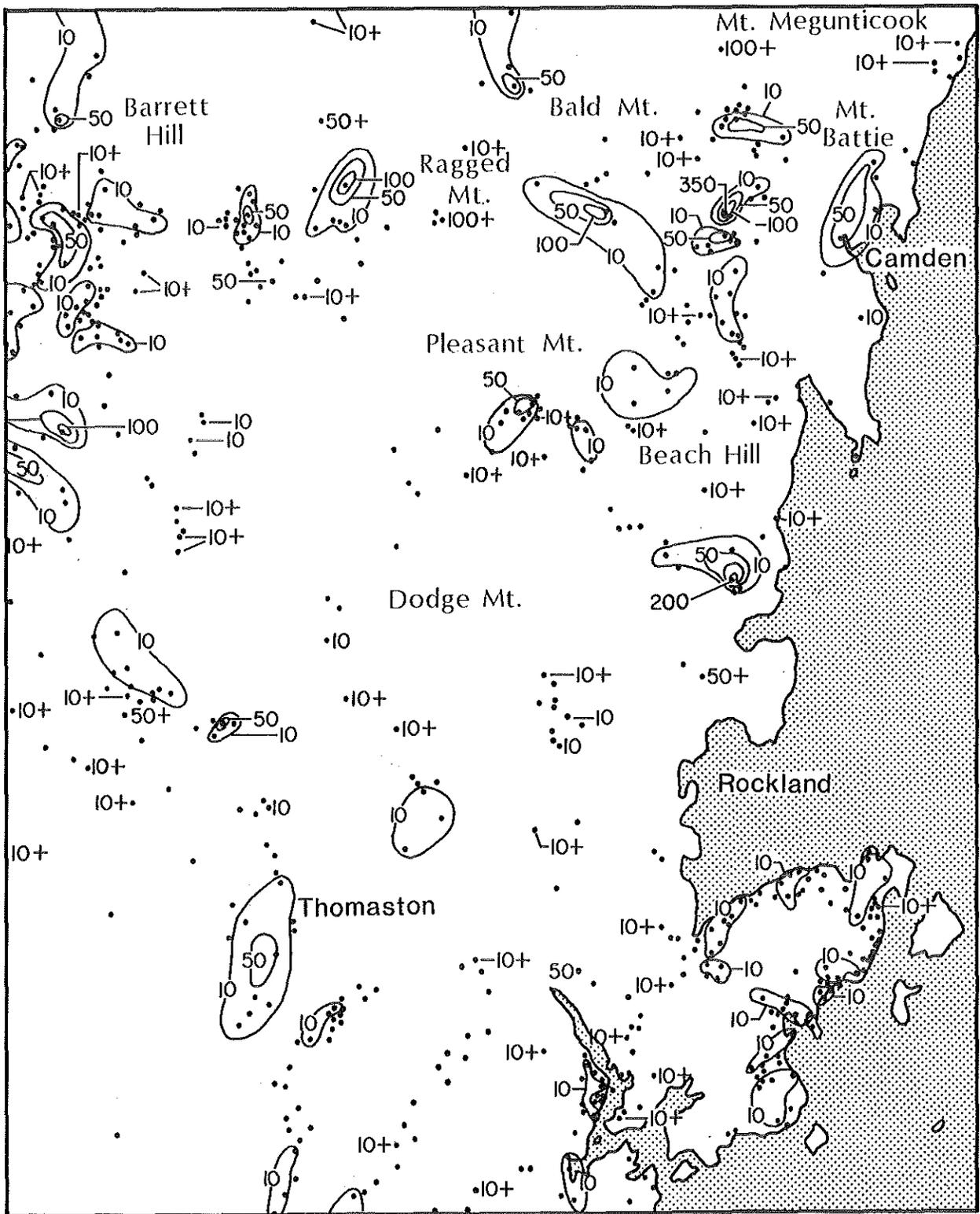


Figure 60. Map of the Rockland, Maine, area showing contours of bedrock well yield. Yield contours are shown as 10, 50, and 100 gpm. High-yield wells outside a contour are shown. Well locations are indicated by a dot.²⁸ (1:125,000 scale)

CHAPTER 4

SPECIFIC PROBLEMS AND CASE STUDIES

INTRODUCTION

Hydrogeologic data available from the Maine and U.S. Geological Surveys are intended to aid both in the location and protection of ground water supplies. While some people are looking for suitable well locations, others are seeking acceptable sanitary landfill sites, sludge disposal sites, and septic system sites. These seemingly different uses of ground water data are in reality essentially the same, but with different emphases. The well driller is looking for saturated, permeable gravel or well-fractured bedrock, while the landfill operator wants a thick cover of unsaturated material that does not overlie a bedrock aquifer zone and is not near a gravel aquifer. Both are able to make ground water decisions using the concepts and information discussed in this handbook.

LOCATING POTABLE WATER SUPPLIES

INDIVIDUAL DOMESTIC WELLS

As was mentioned at the beginning of the section on "Available Hydrogeological Data", for the person wishing to construct a water well on a parcel of land of two acres or less, the published ground water data are generally of little specific use. Other kinds of geologic information and on-site inspection by a hydrogeologist, however, may be of help, most particularly in the case where neighboring wells indicate a problem, or where a dry hole has already been completed on the lot.

For parcels of land greater than two acres, available information relating to surficial geology, gravel aquifers, and overburden thickness can be a useful guide for construction of a domestic dug, driven, jetted, or drilled well in the overburden. Some site-specific information, however, such as a test pit, gravel pit, or existing neighboring well, will give a greater assurance of success.

For parcels of land of 10 or more acres, published hydrogeological information can be helpful in selecting a favorable site for constructing any type of domestic water well, including a drilled bedrock well. Bedrock well yield maps show areas of potentially high yield (10 or more gpm). Overburden thickness maps and bedrock well depth maps at the same scale indicate the likely range of casing length and well depth. Even for land tracts of 10 or more acres, however, it is possible that none of the available hydrogeologic data will guide well location or construction. The bedrock aquifer maps are based on the results of existing wells. In places where there are no such wells, these maps obviously must be blank. It should be clear that many tracts of land in Maine cannot be evaluated fully as to the availability of potable ground water through use of the published hydrogeological information, but the use of this information will allow the owner or prospective buyer to evaluate the probability of locating potable water supply and the likely type of well required.

A landowner should discuss well location and construction with the driller or digger. It is important to be aware of proposed or existing septic tank and field locations, and of the State regulations pertaining to their location and construction. Most often the well is kept uphill at a horizontal distance of 100 feet from waste disposal facilities and other potential sources of contamination. The homeowner should bear in mind that these State regulations in no way guarantee potability of a domestic water supply, and that in some geological situations additional separation and/or construction features (septic tank or well) may be necessary.

Common problems encountered when drilling domestic wells in Maine include lack of water, water that will not clear, and wells that collapse. Dry holes occur because the well does not intersect a water-bearing fracture. Usually at a depth of around 300 feet, a dry hole is abandoned and a second well begun at a new site 20 to a few hundred feet away. The selection of the new drilling site is often based on a hunch. A hunch, however, has its limitations in Maine because the geology is so highly variable from one place to another. The advice of a hydrogeologist will improve the chances of finding water in a location where a dry hole has been drilled.

In cases where a bedrock well of 200 feet or more in depth yields too little water to be useful, well drillers employ several methods to open fractures around the borehole. The best technique is to build up a sustainable pressure in the

well by pumping water into it in a process that was described earlier called "hydraulic fracturing". Another, but less successful, technique is to use dry ice to build up pressure in a capped well. Use of dynamite is discouraged because it rarely works well and occasionally does harm to neighboring ground water sources.

Occasionally a well is drilled that obtains a plentiful supply, but one that will not clear even though the well is pumped for weeks or months. The material clouding the water is fine sand to clay-sized particles that are derived from the bedrock itself. They are not well cuttings, but may be fault gouge (ground up rock) or disaggregated rock left by deep-weathering processes. In a few cases, the fine material has refilled wells to 1/3 or 1/2 the original depth. A possible solution to this problem is to locate the depth at which the material enters the well and seal it off with additional casing or a concrete plug. Raising the pump intake pipe above the source of the fine materials is sometimes effective. Another alternative is to drill a new well where the problem is less likely to occur.

Some bedrock in Maine is soft and oxidized at depths of several hundred feet below ground surface, particularly where there are major fracture zones. Deep weathering is indicative of ground water movement at depth and often accompanies discovery of large yields. In some cases, however, the bedrock is so weathered and soft for a considerable depth that well construction is precluded. In these situations, it is best to move and drill another well.

Selecting a new well location when a problem has been encountered, be it lack of sufficient water, cloudy water, or caving bedrock, requires considerable experience and expertise. On-site investigation by the driller and a hydrogeologist is needed if the problem situation is not to be repeated.

COMMUNITY WELLS

Where hydrogeologic conditions permit, a single well can be constructed to supply a group of homes. These so called "community water systems" may be a good choice where low yield or contamination of individual wells is likely. Although all of the available hydrogeologic maps and reports are helpful and should be consulted, the greater water requirements of a community well necessitate the assistance of a hydrogeologist if excessive drawdown, dry well, contaminant migration, and similar problems are to be avoided. Furthermore, any shared water system necessitates some form of legal agreement so that the system is maintained for all users, even though property ownership changes from year to year.

MUNICIPAL, INDUSTRIAL, AND COMMERCIAL WELLS

Municipal wells are constructed primarily in gravel deposits from which yields of 500 to 1000 or more gallons per minute are available. Bedrock wells of several hundred gallons per minute might be considered for small communities, or anywhere augmentation is required. Industrial and commercial wells are most often in the range of 50 to 500 gpm, for which bedrock aquifer zones are also suitable for single or multiple-well systems. Available maps are used to locate areas where such high-yield wells are feasible, but a hydrogeologist is needed to evaluate the available data and to conduct field investigations so test wells can be drilled in the best locations within the potential aquifer areas.

Because these wells supply large amounts of water, the possible sources of contamination need careful consideration. Potentiometric surface maps can be used to give the general directions of flow in the bedrock. Surficial geology, overburden thickness, bedrock surface topography, and topographic maps should be consulted. This general information can be reinforced by observations made in any test wells, especially during a pump test of the aquifer. The long-term yield of the aquifer is calculated through analysis of pump test data, and through analysis of the surface area likely to contribute recharge to the aquifer. The ultimate long-term yield cannot be greater than the volume of precipitation that falls on the contributing area, less the runoff and evapotranspiration. Exceptions to the above are planned ground water mining and ground water recharge through inducement from an adjacent water body.

PREVENTING GROUND WATER POLLUTION

Sources of ground water pollution may generally be divided into two categories: planned releases of contaminants, and accidental releases of contaminants. Planned releases include activities such as the spreading and storage of road salt, applications of agricultural chemicals, the use of septic systems, and leachate from unlined landfills and lagoons. These releases are supposed to be spread widely or slowly enough so that dilution minimizes their impact. Accidental releases include leaking storage tanks, spills, transport accidents, and breaks in the liners of engineered landfills and lagoons. These releases often occur as a result of poor management and design, or lack of foresight. The examples that follow represent only a fraction of the documented contamination incidents in Maine.

LEACHATE FROM BARNYARDS, SEPTIC TANKS, ROAD-SALT STOCKPILES, DUMPS, ETC.

Many of our cultural activities result in placing in or on the ground soluble products that may produce leachate that is detrimental to ground water quality. Barnyards, agricultural lands, dumps, septic tanks, deicing salt stockpiles, and petroleum storage depots are common potential sources of ground water contamination. Drillers, homeowners, and municipal officials should be conscious of all kinds of potential contamination sources in the vicinity of existing or proposed water wells and potentially valuable aquifers and should be aware of the probable directions of contaminant movement.

Movement of ground water contaminants follows the hydrologic principles that govern the movement of ground water which have been discussed previously in this handbook. For a source of contamination to be a threat to an existing or proposed well, it must be physically possible for ground water to move from the contamination source to the well. Land topography, bedrock topography, and overburden geology and thickness must be considered. Effects of pumping the well on the natural flow systems, water tables, and potentiometric surfaces must be recognized. In crystalline bedrock, where the fracture geometry is most important but most difficult to investigate, the determination of subsurface flow directions requires, first, educated guesses, and second, detailed on-site study.

A few examples of ground water pollution in Maine demonstrate how contamination occurs, how long it persists, and what can be done to avoid or correct the problem.

Barnyard Wastes

A dairy farmer found that his well was contaminated by bacteria, nitrate, and chloride and occasionally became turbid following heavy rain. The well is located slightly downhill and less than 100 feet from his barn and feedlot (Figure 61). Soil in the area is a patchy cover of clay or till. Bedrock crops out in and around the barn. The well casing was intact as far as could be seen, but a chlorine solution poured around the top of the well moved downward into the well after several hours. A number of fractures are evident in the bedrock. The most obvious joints run in the direction of the feedlot to the well, approximately north-south. Runoff from a watering trough in the feedlot runs in a ditch, spreading pollutants out over a considerable area north of the well. The well supplies all the water for the farm and is pumped down significantly, forming a cone of depression (or pressure relief) that apparently spreads out beneath the source of contamination. It appeared that the animal wastes were infiltrating directly into the bedrock aquifer through open joints and had migrated downgradient towards the well.

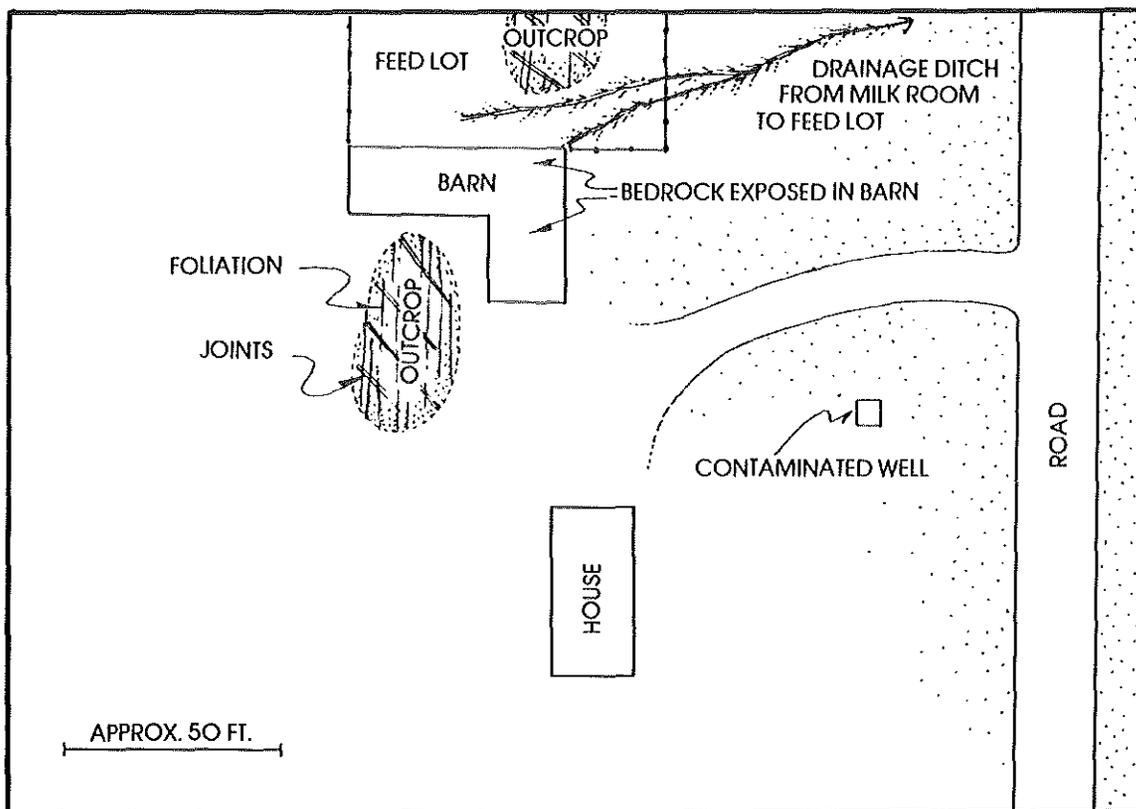


Figure 61. Map view of dairy farm where animal wastes infiltrated shallow rock fractures and contaminated the bedrock well.

The well was rehabilitated by installing 4-inch plastic casing within the original 6-inch pipe to a depth 30 or 40 feet below ground surface. A rubber packer at the lower end of the plastic casing sealed off all the water-bearing fractures above and stopped the inflow of contaminated water that fortunately was affecting only the near-surface bedrock fractures.

This case is a typical example of a water well too close and downgradient from a source of contamination. Had there been a thick soil cover in the area, it is likely that the contaminants would have attenuated before local recharge entered the well. Where the soil cover is thin, and where a well is to be pumped heavily, it is most important to consider ground water flow directions relative to potential pollutants before selecting a site for a water well.

Agricultural Chemicals

Arsenic compounds, DDT, Dieldrin, and Lindane used on blueberry lands in Maine were detected in ground and surface water utilized in part for human consumption. The blueberry fields are located on sand and gravel deposits of high permeability that are in part underlain by poorly permeable clay (Figure 62). Chemicals applied to the fields were able to

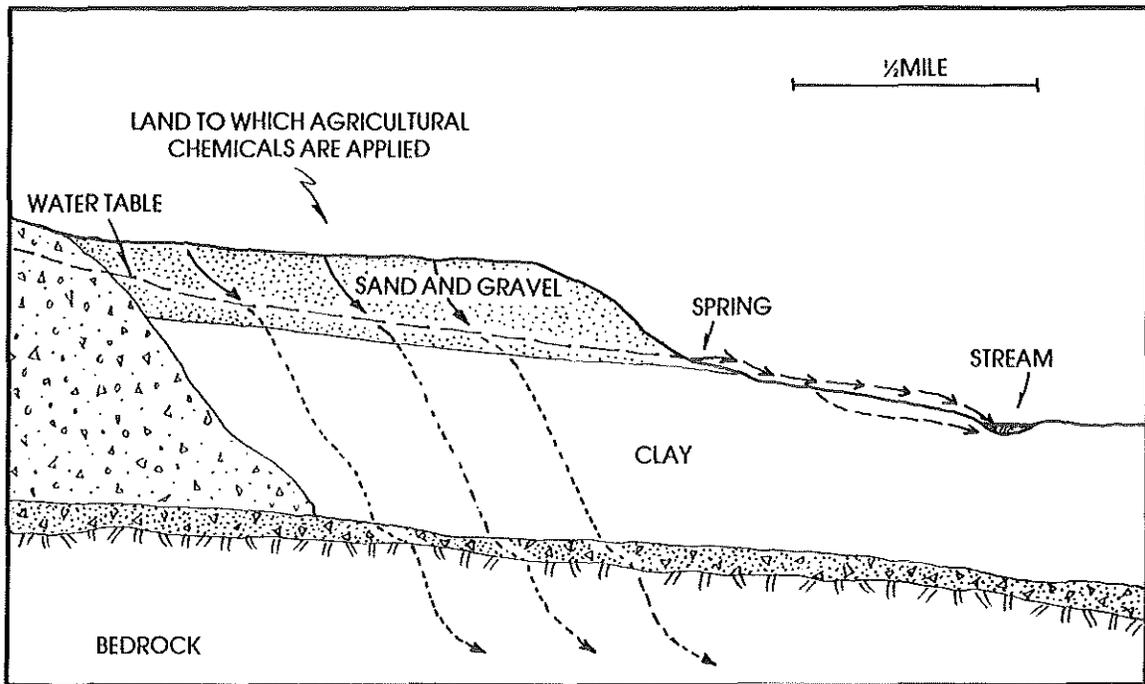


Figure 62. Schematic cross-section through glacio-marine delta overlying marine clay. Agricultural chemicals applied to blueberry fields on the highly permeable sand and gravel delta are carried downward to a shallow water table on the clay surface. Contaminated ground water is discharged at the spring and is transported by surface and subsurface flow to the nearby stream.²⁹

move rapidly downward with little or no alteration and mix with the ground water that flows nearly horizontally over the underlying clay. Discharge occurs at numerous contact springs at the edges of the sand and gravel deposit from which chemicals could be carried to streams, ponds, and lakes a number of miles from the site of original application to the crop lands.

Another case involving contamination caused by agricultural chemicals occurred in the potato fields of Aroostook County where application of Temik (aldicarb) caused the contamination of more than 100 wells throughout the areas of application. Although the chemical was thought to break down rapidly, cold soil conditions apparently slowed its breakdown, such that recharge water carried the pesticide into underlying ground water.

In both of these cases, better knowledge of the longevity of agricultural chemicals in the ground water environment is needed if such problems are to be avoided.

Stored Agricultural Products

Potatoes in Maine are stored for a number of months after harvest in potato houses that are partly below ground surface to maintain a damp, cool condition. One such storage building apparently at times become so wet that water ran over the potatoes. Runoff from rotten potatoes left in this building contaminated a drilled bedrock well about 125 feet away (Figure 63). The well is located on a bedrock exposure, and soil cover is generally thin. The 250-foot-deep well was polluted by rotten potatoes at least two times resulting in a bad smell, high total coliform count, and high iron and manganese content. The metal compounds are probably released from the rock and well casing because of the lower pH of the contaminated water. The problem disappeared when the source was cleaned up. It appears that water from the potato house can move directly into an open fracture that carries the pollutants down into the neighboring well. The problem might be solved by putting deeper casing into the well, or by moving the potato storage house to a more distant location, preferably one where there are at least several feet of soil cover.

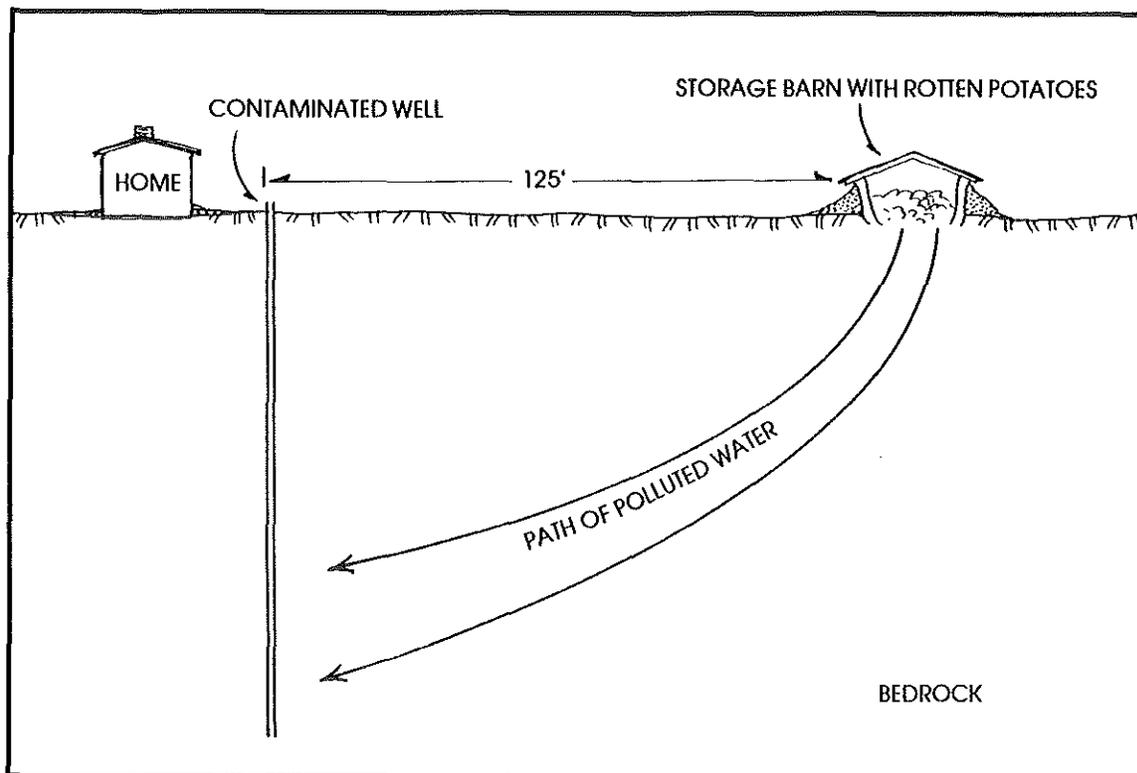


Figure 63. Sketch of a drilled bedrock well that has been contaminated by runoff from rotten potatoes in a nearby storage building.

Solid Wastes

A municipal solid waste disposal site in southwestern Maine was operated for about 15 years before local ground water pollution was detected in a nearby pond and dug well (Figure 64). About three years before noticeable contamination occurred, tannery sludge was dumped at the same site within about 1000 feet of the affected pond and well. The dump area is located in a sandy aquifer that overlies silty clay at a depth of 5 to 25 feet below ground surface. The slope of the underlying clay layer apparently is in the direction of the contaminated pond and well: thus, shallow ground water flow moves essentially parallel to the clay surface downslope, as shown in Figure 65. Some contaminated water is probably leaking through the clay layer and migrating into the underlying bedrock. Movement of ground water through the clay is very slow, so that sorption and ion-exchange processes may purify the leachate before it reaches the bedrock aquifer. The

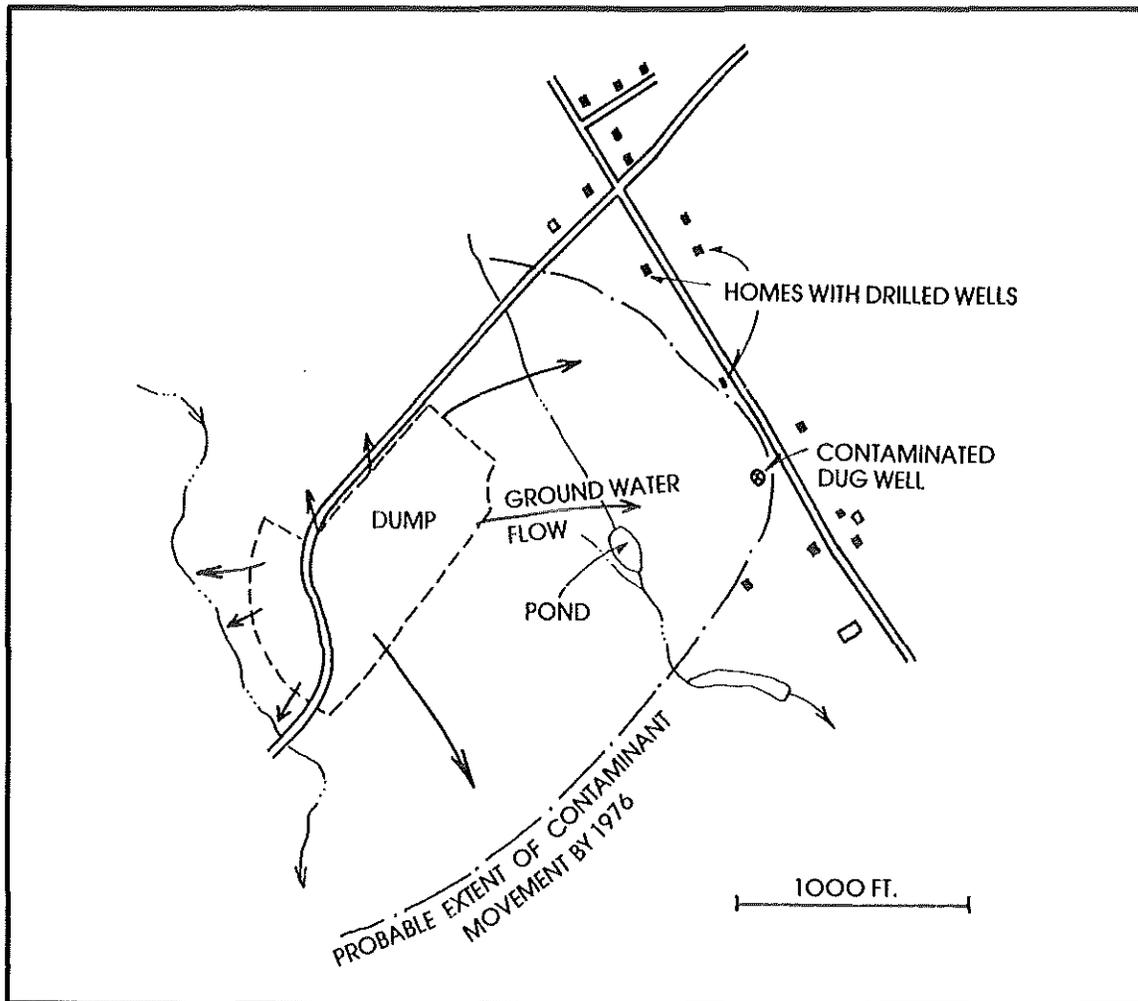


Figure 64. Sketch map of the dump and area of contaminated ground water.³⁰

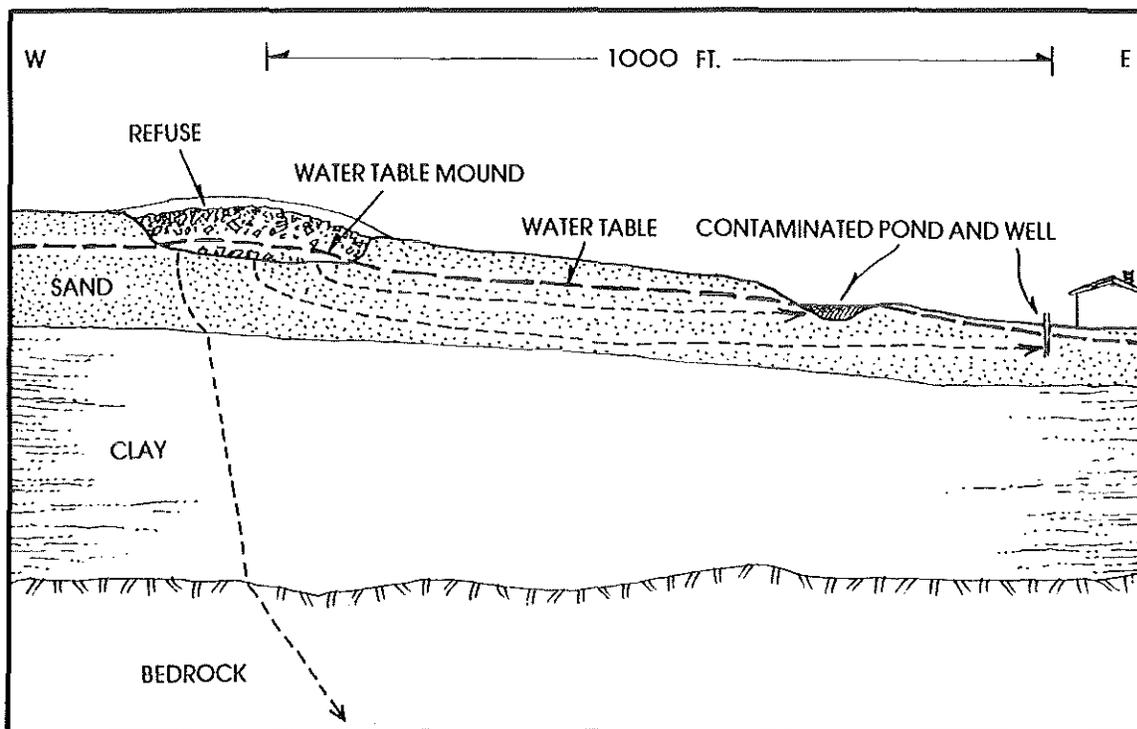


Figure 65. Schematic cross-section through dump and contaminated sand aquifer.

contaminated ground water is high in dissolved solids and has a biological oxygen demand (BOD). It has a low pH that causes iron and manganese to be released from the sediments.

A mound of ground water developed under the refuse because of the increased infiltration through the opened and disturbed land (Figure 65). The mound rises high enough to saturate the lower levels of the refuse, causing leachate formation to increase, and natural attenuation processes that normally occur in unsaturated soils to decrease. Also, the water mound causes radial ground water flow away from the dump area that affects the regional water-table gradient.

Since the dump was discontinued, the surface of the refuse has been covered by a layer of clay. It is hoped that reducing the infiltration capacity of the disturbed area in this way will cause the water-table mound to shrink and leave the lower levels of the refuse unsaturated, so that natural purification processes can once again attenuate the leachate that forms. This problem might have been avoided if ground water flow directions and other hydrogeologic characteristics of the site and region had been determined before locating the dump.

Road Salt

Salt storage facilities and their associated piles of mixed sand and salt are common throughout Maine. Each year

salt (sodium chloride) is brought to these facilities where some is stored under cover in a shed, and the remainder is mixed with sand that is left as an uncovered pile. Many are located in, or adjacent to, sand and gravel pits. Because of the concentration and high solubility of salt, ground water contamination in the vicinity of salt sheds and salt/sand piles is common. In Maine, for example, nearly 150 domestic wells, 90% of them bedrock wells, are known to be contaminated by improper road salt and salt/sand storage. Salt moves away from such facilities not only through highly permeable sand and gravel deposits, as is illustrated by the first example, but also through underlying bedrock fractures, as is shown by the second example.

(1) Ground and surface water became contaminated by chloride during the 30 or more years of operation of a state facility that includes a covered salt storage shed and a large pile of mixed sand and salt. This facility is adjacent to a gravel pit, where a town salt/sand pile is situated. The two sites are separated by a small, intermittent stream as depicted in Figure 66. Clayey glacial till underlies the state storage

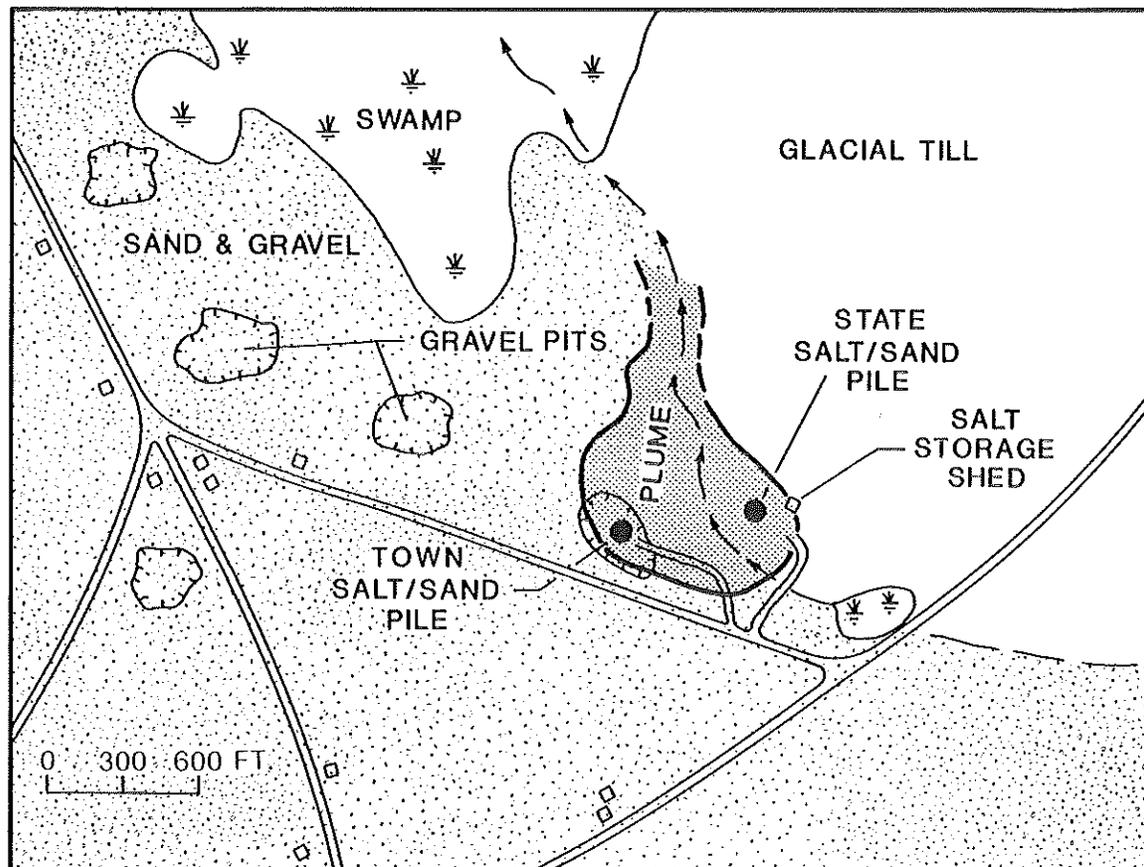


Figure 66. Winter road-deicing salt and sand mixing and storage area where both ground and surface water are contaminated by the salt. No household wells are known to be contaminated.

shed and salt/sand pile, while sand and gravel underlie the town salt/sand pile.

Runoff in the small stream has shown chloride levels as high as 3500 mg/L, which is significantly higher than the expected background of 20 to 50 mg/L and the drinking water maximum of 250 mg/L.

Ground water beneath the two sites is also contaminated by salt, most severely where the state salt/sand pile is located annually, and less severely in the adjacent gravel pit where the town salt/sand pile is located occasionally. The clayey glacial till underlying the state pile appears to have restricted the extent of ground water contamination, while the more permeable sand and gravel underlying the town pile appears to have permitted wider spread of the much more limited amount of salt stored there. The contaminant plume is spreading radially away from these two sources, as well as in the downgradient direction parallel to the small stream. Possible contamination of the underlying bedrock is not known in this case.

Prevention of all surface and ground water contamination by road salt in Maine and northern New England is probably neither practical nor possible. Gravel pits, however, are a particularly poor location for salt storage because of the high permeability of the soil. In all cases, surface and ground water migration paths should be investigated before road salt or salt/sand storage facilities are established so that degradation can be minimized. In most cases, salt and salt/sand mixtures must be stored under cover.

(2) In the second case involving road salt, a stockpile of mixed sand and deicing salt was stored for about six years in a residential area within 200 feet of a drilled bedrock well (Figure 67). Within about two years the well owner was replacing the plumbing in his house because of excessive corrosion. When a water analysis was made, it was found that the well produced water with more than 2000 parts per million chloride. The well is 138 feet deep in a gray and green slate. The overburden is glaciomarine silty clay from 5 to 10 feet thick. The well yields 30 gpm from one or more fractures intersected at a depth of 133 feet. The stockpile was slightly upgradient of the well site, but more than 100 vertical feet above the point at which ground water flows into the well.

After having produced fresh water for 20 years, the well became severely contaminated with sodium chloride within two or three years of placement of the salt/sand stockpile on the adjacent property. No other wells in the residential area are known to be contaminated. It appears that the fractures feeding this well open to the surface very near the stockpile. If the principal water-bearing fractures in the slate parallel the rock foliation, they are oriented in a NNE-SSW direction, which is approximately the direction the well is from the

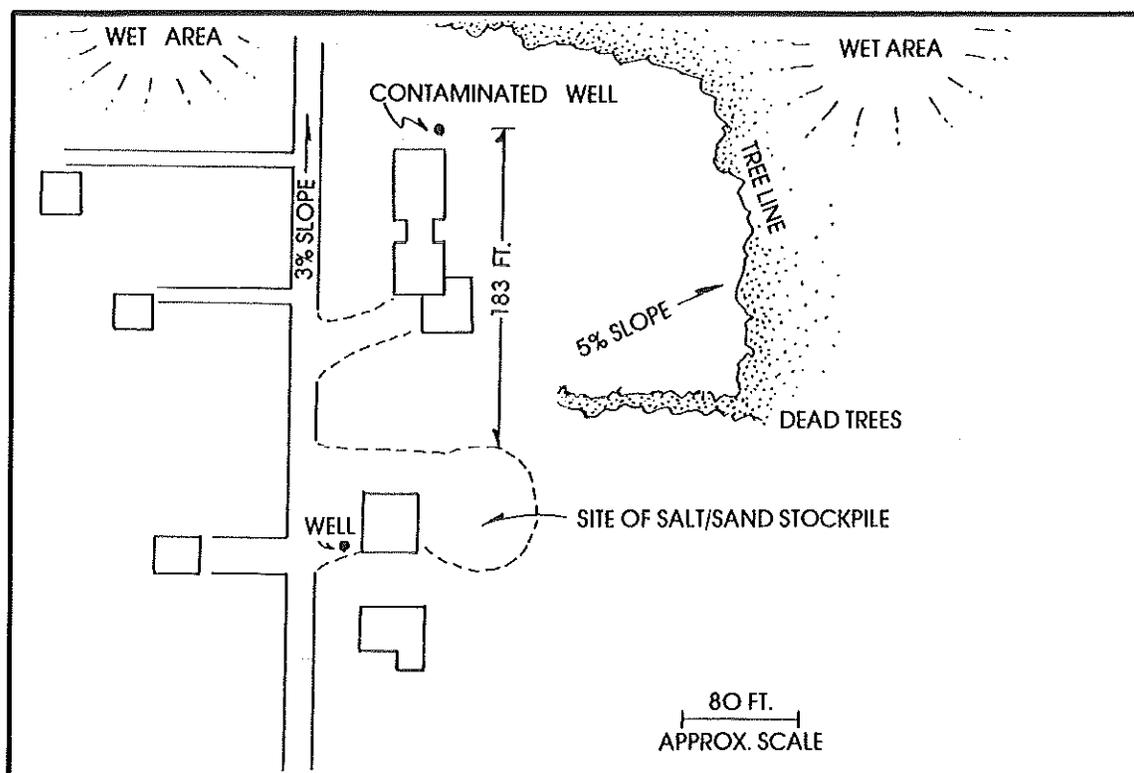


Figure 67. Sketch map of residential area where a stockpile of salt mixed with sand for winter road maintenance caused a nearby drilled well to become salty within several years.

stockpile. The well on the property on which the stockpile was located is not very contaminated yet. This well is located west of the pile and apparently is not fed by any water-bearing fractures that cut across the foliation in the bedrock. It is possible that this well may in time become affected by the salt; a test of electrical conductivity showed that this well has the highest level of several tested in the residential area--an indication that some contamination has occurred already.

The solution to this problem was to remove all of the stockpile and contaminated soil beneath it, so that no additional wells become polluted. The highly contaminated well must be considered a total loss, as it probably will not correct itself for years. A replacement well was drilled several hundred feet from the affected well and produces good quality water.

PETROLEUM PRODUCTS

Between 1979 and 1983, 158 underground petroleum tank leaks were documented in Maine at locations throughout the State. In total, 76 wells were found to be contaminated most

often by gasoline that leaked from buried tanks and connecting pipes at retail and commercial establishments. Three examples of conditions that lead to long-term contamination of water wells are described in the following sections. In all these cases, new ground water sources outside of the contaminated zone had to be located and constructed. Control and clean up of the spilled petroleum products was considered, and in cases 2 and 3 field evaluated, but for the most part the contamination is being allowed to dissipate by natural ground water movement. Prevention is probably best achieved by better construction and maintenance of the underground tanks and plumbing.

(1) Two drilled wells on a Maine island were found to yield water contaminated with petroleum. The smell of gasoline in the water was obvious, and the water caused some gastrointestinal distress in two persons who drank it. Upon investigation it was found that gasoline and kerosene had been stored in subsurface tanks and sold in front of two local stores during the last 20 or 30 years. Both stores no longer sell either product. It was rumored that at least one of the several tanks had rusted through and leaked 10 or more years earlier. It was not known whether any of the other abandoned tanks leaked or were ever removed.

The sites of the buried tanks and former pumps are upgradient from the affected wells (Figure 68). The overburden is a gravelly material grading to clay at the oceanside. The bedrock surface dips in the direction of the two wells; thus, the flow direction of the near-surface ground water is most likely from the tanks towards the contaminated wells. Some gasoline and kerosene migrated downward into the bedrock aquifer and flowed into the wells as they were being pumped. Possibly much of the petroleum contamination passed over the bedrock surface and into the nearby sea. The level of contamination in the wells has never been so great that it could not be corrected, at least superficially, with treatment facilities. Many other homes in the contaminated area have avoided drilling wells, and have obtained water from a community spring. At least one other drilled bedrock well just south of the two contaminated ones may become affected by the spilled petroleum products. It is reported that the soil around the well smells of gasoline. The ground water contamination is likely to persist for years, making it risky to drill a well anywhere in the area.

(2) Three homeowners and a high school in a small central Maine community found gasoline in their wells in 1982. Testing showed concentrations ranging from .34 to 50 ppm in these supplies making them unfit for household use, as well as for drinking. Buried gasoline tanks at the closest general store were pressure tested, disclosing one tank with a leaking corrosion hole. This tank was subsequently dug up and replaced by a new tank.

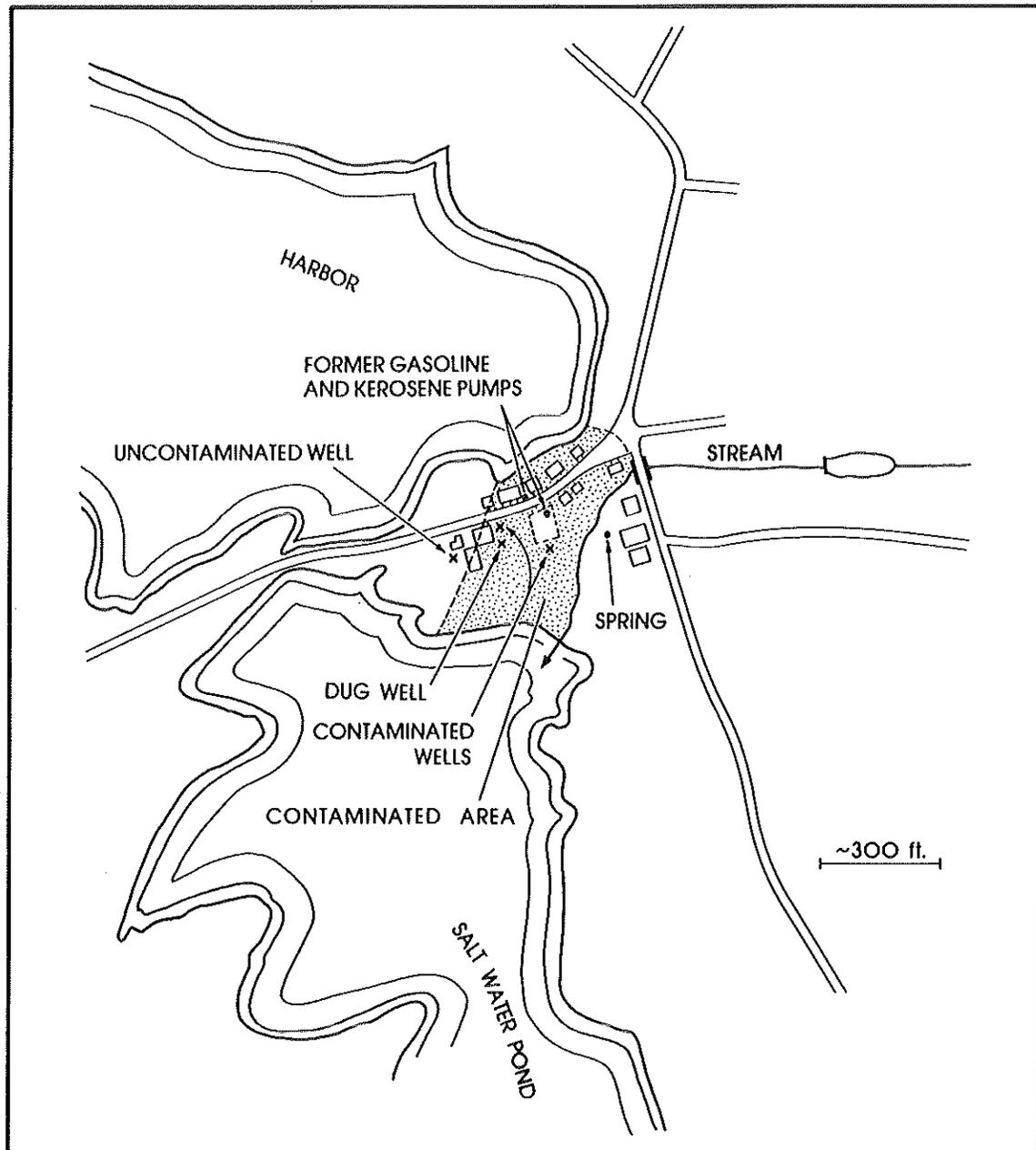


Figure 68. Sketch map of an area where leaking of gasoline and kerosene tanks has caused ground water pollution. Leakage has occurred over at least two decades, and pollution will persist for many years to come.

Because of the suspicion that a large volume of gasoline had leaked into the ground, an extensive hydrogeologic investigation that included construction of numerous observation wells was undertaken to define the extent of the contamination, the source or sources of the gasoline, and the direction and rate of migration. This work defined the contamination plumes shown in Figure 69. (Refer to Figures 47 and 48 for additional information.)

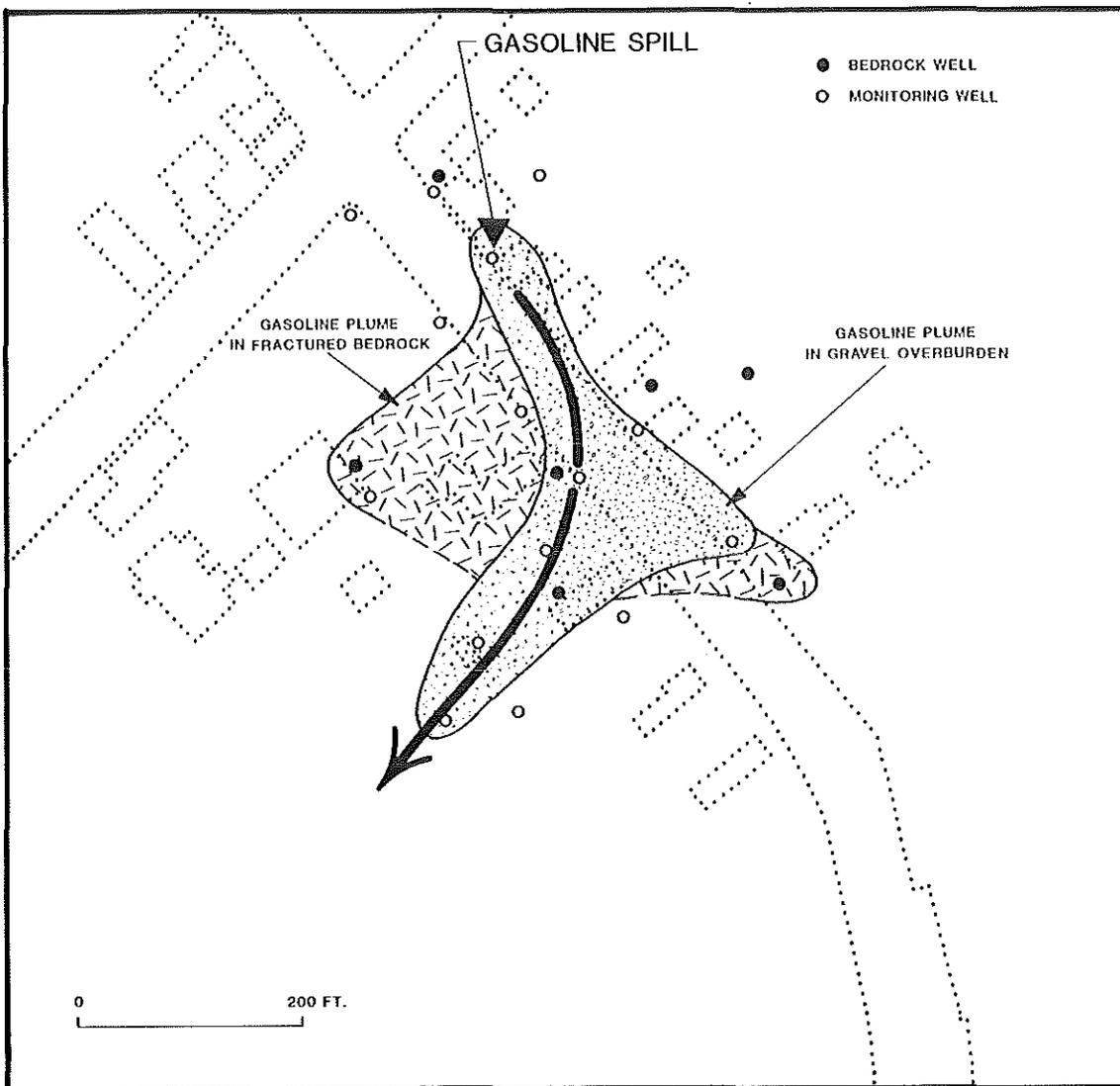


Figure 69. Gasoline plumes in overburden and crystalline bedrock aquifers beneath a village.¹⁸

It was found that the gasoline leaked directly into a sand and gravel aquifer with a shallow water table and steep hydraulic gradient. The contamination moved with the shallow ground water along a narrow path almost directly to two of the affected wells. Recharge in the immediate vicinity of these two wells carried the dissolved gasoline downward through the sand and gravel and into fractures in the underlying limestone bedrock. Although not situated within the sand and gravel contaminant plume, pumping similarly induced contaminated water to migrate through the fractured limestone to the other two bedrock wells as indicated by Figure 69.

(3) In another small central Maine community, a gasoline spill in about 1979 from buried tanks or piping at a general store contaminated two wells in a short time, but then seemed

to have no further damaging affect. About four years later, however, gasoline was detected in an additional five wells by homeowners. In this case, gasoline concentrations were in the range of .015 and .5 ppm, making the water unfit to drink.

Hydrogeologic investigation, including construction of monitoring wells, disclosed that the spilled gasoline had spread a relatively short distance in the clayey glacial till overburden that underlies the community, even after four years. In contrast to this, however, contaminated water had migrated a significant distance through fractures in the underlying metamorphosed limestone bedrock forming the plume shown in Figure 70. This migration path through the bedrock fractures was at about right angles to the direction of shallow ground water flow. A major fracture zone trending beneath the community in a northeast direction was found to be intersected by most of the contaminated bedrock wells. Pumping these wells over the four year period had induced the contaminated ground water to move towards them along the major fracture zone in an easterly and northeasterly direction.

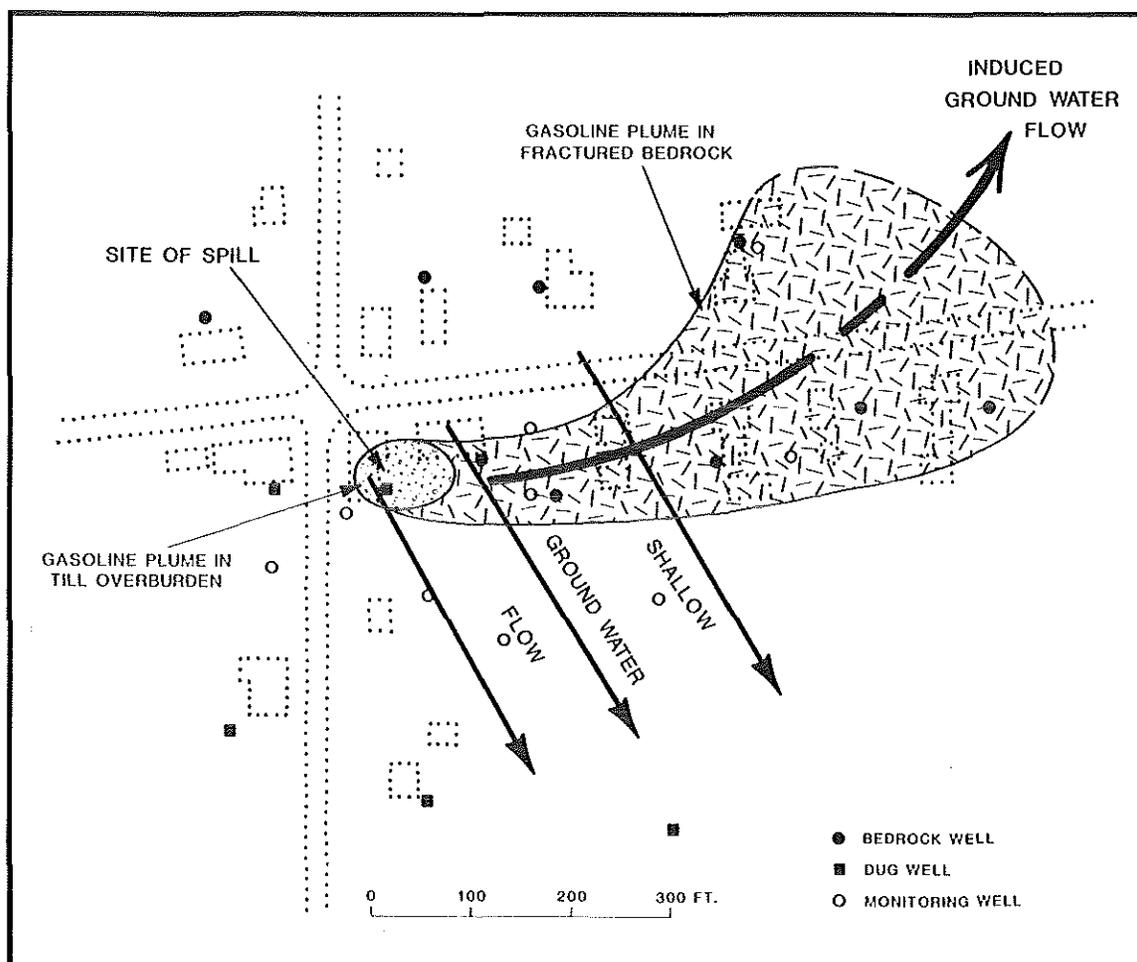


Figure 70. Gasoline plumes in overburden and fractured bedrock aquifers beneath a village.¹⁸

HAZARDOUS WASTES

Of the many substances that can contaminate ground water, those commonly referred to as "hazardous wastes" are of special concern because of their detrimental effect on human health. Many of the organic chemicals in this classification are waste products from industrial and commercial activities that were disposed of in large volumes at a number of sites in Maine, or were buried with domestic wastes at local landfills. These man-made products persist in dangerous forms for many years, making them very difficult if not impossible to remove from ground water sources. Two of more than 10 examples of major ground water contamination by hazardous wastes in Maine are given below. Both of these sites have been investigated in detail in order to define ground water movement and contamination characteristics and to devise appropriate control and cleanup measures. Much of the damage to ground water resources could have been avoided if the hazardous wastes were not disposed of in highly permeable geologic formations.

(1) After several years of resident's complaints, thirty household wells near a hazardous waste facility in south-central Maine were found to be contaminated by organic solvents (Figure 71). Most of these wells were drilled through an overlying sand and gravel aquifer into the underlying bedrock. Hydrogeologic investigation found both the sand and gravel and underlying bedrock aquifers to be significantly contaminated, and found that the same chemicals had migrated through the bedrock more than 4000 feet to discharge points along a major river. The organic chemical contamination is so widespread that local ground water sources cannot be used for the foreseeable future. Municipal water from distant sand and gravel springs had to be extended into the affected area for the use of the homeowners.

(2) Industrial solvents and plasticizers were disposed of for about 25 years at a municipal landfill in central Maine that is situated in a large sand and gravel deposit adjacent to a lake (Figure 72). Although only one water well is known to be contaminated by these hazardous wastes, the site has undergone extensive hydrogeologic investigation because of the large volume of disposed waste and potential for great and long-lasting harm to the lake and surrounding residents. Monitoring wells disclose migration of the contamination to the northeast, east, and south of the disposal site. The site is closed and municipal water is now supplied to area residents.

NATURAL CONTAMINANTS

Most constituents found in ground water come from the soil or rock with which the water is in contact. When these natural compounds are excessively concentrated, ground water becomes less useful for drinking and other purposes. Because iron-sulfide compounds are common in the bedrock, high iron content

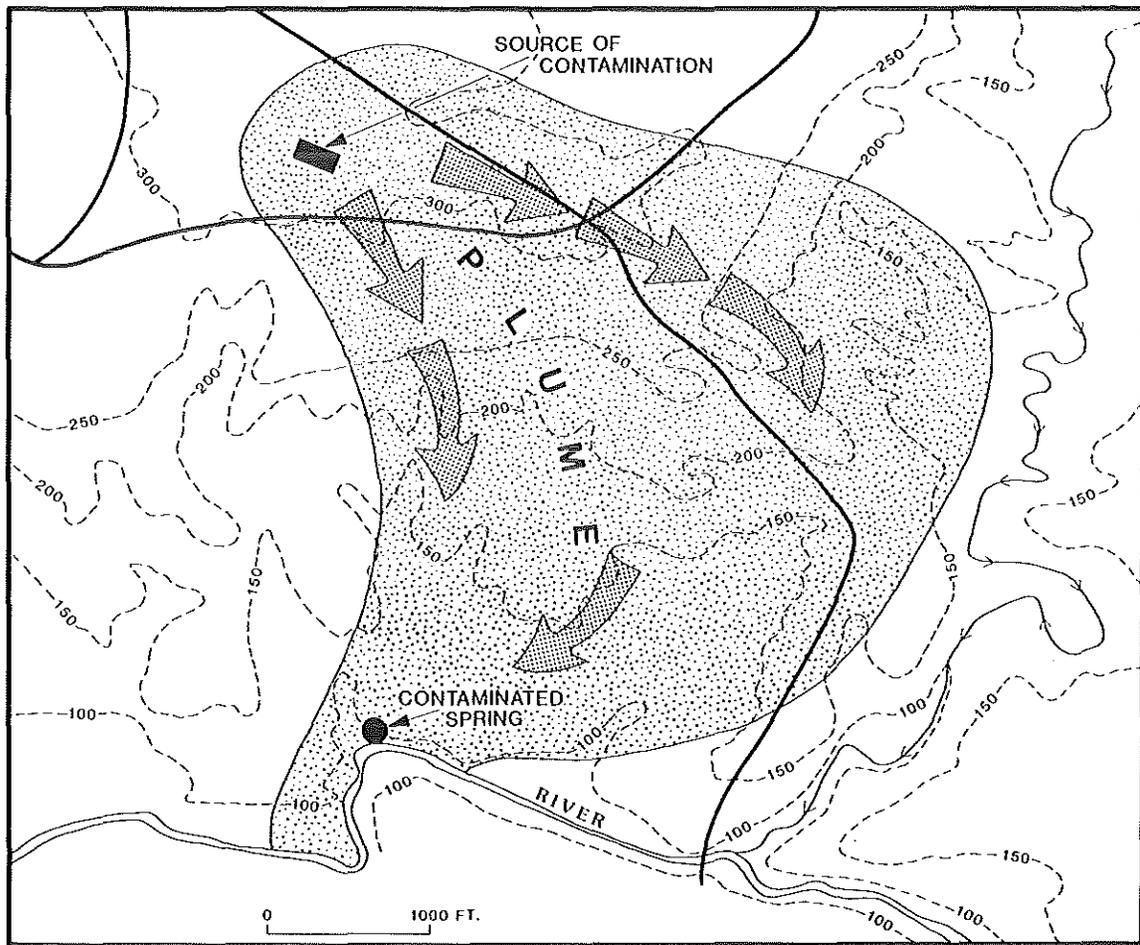


Figure 71. Hazardous waste site where 30 household wells are contaminated by wastes that are migrating to downgradient springs adjacent to a river. A municipal water system was extended to this area.

is a common nuisance in Maine. Where incorporated into the glacial overburden, this rock contributes iron to ground water in gravel aquifers. It is very difficult to predict where excessive iron will occur in gravel aquifers, but somewhat easier for bedrock aquifers. Bedrock geologic maps are helpful in a general sense because rock units are often mapped on the basis of their lithologies (mineral makeup). Bedrock geologic maps covering much of the State are available from the Maine Geological Survey. Rocks containing high concentrations of iron sulfides should be avoided when drilling wells. Rusty-colored rocks are often a good indication of high iron content.

Areas where limestone-bearing rocks occur are most likely to yield hard ground water, a problem for some household and commercial uses. Geologic maps and on-site inspections are an aid to avoiding ground water that is excessively hard due to lime (calcium carbonate) content.

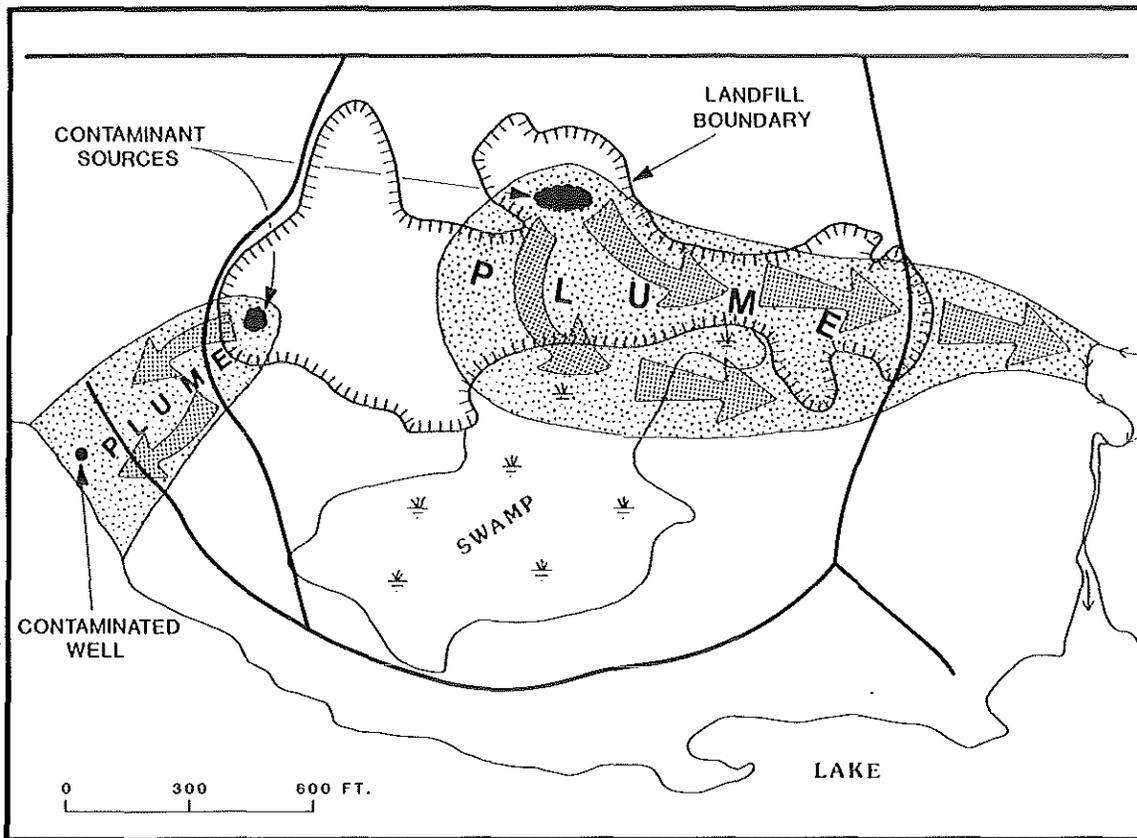


Figure 72. Municipal landfill where industrial chemicals were disposed of for about 25 years. Hazardous wastes are migrating downgradient to the lake and tributary stream in two major plumes. To date, only one of many lakeside household wells has been polluted.

Wells in swampy areas are sometimes affected by hydrogen sulfide gas (rotten egg smell), generated by rotting vegetation. Dug wells are most likely to be contaminated by this source, but some bedrock wells are susceptible to swamp water contamination. Bedrock wells are also subject to hydrogen sulfide contamination where the water-bearing bedrock is composed of concentrated sulfide minerals.

Swampy areas with black organic soils can be avoided as a well site. Sulfide-rich zones in bedrock are more difficult to avoid, but bedrock geologic maps from the Maine Geological Survey can be used to avoid areas of significant sulfide mineralization.

At least 35 drilled bedrock wells in the State have struck salty water at inland sites where salt-water intrusion, road salt, or other human sources of salt contamination do not seem to be the source of the sodium chloride. All of the salty wells (defined as having more than 250 ppm chloride) are within or very close to the limit of marine submergence (Figure 73).

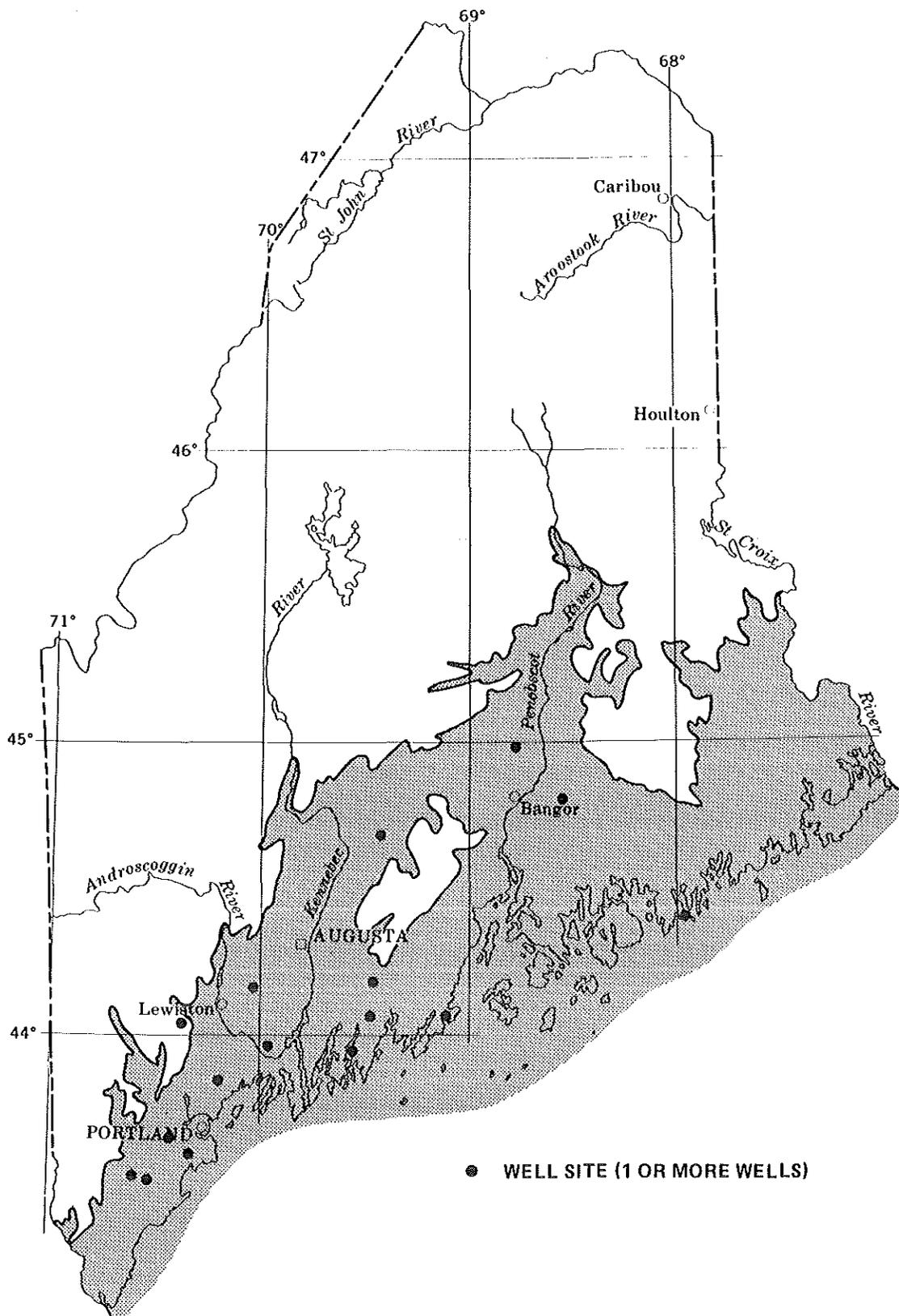


Figure 73. Locations of inland salt-water wells in Maine.²²
 Shading represents approximate area of post-glacial submergence. (heavy line is the 300 ft. contour)

The source of the sodium chloride seems to be sea water trapped in the rocks since the marine transgression that followed the retreat of the last glacier. Drilling water wells in the neighborhood of salt wells is not advised, but where the problem is encountered, and cannot be avoided by cementing out the salty water in the well, geologic advice is needed to locate a new well at a more promising site.

RADON

The radioactive gas radon is present in nearly all ground water occurring in Maine. Radon is a decay product of uranium that tends to be concentrated in granites and highly metamorphosed rocks. The gas diffuses into ground water as it slowly flows through fractures in the source rocks. When heated or agitated, the dissolved radon readily diffuses from the water into the air, thus it tends to be concentrated in the air of kitchens and bathrooms. In addition to ground water supplies, another source of radon gas in homes is from granite block foundations and even the dirt floors in older houses that overlie source rocks.

One well in the central coastal part of Maine showed an extremely high radon level of 750,000 picocuries (a measure of the rate of radioactive disintegration) per liter (pCi/L). The well was found to be drilled 325 feet into a highly metamorphosed rock and to yield only 1.5 gpm. Neighboring wells that are within a radius of 1000 feet, but typically shallower in depth, showed radon levels ranging from 11,000 to 37,000 pCi/L. It appears that the fracture system feeding the highly contaminated well passes through a deep vein of uranium-rich bedrock while the shallower neighboring wells do not. The ground water from the deep fractures has a long residence time in the uranium-rich bedrock, which in part accounts for the very high radon levels. In addition, its low yield of 1.5 gpm suggests that the feeding fractures have little direct communication with shallow sources of recharge, thus there is little chance for dilution and little possibility for the radon gas to migrate upwards out of the bedrock aquifer and into the atmosphere.

Several remedies are available for removal of radon from water supplies. One is filtration by granular activated carbon, and the other is aeration and dispersal of the gas to the atmosphere outside of the dwelling. Concentrations in the air of a building can also be reduced by ventilation. Well insulated homes with slow rates of air exchange typically have higher radon concentrations in the air if there is a radon problem with the water supply.

WELL CONSTRUCTION

The actual construction of a water well is extremely important to the maintenance of good ground water quality. Occasionally, the reason for well contamination can be traced to faulty construction, most notably the watertightness of the seal between the bedrock and the lower terminal of the casing. Usually, however, the workmanship is acceptable, but the methods employed are not sufficient to offset local pollution problems. The wells discussed earlier that were contaminated by animal wastes or rotting potatoes are examples. Both problems might have been avoided if local conditions had been evaluated and more casing had been installed to shut out near-surface ground water that had a high potential for contaminating the wells.

Sometimes the basic type of well to be constructed must be considered relative to local potential for contamination. Overburden wells, which are more prone to contamination from shallow waters, are a poor choice where septic tank effluents from neighboring properties or agricultural chemicals and animal wastes from nearby farms are likely to contaminate the ground water. Bedrock wells, which are more susceptible to salt and radon contamination, may be a poor choice in other areas.

A common problem with dug wells of large diameter is that the top is left open or is not covered well enough to prevent trash or animals from falling into the well. A sanitary cover on an open well is essential. During construction of the well, whether dug or drilled, the soil is disturbed around the hole. Surface water is able to follow the casing downward into the underlying ground water. Cement grout is installed around the casing of some gravel and bedrock wells to make a good seal with the surrounding formation (Figure 74).

Where any type of well is fitted with a hand pump, or where water is discharged near a well, care must be taken to direct the discharge away from the well so that surface contaminants will not be washed directly back into the ground. A concrete slab may be poured around the well to prevent the waste water from reentering the ground next to the well.

PREVENTING UNDESIRABLE CHANGES IN GROUND WATER LEVEL OR FLOW

Humans can have a greater effect on ground water levels than the natural processes which produce seasonal high and low water tables. Large changes in water level can be detrimental to the availability of ground water, to use of land, and to the capacity of aquifers to store and transmit water. The following examples illustrate situations that might be avoided by application of available ground water information.

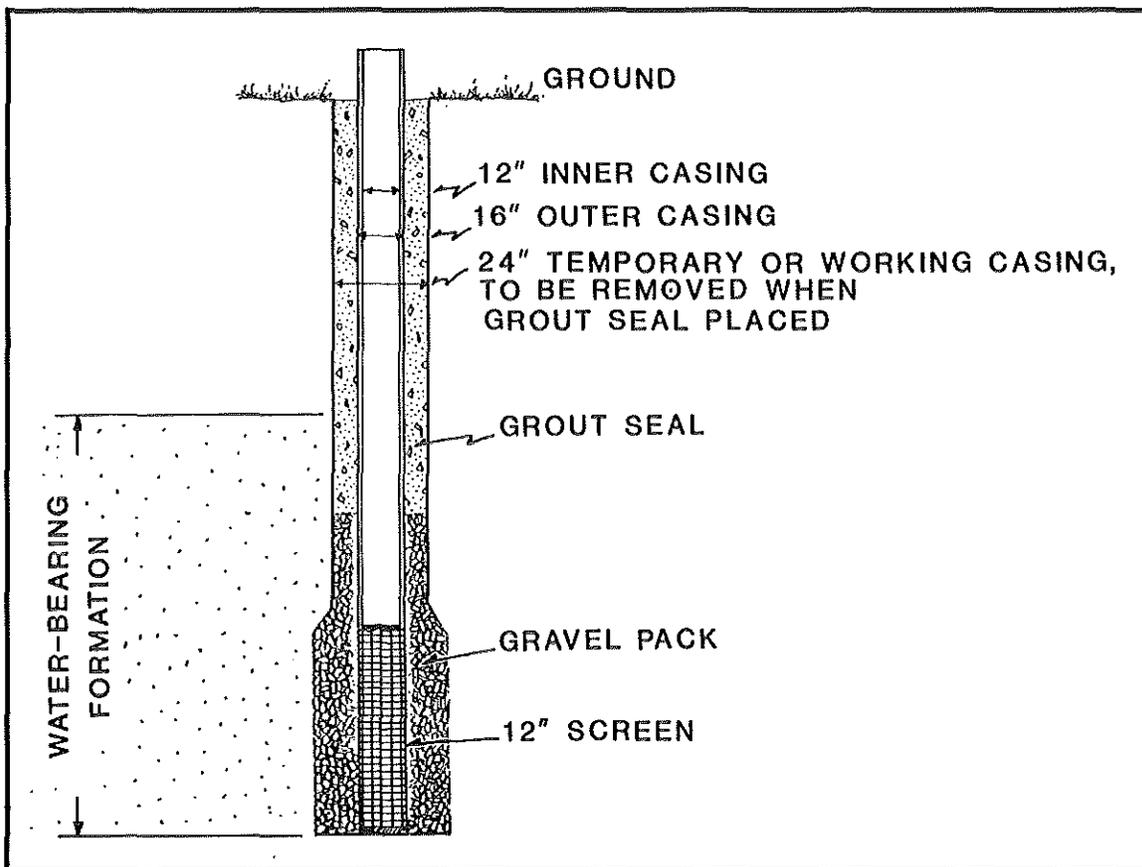


Figure 74. Schematic diagram of a typical municipal gravel well in which a cement grout seal is installed to prevent contamination of the ground water.³¹

DECREASE IN INFILTRATION AND GROUND WATER RECHARGE

It is obvious that if precipitation cannot infiltrate the ground surface, there can be no addition of recharge water to ground water supplies. Paving and building in urban places greatly decreases the infiltration rate in the area. The result is most dramatically seen in the change in runoff characteristics from a developed watershed. Figure 75 is a comparison of two stream hydrographs in which the rate of surface runoff is measured against time. Water from the developed, or urbanized, watershed runs off quickly, so that there is little chance for recharge of ground water.

Urban development can have local effects on ground water levels, such as causing a few shallow wells to require deepening, or regional consequences such as those which have occurred over much of Long Island, New York. In the highly urbanized residential areas, ground water is used for drinking and cooling purposes. The combination of surface paving and unrestricted pumping for cooling purposes has caused a significant drop in the water table. Some relief was obtained by catching surface runoff from the residential areas and

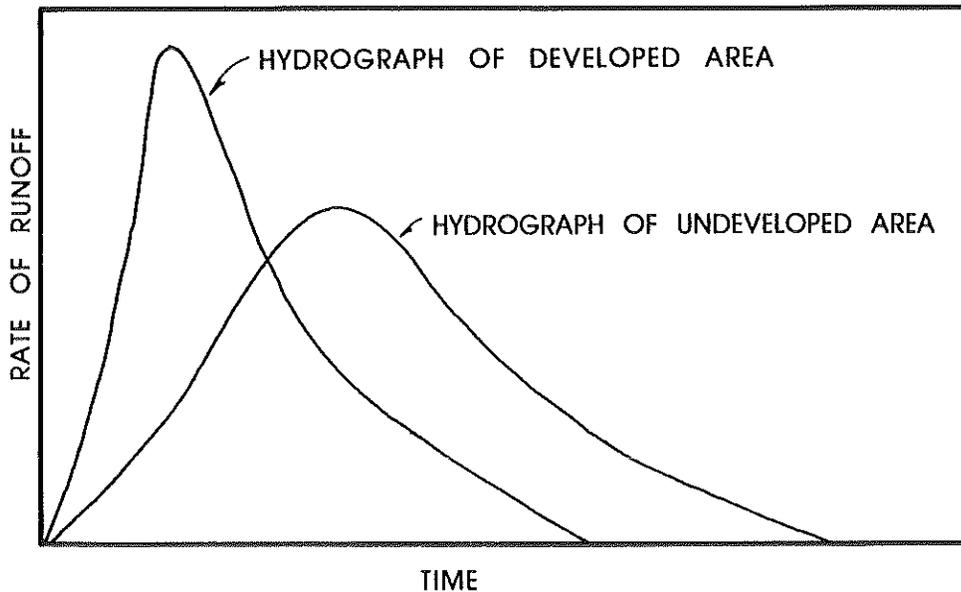


Figure 75. Schematic stream hydrographs showing an increase in the rapidity of runoff from a developed watershed. Paving in the developed area decreases the rate of infiltration and thereby the volume of ground water recharge.³²

directing it into neighborhood recharge sumps (Figure 76). An ironic note is that on the most eastern end of Long Island in Brooklyn, ground water withdrawals have decreased over the last decade to the point that homes built in the 1960's, when water levels were low, now suffer from basement flooding.

OBSTRUCTION OF GROUND WATER FLOW

Construction of highways can obstruct or constrict ground water flow, raise local water levels, and waterlog adjacent land. An example is the large road embankment for an interstate highway that was built across a wide area of permeable and saturated sand, gravel, and swamp deposits (Figure 77). The flat land was largely in open field, but several years after the highway was completed, many of the fields became waterlogged and difficult to farm. A few dwellings were also affected. The explanation for the detrimental rise in the local water table was that the highway embankment obstructed ground water movement. The original low water-table gradient steepened in response to the obstruction, causing the water table on the upgradient side of the embankment to rise several feet. The obstruction may have been caused by the blockage of old drains, or by the lower permeability of the fill material and the compression and reduced permeability of the underlying unconsolidated materials. The problem might have been avoided by relocating the highway to a less sensitive area, or by providing channels for ground water movement in the lower part of the embankment.

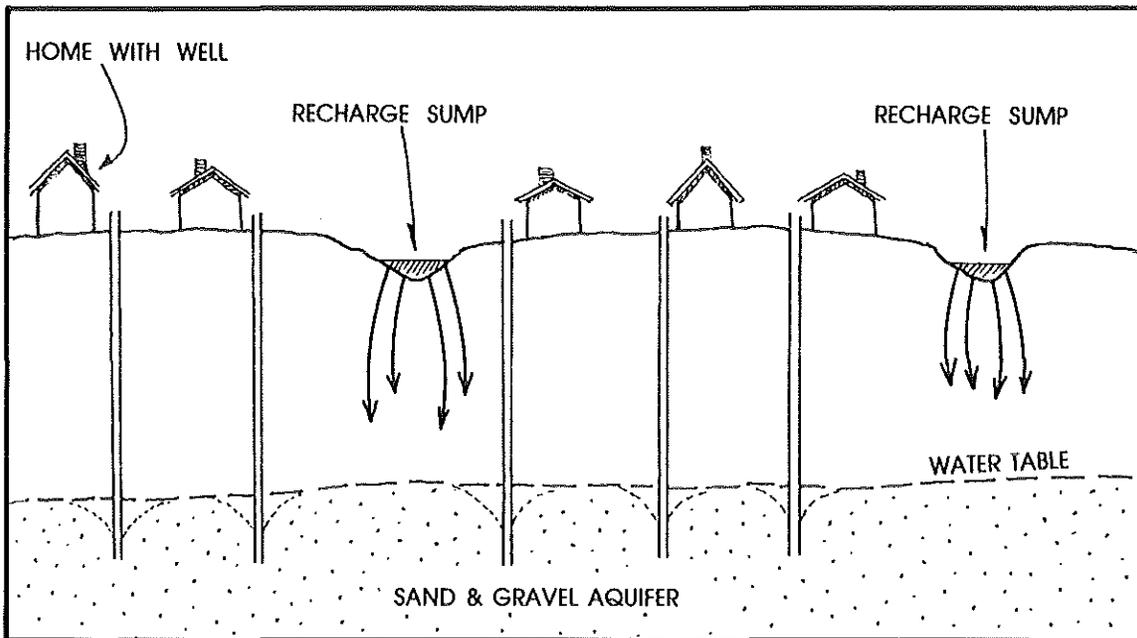


Figure 76. Schematic cross-section through urbanized area of Long Island where recharge sumps are used to maintain the ground water level.

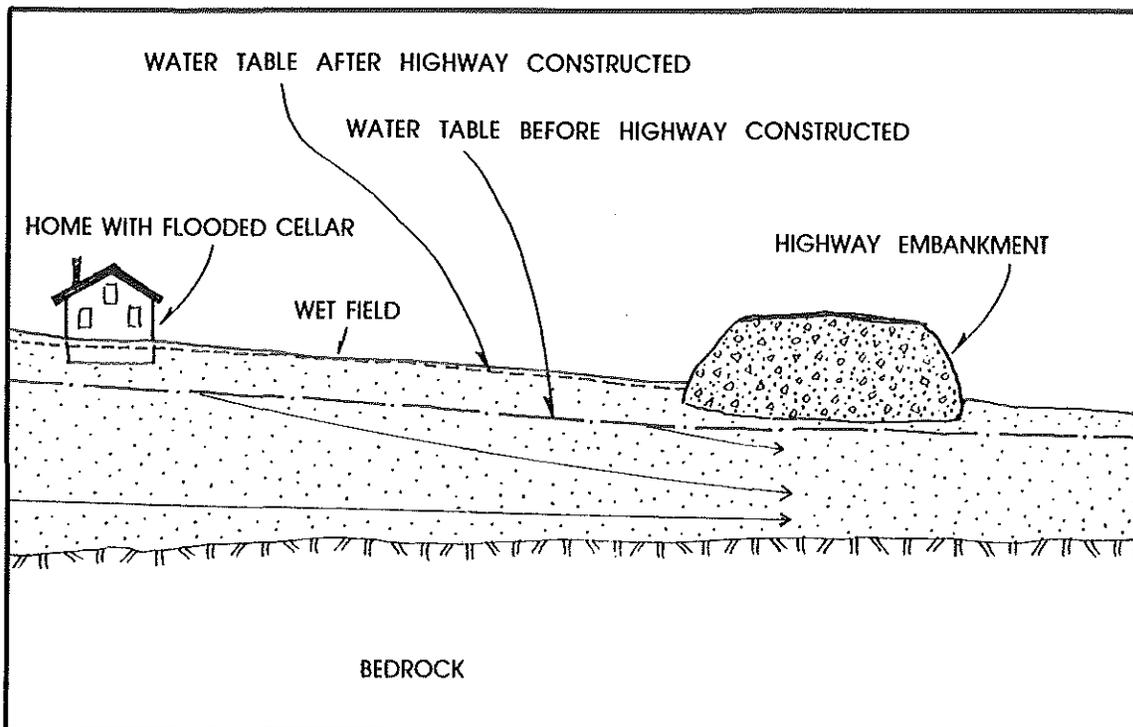


Figure 77. Schematic cross section of an area where a highway embankment resulted in a detrimental rise in the local water table.

EXCESSIVE GROUND WATER WITHDRAWAL

Extraction of ground water from an artesian aquifer causes changes in the shape of the aquifer, some of which may be permanent. Water released from storage is derived in part from shrinkage of the aquifer pore spaces. The phenomenon affects confined gravel aquifers more than crystalline bedrock aquifers. In a number of places in this country, the shrinkage of the aquifer pore spaces due to ground water withdrawals has caused land subsidence that is obviously detrimental to local buildings, roads, and other structures. Some of the ability of the aquifer to store water may also have been lost. Subsidence due to ground water withdrawal is not known in Maine, but the possibility exists, especially for extensive gravel aquifers confined by a relatively thick cover of silt and clay.

SURFACE-WATER IMPOUNDMENTS

Any place that surface-water levels are raised by damming a stream, local ground water levels rise. A farm pond, for example, if built by damming a water course, causes the surrounding water table to rise, possibly waterlogging fields adjacent to the pond (Figure 78). Much larger impoundments can cause more significant changes in ground water level.

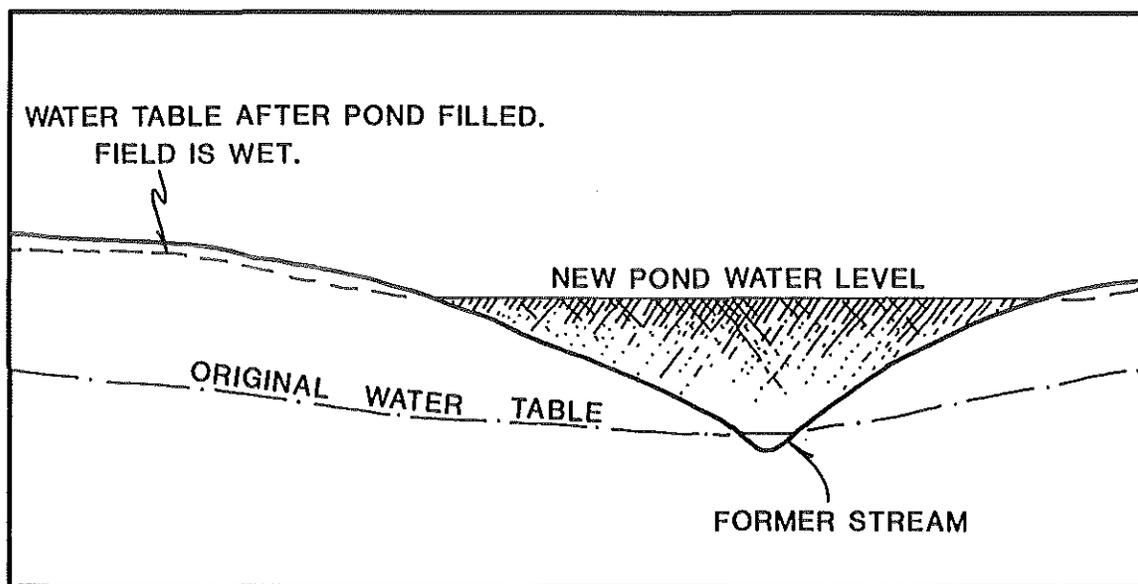


Figure 78. Schematic cross-section of a farm pond that has caused an undesirable rise in the local water table.

APPENDIX

WHERE TO GO FOR HELP

Individuals, groups, or developers with ground-water problems have several potential sources of information and assistance. For large projects and serious problems, it is often wise to engage a consulting geologist or hydrologist. Many other problems can be dealt with by an informed homeowner, with help from a well driller or plumber.

Both state and federal governments provide information and assistance with ground-water problems. The list below describes programs dealing with ground water.

Federal Agencies

Title -----	Type of Information or Assistance -----
U.S. Geological Survey 26 Ganneston Drive Augusta, ME 04330 622-8208	Water levels, hydrologic atlas maps, some ground-water quality information.
Farmers Home Administration 40 Western Avenue Augusta, ME 04330 622-8215	Loans and (grants) for rural water supply development for eligible individuals.
U.S. Environmental Protection Agency New England Region JFK Building Boston, MA 02203 1-617-223-7223	Information and assistance with certain toxic and hazardous waste disposal practices. Coordinates "Superfund" activities.

State Agencies

Title -----	Type of Information or Assistance -----
Maine Geological Survey Department of Conservation Station 22 Augusta, ME 04333 289-2801	Sales of aquifer maps, ground-water quality reports, general assistance in well location, administers water well information reporting program.
Maine Department of Environmental Protection Station 17 Augusta, ME 04333 1-800-432-1942	Administers water pollution laws, regulates salt-sand storage (Water Bureau, 289-3901); conducts oil, gasoline and hazardous waste investigations and clean up (Oil & Hazardous Materials, 289-2651); administers land use and land disposal laws (Land Quality Control, 289-2111). Citizens Environmental Assistance Service coordinates permit applications and requests (289-2811).
Maine Drinking Water Program Department of Human Services Station 11 Augusta, ME 04333 289-3826	Sets standards for drinking water, advice on water quality problems in wells. Administers public water supply sampling program.
Public Health Lab Department of Human Services Station 11 Augusta, ME 04333 289-2727	Water analysis services, including bacteriological, chemical, and radiological.
Health Engineering Department of Human Services Station 11 Augusta, ME 04333 289-3826	Administers the Plumbing Code including on-lot sewage disposal regulations.
Department of Transportation Well Claims Station 16 Augusta, ME 04333 289-3321	Replaces wells damaged by state road construction or road salting.

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TABLE OF COMMONLY USED SYMBOLS

Q	Pumping rate of a well, or discharge rate of a spring or stream
K	Hydraulic conductivity, or coefficient of permeability
i	Hydraulic gradient
A	Area
T	Transmissivity
S	Storativity
gpm	Gallons per minute
ppm	Parts per million
mg/l	Milligrams per liter
ppb	Parts per billion
pCi/l	Picocuries per liter

