Ground-Water Resources of the Lowell Area Massachusetts

By JOHN A. BAKER

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CONTENTS

ILLUSTRATIONS

[Plates are in pocket]

TABLES

GROUND-WATER RESOURCES OF THE LOWELL AREA, MASSACHUSETTS

By John A. Baker

ABSTRACT

The Lowell area includes most of the Lowell metropolitan area (the core city of Lowell and the surrounding towns of Billerica, Chelmsford, Dracut, and Tewksbury) and parts of the towns of Bedford, Carlisle, Concord, and Tyngsborough. The rapid growth since World War II of communities within the Lowell area has created problems related to the search for new water supplies and to the more effective development and management of both new and old supplies. The purpose of this report is to provide information on the ground-water resources as an aid to understanding and resolving some of the problems.

Ground water occurs in bedrock and in overlying unconsolidated deposits. The bedrock is a source of small supplies of water throughout the area. Glacial till also is a source of small supplies of water, but shallow wells in till may go dry during extended dry weather. Stratified deposits (ice-contact deposits and outwash and alluvium) yield small to large supplies of water.

The stratified deposits form the principal ground-water reservoir; the deposits partly fill the buried valley system of the preglacial Merrimack River. Most preglacial valleys correspond roughly in position to the valleys of the present streams. However, an exception to this is a segment of the preglacial valley of the Merrimack River, which extends southeastward from the present Merrimack valley and corresponds generally in position with the valleys of Black Brook and River Meadow Brook. The stratified deposits are more than 140 feet thick at places. In general, the more permeable materials are included in the ice-contact deposits, and the less permeable materials are included in the outwash and alluvium. The ground water occurs under water-table conditions.

Recharge in the Lowell area is derived principally from precipitation. The principal recharge areas are the outcrop areas of ice-contact deposits and areas of outwash and alluvium. Recharge follows an annual cycle; most of the annual recharge occurs during the period from about the middle of October to April. Ground water is discharged principally by effluent seepage to streams and by evapotranspiration. Ground water is withdrawn largely for water supplies by municipal wells of Lowell, Chelmsford, and Dracut. In 1959 ground water was pumped at an average rate of about 11 million gallons per day.

The quality of the ground water is generally satisfactory except for local iron and manganese concentrations that exceed those recommended by U.S. Public Health Service (1961). The presence of undesirable amounts of iron in the water was a factor in decisions by the town of Billerica and the city of Lowell to abandon wells as a principal source of water.

Recharge and the storage capacity of the ground-water reservoir in the Lowell area are large enough to support a substantial increase in ground-water withdrawal. The most favorable areas for further development of ground water are the ground-water reservoir of the Merrimack River watercourse and the ground-water reservoir in the abandoned valley of the preglacial Merrimack River.

INTRODUCTION

PURPOSE AND SCOPE OF THE REPORT

This report presents the results of an investigation of ground-water resources in the Lowell area by the U.S. Geological Survey in cooperation with the Massachusetts Department of Public Works. The report has been prepared in response to a need for information on the water resources of the Lowell area which could be used as a basis for solving present and future water problems.

The rapid growth since World War II of the communities in the Lowell area has been accompanied by new problems of water supply. The basic problems are where to seek new sources of supply and how to develop and manage both new and old water supplies most effectively. By describing the conditions controlling the occurrence of ground water and by discussing some factors bearing upon further development of the ground-water resources, this report contributes toward the resolving of these problems.

This investigation was under the supervision of H. N. Halberg, former engineer-in-charge, and O. M. Hackett, district geologist. Chemical analyses of ground water were made by the Quality of Water Branch of the Geological Survey. Unpublished geologic maps of the Billerica, Lowell, Tyngsboro, and Westford quadrangles were furnished by the Geologic Division of the Geological Survey.

The writer acknowledges the cooperation of well owners, well drillers, consulting engineers, and owners and operators of public and industrial water supply systems who generously supplied data used in writing this report.

PREVIOUS INVESTIGATIONS

Several geologic reports are particularly significant with respect to the Lowell area. The main features of the bedrock geology are shown on a geologic map of Massachusetts and Rhode Island by Emerson (1917) and are discussed in reports by Jahns (1941) and Currier and Jahns (1952). Surficial deposits in parts of the Billerica and Wilmington quadrangles are shown on an unpublished map by Castle (1950). The preglacial Merrimack River valley was described by W. O. Crosby (1899) and later was explored by the Geological Survey using seismic methods (Lee, Farnham, Raspet, and Currier, 1940). A report by Chute (1960) describes the geology of the Mystic Lakes-Fresh Pond buried valley south of the Wilmington quadrangle. Surficial deposits in the Lawrence and Wilmington quadrangles, adjacent to the Lowell area on the east, are shown on maps by Castle (1958, 1959).

Four reports dealing with water resources are of general interest. One, a report on land and water resources of the New England-New York region by the New England-New York Inter-Agency Committee (1955) contains a chapter on the Merrimack River Valley. Two reports by I. B. Crosby (1937, 1939) describe the occurrence of ground water in relation to buried valleys in northeastern Massachusetts. The fourth, by L. A. Barbour (1917), describes the occurrence of iron and manganese in the Lowell ground-water supply and discusses the removal of these substances from the water.

METHODS OF INVESTIGATION

Fieldwork by the writer, carried on from April to September 1954, included a reconnaissance of the geology of the area, an inventory of wells, springs, and test holes, and the collection of samples of water for chemical analysis. Additional hydrologic and geologic data collected during the period 1954–59 were incorporated into the report when it was revised for publication. Many well data were collected by earlier workers—notably, M. L. Brashears, Jr., C. M. Roberts, H. N. Halberg, E. W. Reed, H. S. Taylor, and M. A. Pistrang. Measurements of ground-water levels in the Lowell area were begun with the establishment of an observation-well network in 1939.

The geologic map of the Lowell area showing the distribution of unconsolidated deposits (pl. 2) was compiled largely from unpublished maps showing the surficial geology of the Billerica, Lowell, Tyngsboro, and Westford quadrangles. The units shown on these maps were modified, on the basis of fieldwork by the author, to suit the purpose of this report.

Basic data collected during this investigation but not incorporated in the report include records of 7 springs, records of about 550 wells or groups of wells and test holes, logs of 160 wells and test holes, and periodic measurements of ground-water levels in 12 observation wells. These data may be examined at the office of the Geological Survey, Ground Water Branch, room 206, 211 Congress Street, Boston, Mass. The locations of wells, test holes, and springs are shown on plate 2.

LOCATION AND DESCRIPTION OF THE AREA

The Lowell area is located in northeastern Massachusetts (fig. 1) and is almost wholly within Middlesex County. The area covers about 115 square miles. It includes most of the Lowell metropolitan area, which—according to the U.S. Department of Commerce, Bureau of the Census—consists of the core city of Lowell and the surrounding towns of Billerica, Chelmsford, Dracut, and Tewksbury. In addition, the Lowell area includes most of the town of Carlisle and parts of the towns of Bedford, Concord, and Tyngsborough.

The pattern of development since World War II is indicated by the population trends of the Lowell metropolitan area from 1945 to 1955. In this decade the population of the metropolitan area increased by 7.6 percent owing to the growth of the suburban towns. Meanwhile, the population of the city of Lowell decreased by 7.3 percent. In 1960, according to the census of population, the metropolitan area had a population of 157,982.

Early in the history of Lowell the development of waterpower at the falls of the Merrimack and a plentiful supply of the soft river water, so necessary for textile processing, helped make the city a leading textile center of the Western Hemisphere and earned it the title "The Spindle City". The peak of Lowell's importance as a textile center was reached in the early twenties. Subsequently, Lowell's textile industry declined in importance, and other industries grew. According to the Massachusetts Department of Commerce (1960), the six principal types of manufacturing firms, in the order of importance as employers, were those producing textiles, miscellaneous manufactured products, leather and leather products, electrical machinery, food and food products, and apparel and other finished goods. These industries require moderate amounts of water for processing and cooling.

Agriculture is practiced to a small extent in the rural areas of Middlesex County, including towns adjacent to Lowell. Poultry, poultry products, and dairy products account for most of the farm income, but crops—the most important of which are market vegetables and hay—and fruits and berries are also important.

The Lowell area has excellent transportation facilities. The Boston and Maine Railroad provides passenger and freight service, and the New York, New Haven and Hartford Railroad Co. provides freight service. Two bus companies provide local passenger service, and three bus companies provide interstate passenger service. Rail, harbor, and airport facilities at Boston, which is 25 miles south of Lowell, are easily accessible. The area also is served by an adequate system of hard-surfaced Federal and State highways. Many paved secondary highways serve the rural districts.

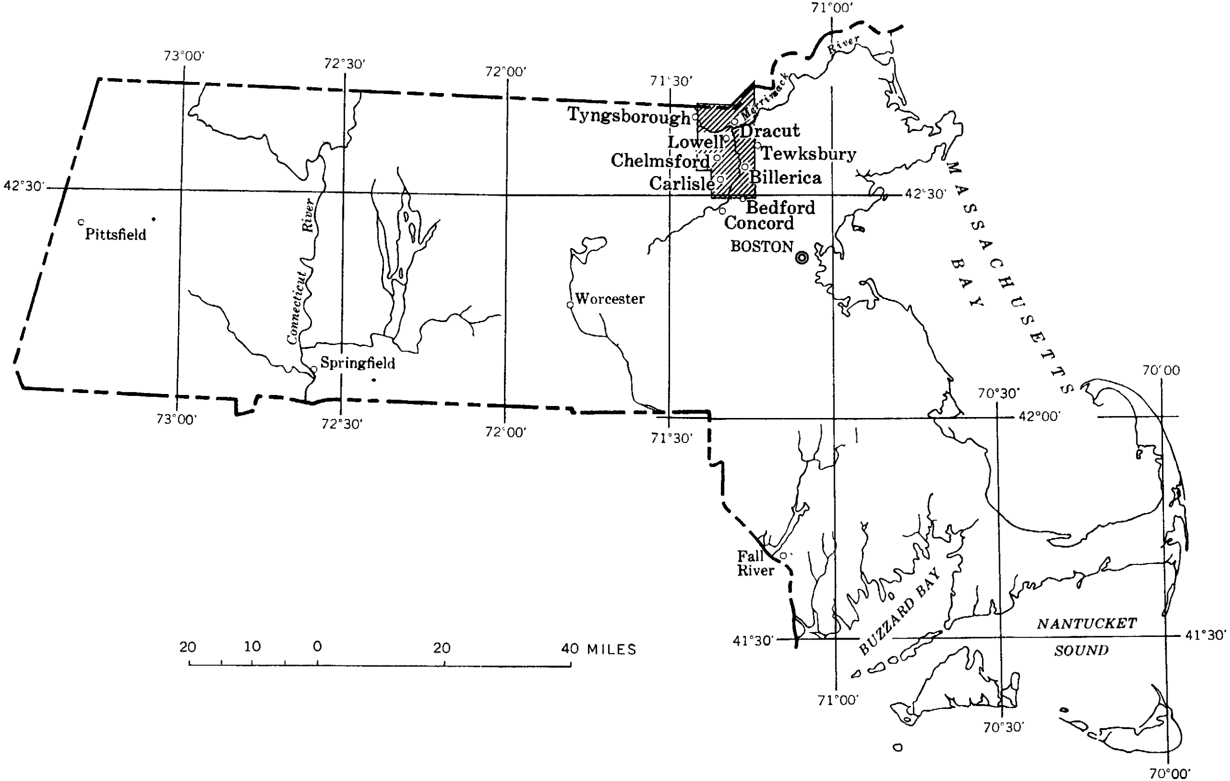

Figure 1.—Index map of Massachusetts showing location of the Lowell area.

CLIMATE

The climate of the Lowell area is humid and is characterized by fairly uniform monthly precipitation, cold winters, and warm summers. Temperature extremes are somewhat subdued by the tempering effect of the Atlantic Ocean, which is about 25 miles to the east. The mean annual temperature at Lowell, based on 25 years of record (1931–55), is 49.8°F. The mean temperature for January, the coldest month, is 26.6°F, and the mean temperature for July, the hottest month is 73.7°F. The growing season averages about 165 days and generally lasts from about May 1 to about October 14. Records of monthly temperature and precipitation for the period 1931–55 are summarized graphically in figure 2.

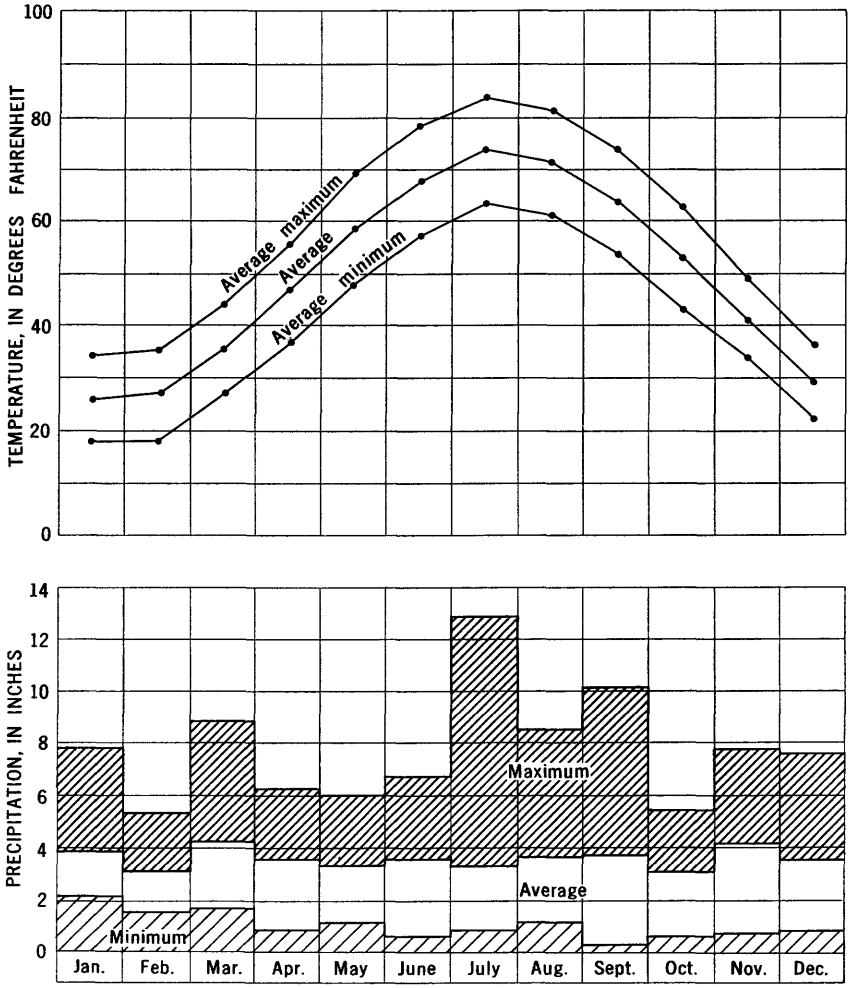

FIGURE 2.—Graphs showing monthly precipitation and temperature at Lowell, Mass.

The average annual precipitation at Lowell, based on 25 years of record (1931–55), is 43.40 inches. In general, the monthly precipitation is distributed evenly throughout the year, but deviations from the average for any one month or year may be considerable. The largest amount of annual precipitation, 59.93 inches, was recorded in 1888; the least amount, 27.85 inches, was recorded in 1914. The average annual snowfall is about 41 inches, equivalent to about 4 inches of water.

PHYSIOGRAPHY AND DRAINAGE

The Lowell area lies within the Seaboard Lowland section of the New England physiographic province (Fenneman, 1938, p. 370). The topography of the area is characterized by rounded hills and broad, poorly drained lowlands, of which the valleys of the Merrimack River and its tributaries are the most prominent.

The maximum relief of the area is about 360 feet, but the local relief commonly is less than 250 feet. The highest point, the crest of Robbins Hill, has an altitude of 408 feet; the lowest point, where the Merrimack River leaves the area, has an altitude of about 48 feet.

The Lowell area is drained by the Merrimack River and its tributaries. The Merrimack crosses the area from west to east. The Concord River, a major northward flowing tributary, joins the Merrimack at Lowell and together with River Meadow Brook drains the southern part of the area. The rest of the area is drained by small tributaries of the Merrimack, including Beaver Brook from the north, Stony Brook from the west, and Black Brook from the south. Drainage is poor; streams are sluggish, and swamps, ponds, and small lakes are common.

The discussion of topographic and physiographic history that follows is quoted from Lee and others (1940, p. 2).

> The present topography is chiefly the product of a period of intense erosion followed by one of dominant deposition. During the earlier period the bedrock land mass was reduced to a rolling plain consisting of broad, shallow valleys separated by broad, rounded divides. No accurate measure of the relief at this stage is possible but such pertinent data as are available suggest a probable relief of 400 or 500 feet. At this time the area had reached a stage of moderately steep but not gorgelike valley walls and rather broadly rounded hills. During this denudation the valleys doubtless received much sediment derived from the eroded uplands. A subsequent uplift of the region caused renewal of strong erosional activity in which vertical cutting exceeded lateral planation, so that in the lower reaches of the valleys the streams became somewhat entrenched in the valley floors and distinct gorges were developed within the older, broad valleys. The uplands also were scored by sharply defined tributaries. Some or much of the earlier sedimentary filling was removed from the lower valley floors. As a result of regional uplift and consequent revival of erosion, the regional relief was increased to 500 feet or more, and the erosional forms became accentuated, particularly with respect to the major valleys.

Downcutting by streams was interrupted early in Pleistocene time by the passage of one or more ice sheets from the north across the area. Existing landforms were modified first by glacial erosion and then by the deposition of glacial till as ground moraine and as scattered drumlins. Later, as the ice melted, detritus swept from the ice by meltwater formed a variety of ice-contact landforms, such as kames, kame terraces, kame plains, and ice-channel fillings. Then, with further melting and the disappearance of the ice from the immediate area, melt-water streams spread outwash across the bottoms of the valleys. Thus, the preglacial bedrock valleys became partly or completely filled, and the relief of the area was decreased somewhat.

A further effect of glaciation was the partial derangement of the preglacial drainage pattern. The postglacial streams were established on the valley fill and therefore coincide only roughly or not at all with the positions of the preglacial channels. Also, in places, streams were diverted from one preglacial valley to another by dams of ice or glacial drift.

The course of the Merrimack River has long been recognized as an example of just such a change in drainage (Crosby, W. O., 1899). The river follows its preglacial valley southeastward from the west margin of the area to a point east of North Chelmsford. There, it bends northeastward, leaves its preglacial valley, and flows eastward in a narrow postglacial valley across bedrock at an altitude of 90 feet in the city of Lowell. The buried preglacial channel, on the other hand, continues southeastward in the broad valley now occupied by Black Brook to a point east of Chelmsford Center, where it curves sharply to the northeast and extends at least to the Cook Well Field in Lowell (Lee and others, 1940, p. 45). (See p. Y11). The bottom of the preglacial Merrimack River channel is approximately at sea level.

After the disappearance of the last ice sheet from the general area and with the establishment of the present drainage pattern, low terraces were formed along existing streams in Recent time.

GEOLOGIC UNITS AND THE OCCURRENCE OF GROUND WATER

As the geologic features of the Lowell area were examined only briefly during this study, the work of others in this area and nearby areas has been drawn on heavily—especially the work of Currier and Jahns (1952) and of R. H. Jahns, M. E. Willard, W. S. White, and L. W. Currier whose unpublished surficial geologic maps of the Lowell, Billerica, Westford, and Tyngsboro quadrangles have been used in the preparation of the geologic map in this report. Maps by Castle (1958, 1959) of areas that adjoin the Lowell area on the east were also helpful. The rocks in the Lowell area in which ground-water occurs have been divided into two main categories: the consolidated rocks—hereafter referred to as bedrock—and the unconsolidated deposits.

BEDROCK

Bedrock crops out chiefly on the higher ridges and knobs, where it is covered discontinuously by till. On the lower slopes of hillsides and in the valleys the bedrock is covered by till and younger unconsolidated deposits. The following discussion of the ages and regional structure of the consolidated rocks is based largely on Currier and Jahns (1952).

The bedrock formations consist of various igneous and metamorphic rocks. These rocks range in age from middle Paleozoic to Triassic. The metamorphic rocks are the oldest rocks in the area; they consist chiefly of schist, gneiss, and quartzite. The igneous rocks, which intrude the metamorphic rocks, consist chiefly of gabbro, diorite, granodiorite, and granite. Dikes of granite, diabase, and camptonite, and irregular masses of pegmatite, aplite, and quartz intrude all other bedrock types. The bedrock formations apparently lie on the southeastern flank of a major anticline that trends northeast and plunges southwest.

The several bedrock types in the Lowell area appear to have no significant differences in their water-bearing properties; therefore, bedrock (locally termed "ledge") is treated as a single unit in this report.

Bedrock contains water chiefly in openings along joints and fractures. Most joints are planar and are steeply inclined to vertical, but some (called sheeting) are curved, conform roughly to the topography, and are more conspicuous in granite than in other rock types. Where examined in outcrop, joint openings were as much as 6 inches wide, but most of them were less than 2 inches wide. They are spaced from a few inches to several tens of feet apart.

Water in bedrock wells commonly rises and stands above the level where it is first struck. Wells penetrate some distance into rock before intersecting water-bearing joints. When a water-bearing joint is penetrated, pressure created by the weight of water at a higher level in the joint system is released, and—allowing for some loss of head due to friction—the water rises to the level of the water at the intake area. The few available water-level data suggest that the piezometric surface of water in bedrock approximates the position of the water table in overlying unconsolidated deposits. In three drilled wells, Billerica 352, Dracut 29, and Pelham 2, the water overflowed the tops of the casings when the wells were drilled.

The openings in bedrock that store and transmit water are neither uniform nor widespread. They act chiefly as conduits and provide only a small amount of storage. Even where water-bearing openings are large enough to transmit water freely, they are probably dependent on storage in overlying unconsolidated deposits for much of their water.

In general, the yields and specific capacities (yield per unit of drawdown) of most bedrock wells are small; consequently the permeability of bedrock is inferred to be small. The reported yields of 37 bedrock wells ranged from 1 to 130 gpm (gallons per minute). The median yield is 12 gpm. The specific capacities, which are more reliable than yield as an index to the permeability of a water-bearing material, of most bedrock wells are also small—ranging from 0.2 to 1.4 gpm per ft.

Because of the great variety in size, spacing, and attitude of water-bearing openings, neither the depths nor the yields of wells in bedrock can be predicted accurately. In the Lowell area most wells yield at least a few gallons per minute, enough for ordinary domestic use, from depths of less than 200 feet. About half the wells inventoried were less than 100 feet deep. In general, there is an increase of yield with depth, but because the size and number of water-bearing openings commonly decrease with depth, the chances of appreciably increasing the yield become smaller and smaller as a well is deepened. Some geologists believe that in crystalline rocks, such as those in the Lowell area, there is a limiting depth below which it is impractical to deepen a well in attempting to increase the yield. For example, Cushman, Allen, and Pree (1953, p. 95) concluded that "if a well has reached a depth of 300 feet in crystalline rock and no water-bearing fractures have been struck, the chances of finding water are better if a second well is begun in a new location." Ellis (1909, p. 94) concluded: "From a study of the recorded wells it would appear, therefore, that if a well has penetrated 250 feet of rock without success the best policy is to abandon it and sink in another location."

In some bedrock wells the yield may be substantially improved after drilling. For example, it is reported that the yield of a bedrock well in Lowell increased from 27 to 47 gpm after the well was "exploded from the bottom * * * ."

THE BEDROCK SURFACE AND BURIED VALLEYS

Bedrock is one of the dominant factors controlling the occurrence of water in the overlying unconsolidated deposits. Because the bedrock is relatively impermeable, it acts as a barrier to water moving down from the unconsolidated deposits. Also, the relief and configuration of the bedrock surface determine, in part, the thickness of unconsolidated deposits; the thickest deposits are found in preglacial valleys, where the bedrock surface is lowest. Because these preglacial bedrock valleys contain the thicker saturated deposits, from which the larger ground-water supplies in the Lowell area are derived, knowledge of the location and extent of preglacial valleys serves as a guide to systematic exploration for favorable ground-water areas.

The main preglacial valley in the Lowell area is the relatively deep, broad valley of the preglacial Merrimack River. The position and extent of the buried valley as postulated from bedrock outcrops, well data, and seismic data (Lee and others, 1940) are shown in plate 1 by 25- and 50-foot contours on the bedrock surface. Preglacial tributary valleys are not well defined but appear to coincide generally with the valleys of Stony Brook, River Meadow Brook, and the Concord River. A preglacial valley may coincide with the valley of Beaver brook also.

From the northwestern corner of the Lowell area to the mouth of Stony Brook at North Chelmsford, the valley of the preglacial Merrimack coincides generally in position with the present Merrimack valley. The deepest test well within this reach penetrated to a point 6 feet above sea level without reaching bedrock (well Chelmsford 136). From the mouth of Stony Brook the preglacial valley trends southeastward to River Meadow Brook, where it bends sharply to the northeast. It can be traced along the valley of River Meadow Brook from the junction of Highways 3 and 110 at least to the vicinity of well Lowell 96 in the Cook well field in Lowell. The deepest test well within this reach penetrated to a point 4 feet above sea level without reaching bedrock (well Chelmsford 264), and seismic data (Lee and others, 1940, figs. 10–12) indicate that the bottom of the preglacial valley is at or slightly below sea level.

The location and extent of the preglacial Merrimack valley beyond the Cook Well Field in Lowell are unknown. W. O. Crosby (1899, p. 302) suggested that the preglacial Merrimack River flowed southeastward from the Lowell area and into Boston Harbor by way of the present Mystic valley. This hypothesis was accepted by I. B. Crosby (1937, p. 57; 1939, p. 375–376), who also suggested an alternate route for the preglacial Merrimack across Wilmington (adjacent to the Lowell area on the east) and eastward towards Salem. LaForge (1932, p. 79) and Chute (1960, p. 190) questioned the views of the Crosbys with respect to the preglacial Merrimack flowing to Boston Harbor by way of the Mystic valley. Chute wrote:

> That the Fresh Pond buried (Mystic) valley was not formed by the preglacial Merrimack River as W. O. Crosby suggested (1899, p. 302) is indicated by the narrowness of the valley in the southern part of Wilmington. More subsurface studies must be made, however, before the extent of the buried valley north of the Woburn-Wilmington town line can be known.

Castle (1959), in his report on the Wilmington quadrangle wrote:

> The distribution of bedrock exposures and well log data from the central part of the quadrangle, that show bedrock to be at or below present sea level, suggest that a major northwest-trending valley crossed the central part of the area. * * * The preglacial Merrimack River may have flowed southeastward through the Billerica and Wilmington quardrangles (Crosby, 1939, p. 375–377; Lee et al., 1940, p. 37–40); if so, the river almost surely followed the route of this buried valley, ultimately draining eastward or southeastward through valleys that followed the general paths of the Ipswich or Aberjona Rivers.

Data collected during an investigation in the Wilmington-Reading area (adjacent to the Lowell area on the east) cast doubt on the suggestion of an alternate route for the preglacial Merrimack eastward toward Salem by way of Wilmington. The only area through which the channel could pass into Wilmington was explored by seismic methods (Baker, Healy, and Hackett, 1962, p. 46–47). From the results of the seismic exploration, the distribution of bedrock outcrops, and well data it was concluded "that a major preglacial stream did not cross Wilmington, but rather that the preglacial Ipswich here branched into short headwater streams in much the same fashion as the present stream."

In the view of I. B. Crosby (1937, p. 57), the preglacial Concord River was tributary to the preglacial Merrimack and "probably joined the Merrimack in North Billerica." Subsurface data in this area are scarce, but the few data available do not seem to support this hypothesis. The channel of the preglacial Merrimack River is at or below sea level near Lowell; thus, if the preglacial Concord joined the preglacial Merrimack at North Billerica the bedrock surface would lie at or below sea level there. Test borings made at the highway bridge on Highway 3A about 0.7 of a mile south of North Billerica and test wells at the Billerica Water Works about half a mile south of North Billerica suggest that the bedrock surface is about 70 feet above sea level. Seismic data (Lee and others, 1940, figs. 2 and 12) indicate that along the Concord River at North Billerica the bedrock surface is no lower than about 50 feet above sea level and that about half a mile west of North Billerica the bedrock surface is about 40 feet above sea level. If the preglacial Concord was tributary to the Merrimack, the available data suggest that a likely course was southwest of and parallel to Highway 3A along a route marked by wells Billerica 65, 48, 32, and 88 and thence along the unnamed northwest-flowing tributary of River Meadow Brook to join the preglacial Merrimack just south of Lowell in the vicinity of well Chelmsford 259.

If, as suggested by Crosby (1937, p. 57), the preglacial Merrimack extends to the southeast through the northern part of Billerica, then whether or not there is a preglacial Concord River tributary, the present Concord must flow across the buried Merrimack.

I. B. Crosby (1937, p. 57–58) suggested that the preglacial Merrimack also had tributaries extending into the areas drained by Stony Brook and River Meadow Brook. The buried valley of the River Meadow Brook tributary probably extends no farther south than the Chelmsford Water District well field southeast of Chelmsford Center, where well data suggest that the altitude of the bedrock surface is about 60 feet above sea level (well Chelmsford 275, pl. 1). About a mile farther south, seismic data (Lee and others, figs. 2 and 10) indicate that the altitude of the bedrock surface is no lower than about 100 feet above sea level. Little is known of the buried valley of Stony Brook, but southeast of Newfield Pond, well Chelmsford 71 (pl. 1) penetrated to a point 55 feet above sea level without reaching bedrock.

The preglacial Merrimack valley, as interpreted from seismic data (Lee and others, 1940, figs. 10–12) and well data, has an older, broad preglacial valley floor at least 3,000 feet wide that is incised by a younger, inner valley about 1,000 feet wide. (See pl. 2, sections *A–A′* and *B–B′*.) The bottom of the deepest part of the inner valley floor is at about sea level, and the rock terraces on either side of the inner valley are about 50 feet above sea level. The buried walls of the older valley have moderate slopes. Where the valley of the preglacial Merrimack intersects the present surface, it ranges in width from about 500 feet to 2 miles, as indicated by the distribution of bedrock outcrops and by well data.

UNCONSOLIDATED DEPOSITS

The unconsolidated deposits consist of glacial drift and wind deposits of Pleistocene age and of alluvium and swamp deposits of Recent age. The glacial drift exposed in the area was deposited during the advance and subsequent disappearance of ice during the last (Wisconsin) glacial stage (Flint, 1953, p. 900–901). The drift includes till (ice-laid drift) and stratified drift (water-laid drift). The stratified drift is subdivided further into ice-contact deposits and outwash. Alluvium, which cannot be distinguished from stratified drift at most places, is mapped together with the outwash in a unit called outwash and alluvium.

The unconsolidated deposits contain water in openings between particles of gravel, sand, silt, and clay. Compared to bedrock, unconsolidated deposits are relatively porous and permeable. However, the several types of materials forming these deposits have significant differences in water-bearing properties. Fine-textured materials, such as clay and silt, have a large porosity but commonly have a small specific yield and a small permeability. In contrast, relatively coarse-textured materials such as sand and gravel, especially if clean and well sorted, have not only a large porosity but also a large permeability and a large specific yield. Because of their small permeability, fine-textured materials yield little or no water to wells, whereas well-sorted relatively coarse-textured materials yield water freely to wells.

The several classes of unconsolidated deposits are described below in the following order: Till, ice-contact deposits, outwash and alluvium, wind deposits, and swamp deposits. The extent and distribution of till, ice-contact deposits, outwash and alluvium, and swamp deposits are shown on the geologic map (pl. 2), and the subsurface relationships of these units, based on geologic mapping and interpretation of drillers' logs and seismic data, are shown in cross-sections (pl. 2). The wind deposits, which mantle the glacial drift and bedrock discontinuously throughout the area, were not mapped.

TILL

Till is unsorted or poorly sorted unstratified glacial drift deposited directly by glacial ice without subsequent movement by wind or water. As the last ice sheet advanced over the area, it scraped soil from the land surface and scoured and abraded the underlying bedrock. With further advance and subsequent wasting of the ice, the material so derived was deposited either as ground moraine, a thin sheet of till which in this area rests on and conforms roughly to the bedrock surface, or as drumlins—elliptical hills of till also resting on and in some places having a core of bedrock. Till is exposed on hills and ridges but is overlain on the lower slopes of hillsides and in the valleys by younger unconsolidated deposits.

The till ranges in thickness from less than 1 to about 175 feet. On the basis of well data and seismic evidence, the maximum thickness of the ground moraine is about 50 feet, and the average thickness is about 15 feet. In some drumlins, till may be more than 100 feet thick; for example, wells Dracut 186 and 192 reportedly penetrated 175 feet and 160 feet, respectively, of till.

Till is characterized by a wide range in particle size, by a lack of stratification, by little or no sorting, and—at some places—by the angularity of component grains and degree of compaction. Where these characteristics cannot be examined, as in disturbed samples, till cannot always be distinguished from the other deposits.

Two types of till were recognized in the Lowell area. One type consists largely of silt and clay, is compact, is resistant to the shovel, and breaks into small chips. The second type is loose and sandy. Both types contain boulders and, at some places, thin lenses of stratified materials. For example, thin lenses of crossbedded water-laid sand in clayey till were seen in a pit along Highway 110 about half a mile east of the Dracut-Lowell line, and "mason's sand" is said to have been uncovered in an excavation in till about half a mile east of the Concord River and about half a mile south of the Tewksbury-Billerica town line. The relationship of the two tills is imperfectly known, but the loose till rests on the compact till in the few exposures where both were seen.

In general, the ground water in till is unconfined, but where the till contains lenses or stringers of saturated sand and gravel, the water in the sand and gravel may be confined.

Because till is poorly sorted and at many places is compacted, it has a small permeability and yields only small amounts of water to wells. The specific capacity of one well for which yield and drawdown data are available is 0.5 gpm per ft. The reported yields of five wells, including the one for which the specific capacity is given, range from 4 to 15 gpm.

Because till is relatively thin, it can store a relatively small amount of water; consequently, it is a less reliable source of water than either bedrock or some of the younger unconsolidated deposits. In extended dry weather the water table may drop below the bottoms of shallow wells.

ICE-CONTACT DEPOSITS

Ice-contact deposits are stratified drift deposited in contact with the ice. Some deposits of this type may have formed as the last ice sheet advanced, but nearly all those recognized were formed as the ice sheet melted and retreated. Streams flowing from the melting ice washed boulders, gravel, sand, silt, and clay from the ice and deposited these materials between the ice and the higher parts of adjacent hills and ridges first exposed. Meanwhile, additional deposits were formed in channels in, on, or under the ice. With progressive melting of the ice and uncovering of the land surface, streams became graded to lower and lower outlets, and ice-contact deposits were formed at correspondingly lower levels. Finally, only scattered blocks of ice remained, around which the last ice-contact deposits were built.

The ice-contact deposits form distinctive topographic features, including kames, kame terraces, kame plains, and ice-channel fillings. These deposits commonly rest on till or bedrock. The landforms are characterized by one or more slopes marking the former contact with adjacent ice. The so-called ice-contact slopes generally are overlapped along their bases by outwash and alluvium. At one place, in the valley of River Meadow Brook in Lowell, low-lying ice-channel fillings are surrounded and nearly buried by outwash and alluvium. This suggests that there may be places where ice-contact deposits are completely buried.

The ice-contact deposits range in thickness from less than 1 foot to 140 feet. The thickest deposits occupy the preglacial channel of the Merrimack River; the maximum known thickness is near Black Brook in the vicinity of well Lowell 113, where the difference in altitude between the bedrock (as extrapolated from well data and seismic data) and the surface of the deposits is 140 feet. The thickness of each deposit is partly determined by its position relative to the topography of the bedrock surface. Generally, a deposit is thickest where its exposed margin is nearest the bottom of a preglacial valley. Thus, younger deposits, which commonly form low-level kame terraces and kame plains near the centers of preglacial valleys, pinch out at the exposed contact with till or bedrock but generally thicken toward the ice-contact margin nearest the bottom of the valley and wedge out or thin appreciably where the ice-contact slope dips toward the bottom of the valley. In contrast, older deposits, which commonly form high-level kames and kame terraces at the margins of the valleys, pinch out at the exposed contact of till and bedrock and also wedge out on the valley wall some distance away from the bottom of the valley.

Ice-contact deposits are identified principally on the basis of landforms, but other distinguishing characteristics include stratification, sorting, and smoothness and roundness of component particles. At some places the ice-contact deposits cannot be differentiated from the outwash and alluvium with surety. The landforms of the two units are not everywhere distinctive, particularly with respect to the lowest terraces, and the internal characteristics of both units may be similar. Where a well penetrates both units, identification in the subsurface is especially difficult.

Ice-contact deposits are composed of sorted and stratified sand and gravel and subordinate amounts of silt, clay, and stray boulders. The contacts between beds of different grain size are usually sharp, and individual beds rarely extend laterally for more than a few tens of feet. Crossbedding and cut-and-fill structures are common, and deltaic bedding is fairly common. The bedding may be distorted in places where a supporting wall of ice has melted and allowed a deposit to collapse. Where distorted beds are exposed, they are a good criterion for the recognition of these deposits.

The individual deposits may differ markedly from one another. At one extreme the deposits are poorly sorted and poorly stratified and consist of particles of all sizes. In general, these characteristics are common to the older deposits that form high-level kames and kame terraces at the margins of the preglacial valleys and that are relatively thin (p. Y16). At the other extreme, the deposits are well sorted and well stratified, and consist predominantly of sand. In general, these characteristics are common to the younger deposits that form low-level kame terraces and kame plains near the centers of the valleys and that are relatively thick (p. Y16).

The wide variation in the composition, sorting, and stratification of the ice-contact deposits suggests that some of them have medium or large permeability, ranging from several hundred to more than 1,000 gpd (gallons per day) per sq ft, and others have small permeability, in the order of a few tens of gpd per sq ft. These values are consistent with values of permeability determined from analyses of samples of similar deposits elsewhere in Massachusetts.

The yields of wells in ice-contact deposits range from small to large. The reported yields of 50 wells or groups of wells ranged from 6 to 630 gpm. The reported yields of 13 large-diameter gravel-packed wells ranged from 150 to 630 gpm; the yields of 35 small-diameter wells or groups of wells ranged from 6 to 50 gpm; and the yields of 2 dug wells were 44 and 58 gpm.

The relatively large specific capacity, 106 gpm per ft, of test well Chelmsford 275 and the performance of the group of wells Chelmsford 85–114, which were pumped on a common suction line at the rate of 30 gpm per well without noticeable drawdown, attest to the relatively large permeability of some deposits. Locally, where the ice-contact deposits contain an abundance of fine-grained material, the permeability is small. The small permeability is indicated by the small to moderate specific capacities, ranging from about 7 to about 20 gpm per ft, of small-diameter wells Lowell 64, 66, and 71, which tap ice-contact deposits along the east side of River Meadow Brook about half a mile north of the Chelmsford-Lowell line. After prolonged pumping, many of these wells became clogged with fine sand, and the specific capacities dropped even lower.

Ground water in the ice-contact deposits occurs under water-table conditions throughout most of the Lowell area, but water levels indicate that water may occur under confined conditions locally. For example, the water level in well Dracut 189, which is dug in ice-contact deposits, reportedly rose "a couple of feet" when the owner dug through "a layer of clay" into underlying "gravel."

OUTWASH AND ALLUVIUM

Outwash is stratified drift deposited beyond the limits of the glacier; alluvium represents modern stream deposits. As the last ice remnants melted from the area, the ice-fed melt-water streams spread outwash along the floors of the valleys. Then, after the disappearance of the ice sheet, so-called modern streams deposited alluvium. Because deposition proceeded continuously from Pleistocene to Recent time, the distinction between the youngest outwash and the oldest alluvium is arbitrary. Therefore, outwash and alluvium are mapped as a unit for the purposes of this report. The deposits underlie the valley floors and some of the adjacent terraces. At most places the outwash and alluvium unit overlies older unconsolidated deposits (pl. 2), but at some places it overlies bedrock.

The outwash and alluvium unit ranges in thickness from less than 1 foot, where it pinches out against ice-contact deposits or till and bedrock, to at least 98 feet, where it overlies the channels of preglacial streams. The maximum known thickness, 98 feet, is at well Chelmsford 278, near River Meadow Brook.

The outwash and alluvium unit consists mostly of sand and subordinate amounts of gravel and silt derived from the glacier and possibly from older unconsolidated deposits. Deposits of diatomaceous earth were seen at two places along the Concord River, one about 0.2 mile north of the highway bridge on Highway 3A in Billerica, and the other at the site of test holes Billerica 272–85. Except for channel deposits of some existing streams, the outwash and alluvium unit is moderately well sorted and well stratified. In general, it is finer textured and more homogeneous than the ice-contact deposits; however, the youngest ice-contact deposits and the oldest outwash are very similar lithologically and cannot readily be differentiated.

The permeability of outwash and alluvium is generally medium but ranges from small to large, as inferred from the composition of the deposits and from the specific capacities of wells. The specific capacities of 20 wells ranged from 2 to 108 gpm per ft, and the median was 20 gpm per ft.

The reported yields of 28 wells or groups of wells, including the wells for which specific capacities are given, ranged from about 15 to about 720 gpm. The reported yields of 12 large-diameter gravel-packed wells ranged from about 200 to about 720 gpm; the reported yields of 15 small-diameter wells or groups of wells ranged from about 15 to about 250 gpm; and the yield of a large-diameter dug well was 200 gpm.

Ground water in outwash and alluvium occurs under water-table conditions throughout most of the Lowell area but may occur under confined conditions locally. For example, the water level in well Lowell 42, in outwash and alluvium, was about 1 foot above the land surface when the well was inventoried. The water probably is confined by an overlying semipervious layer of local extent.

WIND DEPOSITS

Wind deposits consist of silt and fine sand deposited as a thin, discontinuous blanket over bedrock and glacial drift. According to Castle (1958, 1959), the thickness of wind deposits in the Lawrence and Wilmington quadrangles, adjacent to the Lowell area on the east, "averages from 1 foot to 2 feet and generally does not exceed 4 feet." Wind deposits probably are of the same order of thickness in the Lowell area. These deposits are characterized by a lack of stratification, by good sorting, and by their relatively fine texture. The wind deposits, which lie above the water table throughout most of the area, do not yield water to wells, but they are sufficiently permeable to allow infiltration of water and percolation to underlying deposits.

SWAMP DEPOSITS

Swamp deposits consist of decayed or decaying organic matter (peat and muck) intermixed in places with silt and fine sand. These deposits accumulated in poorly drained parts of the area during Recent time. They are widespread in the valleys, where they overlie outwash and alluvium. Elsewhere, they occur locally in kettles, rock basins, and depressions in ground moraine. The swamp deposits range in thickness from a few inches to several feet. The maximum known thickness of peat is 7 feet beneath the flood plain of the Concord River about half a mile north of the highway bridge on Highway 3A in Billerica. Swamp deposits are relatively impermeable; they are not tapped by wells in the Lowell area.

GROUND-WATER CONDITIONS

OCCURRENCE OF GROUND WATER

Ground water in the Lowell area occurs in bedrock and overlying unconsolidated deposits. However, with respect to development of water supplies, the stratified deposits (ice-contact deposits and outwash and alluvium), which partly fill the buried valley system of the preglacial Merrimack River, form the principal ground-water reservoir. The deposits filling the buried valleys are characterized by wide variations in thickness and hydrologic properties. The thickness of the stratified deposits is at least 140 feet along the deepest parts of the preglacial valleys. The deposits thin toward the sides of the valleys, where they pinch out against the valley walls. In general, the more permeable saturated materials are included with the ice-contact deposits, but the saturated thickness of these deposits is not everywhere large. This is particularly true of the high-level terraces (p. Y16). An example is provided by high-level terraces along the Merrimack River northwest of Swains Pond in North Chelmsford. Here, surface exposures and well data suggest that the deposits pinch out at the contact with till hills to the west and also a short distance east of the contact with overlying outwash and alluvium. (See section A–A′, pl. 2.) Although they thicken between the exposed contacts, the deposits are drained by small streams flowing into Swains Pond; the saturated thickness there is small, probably on the order of 10 to 20 feet.

The ground-water reservoir functions basically as a water-table system. Locally, where relatively impermeable materials overlie permeable materials, water in the permeable materials may be confined or semiconfined.

The depth to water is generally less than 10 feet below land surface in areas underlain by outwash and alluvium and less than 35 feet below land surface in areas underlain by ice-contact deposits.

Observations of water levels in many wells throughout the Lowell area show that the shape of the water table conforms roughly to the topography of the area. The water table is generally highest under the hills where it is also at greatest depth below the land surface. It intersects the land surface in most ponds and streams and in the swamps during at least part of the year. In the lowland areas, which are underlain chiefly by stratified deposits, the water table is virtually flat, and hydraulic gradients are generally small. In the hilly parts of the area, which are underlain chiefly by till and bedrock, the configuration of the water table is irregular, and hydraulic gradients are relatively large.

The ground-water reservoir is traversed by the Merrimack River, Stony Brook, Black Brook, River Meadow Brook, the Concord River, Beaver Brook, and smaller tributaries. The streams and the ground-water reservoir are closely interrelated. Under natural conditions the ground water moves from interstream areas toward the streams where it is discharged. In times of flood, however, or in places where the water table has been artificially lowered below the level of water in an adjacent stream or pond, the direction of movement may be reversed and water may move from the surface-water body to the ground-water reservoir.

RECHARGE

The source of almost all ground water in the Lowell area is precipitation within the area or immediately adjacent to it and infiltration from bodies of surface water such as the Merrimack River. Some ground water may enter the area as underflow, especially along the watercourses of the Merrimack and Concord Rivers and the watercourses of the smaller streams that enter the area. Hydraulic gradients are small, however, and the rate of underflow into the area is correspondingly small. Of the precipitation that reaches the land surface, part runs off overland and flows away in streams, part is returned to the atmosphere by evaporation and by transpiration from plants, and a part percolates downward to the zone of saturation, where it is stored temporarily as ground water. The process through which water is added to the zone of saturation is termed "recharge."

Recharge follows an annual cycle. During the growing season (p. Y6), most rainfall is retained in the soil to replace more or less continuing losses by evapotranspiration. Consequently, except during an unusually wet late spring or early summer, recharge occurs infrequently and then usually only in small amounts. From the middle of October to April, when plants are dormant, the soil-moisture requirement is generally small. Recharge then generally occurs in comparatively large amounts whenever there is much rain or snowmelt, except at times during the winter when frost impedes or prevents infiltration. Ordinarily, most of the annual recharge occurs during this part of the year.

The principal recharge areas are the outcrop areas of ice-contact deposits and outwash and alluvium. These deposits are sufficiently permeable to absorb water readily. The deposits commonly form terraces and plains whose flat surfaces retard surface runoff, thereby affording maximum opportunity for recharge whenever rain or snowmelt occurs. Under natural conditions, the infiltration of rain or snowmelt is the main source of recharge in these areas, but the infiltration of surface runoff from adjacent hills may be a source of recharge locally.

Outcrop areas of till and bedrock are also recharge areas, but here the quantity of recharge per unit area is comparatively small owing to the small permeability and storage capacity of till and bedrock and the relatively steep slopes of the land surface.

Where aquifers are situated favorably, recharge from streamflow may take place, provided the materials between the streambed and the water table are permeable enough to allow the movement of water. Under natural conditions, the water table in the Lowell area is higher than stream levels throughout most of the year, and ground water is discharged into streams. However, when the streams are in flood, the natural gradients are reversed, and streams may supply water to the ground-water reservoir. Much of this water drains back to the streams rather quickly after flood waters recede. Recharge from streamflow also takes place when the water table is lowered artificially by pumping ground water from permeable materials adjacent to streams. This results in a process known as induced recharge; this process is an important factor in sustaining the yields of many municipal and industrial well fields throughout the area.

ARTIFICIAL RECHARGE

Artificial recharge is the intentional addition of water to a ground-water reservoir. This may be done by water spreading in recharge canals or basins or by injecting water into recharge wells or infiltration galleries. Artificial recharge is not being practiced in the Lowell area at the present time, but it is a possible means of obtaining the optimum use of the water resources and the ground-water reservoir.

DISCHARGE

Ground water is discharged naturally by evapotranspiration, by effluent seepage to streams and other bodies of surface water, and through springs; ground water is discharged artificially by pumping from wells and springs.

Under natural conditions, the principal discharge areas are stream channels and the swamps; probably most ground water is discharged to streams. Except during times of flood or at places where the water table has been lowered by pumping, ground water seeps into the channels of most of the streams in the area from adjacent unconsolidated deposits. This effluent seepage, or ground-water runoff, accounts for the base runoff of many of the unregulated streams during dry weather and during cold weather when much of the precipitation is stored temporarily as snow or ice.

Ground water is discharged in swamps and other low places by effluent seepage when the water table is high enough to intersect the land surface. Ground water also is discharged in swamps and other low places by evaporation and transpiration at times during the growing season when the water table is at the land surface or only a short distance below the land surface.

Seepage springs discharge ground water in low places and at points of contact between bedrock and overlying unconsolidated deposits, and fracture springs discharge ground water from bedrock. The amount of ground water discharged by springs is very small. Seven springs were inventoried during this investigation; at the time of inventory only one, Mount Pleasant Spring near Black Brook in Lowell (Lowell 4sp), was used. The water was bottled and sold for drinking water. The others—Billerica 1sp and 2sp, Dracut 4sp, and Lowell 1sp, 2sp, and 5sp—are unused or used only occasionally as sources for drinking water.

Some ground water is discharged from the area as underflow through stratified drift along the Merrimack River at the eastern edge of the Lowell area. Compared to the amount of ground water discharged by effluent seepage and by evapotranspiration, the amount discharged by underflow probably is negligible.

Discharge is a continuing process. Ground-water runoff is generally greatest during or soon after periods of recharge, but it continues throughout periods of dry weather. Discharge by evapotranspiration is greatest during the growing season.

In addition to the natural discharge, ground water is discharged artificially by pumping in the Lowell area. The total amount discharged by pumping is roughly equal to the pumpage from municipal water supplies plus the estimated pumpage from other public supplies (mainly institutions) and industrial supplies. This amounted to about 11 mgd (million gallons per day) in 1959. Many individually owned wells supply water to families not served by public water supplies, but the amount is small compared to municipal and industrial pumpage.

Most of the ground water discharged by pumping in the Lowell area ultimately is returned to the Merrimack River and tributary streams in the area. Thus, the water is available for reuse downstream.

FLUCTUATIONS OF WATER LEVELS AND CHANGES IN GROUND-WATER STORAGE

The water table and the volume of water in ground-water storage fluctuate continually in response to changes in the ratio of recharge to discharge. A declining water table indicates that water is being discharged faster than it is being replenished (a net loss of ground-water from storage). A rising water table indicates that water is being replenished faster than it is being discharged (a net gain of ground water in storage). These fluctuations are illustrated by hydrographs for 4 wells (pl. 3).

Records of ground-water levels in these 4 wells and 8 wells for which records are not given in this report (Chelmsford 68, Lowell 4, 9, 18, 22, 26, 33, and 40) have been published in annual water-level reports for the years 1939–57 (U.S. Geological Survey, 1940–60).

The hydrographs show a marked seasonal fluctuation. Net recharge normally occurs in the late autumn, winter, and early spring (p. Y21). The water table is generally highest and the volume of water in storage greatest during this period. On the other hand, in the late spring, summer, and early autumn recharge is normally small, chiefly because most of the rainfall is intercepted in the soil zone and returned to the atmosphere by evapotranspiration. Also, during the growing season, some ground water is discharged by evapotranspiration. Therefore, the water table is generally lowest and the volume of water in storage smallest during the late summer and autumn.

The amplitude of water-level fluctuations and the rate at which they occur in most wells in the Lowell area depend partly on response to variations in the rates of recharge and discharge and partly on the nature of the materials penetrated and the topographic position. Water levels in till fluctuate through a much wider range than water levels in ice-contact deposits or outwash and alluvium (pl. 3), and water levels in upland areas generally fluctuate through a wider range than water levels in lowland areas. However, inasmuch as wells ending in till are located mostly in the uplands, and wells ending in ice-contact deposits or outwash and aluvium are located in the lowlands, the relative effects of recharge and natural discharge on water levels in wells penetrating different materials or located in various topographic positions are not easily separated.

Pumping causes a lowering of the water level in and around the pumped well. The hydrographs of wells Lowell 41 and Lowell 43 (pl. 3) illustrate the effects of pumping at the Cook and Pawtucket Boulevard well fields, respectively. The water levels in wells Lowell 41 and Lowel 43 show frequent steep declines during pumping of nearby wells and subsequent steep rises after pumping stops. The general decline of water levels from the beginning of record to about 1950 is probably the result of combined effects of below average precipitation and heavy pumping at the Pawtucket Boulevard and Cook well fields. The general rise of water levels since 1950 reflects the general increase in precipitation. The water levels in wells Lowell 41 and Lowell 43 and the water levels in other wells in the area which are not affected by pumping are at about the same level or at higher levels than at the beginning of record. This fact indicates that the recharge to the area during 1939–54 has about equaled discharge.

QUALITY AND TEMPERATURE OF WATER

The general chemical character of ground water in the Lowell area is indicated by the analyses of water from 13 wells, and for comparison, the chemical character of surface water is indicated by analyses of water from the Concord River and the Merrimack River. (See table 1.) Ground-water samples were collected from the principal water-bearing units. Table 1 includes analyses of 5 samples of ground water from wells in bedrock, 2 samples from wells in till, 4 samples from wells in ice-contact deposits, and 2 samples from wells in outwash and alluvium.

Chemical constituents, dissolved solids, and hardness of water data listed in table 1 are reported in parts per million (ppm) by weight. The accuracy and the completeness of the type of chemical analysis presented in table 1 can be checked by expressing the chemical constituents in terms of chemical equivalence. Parts per million can be converted to "equivalents per million," as is shown in figure 3. Equiv-

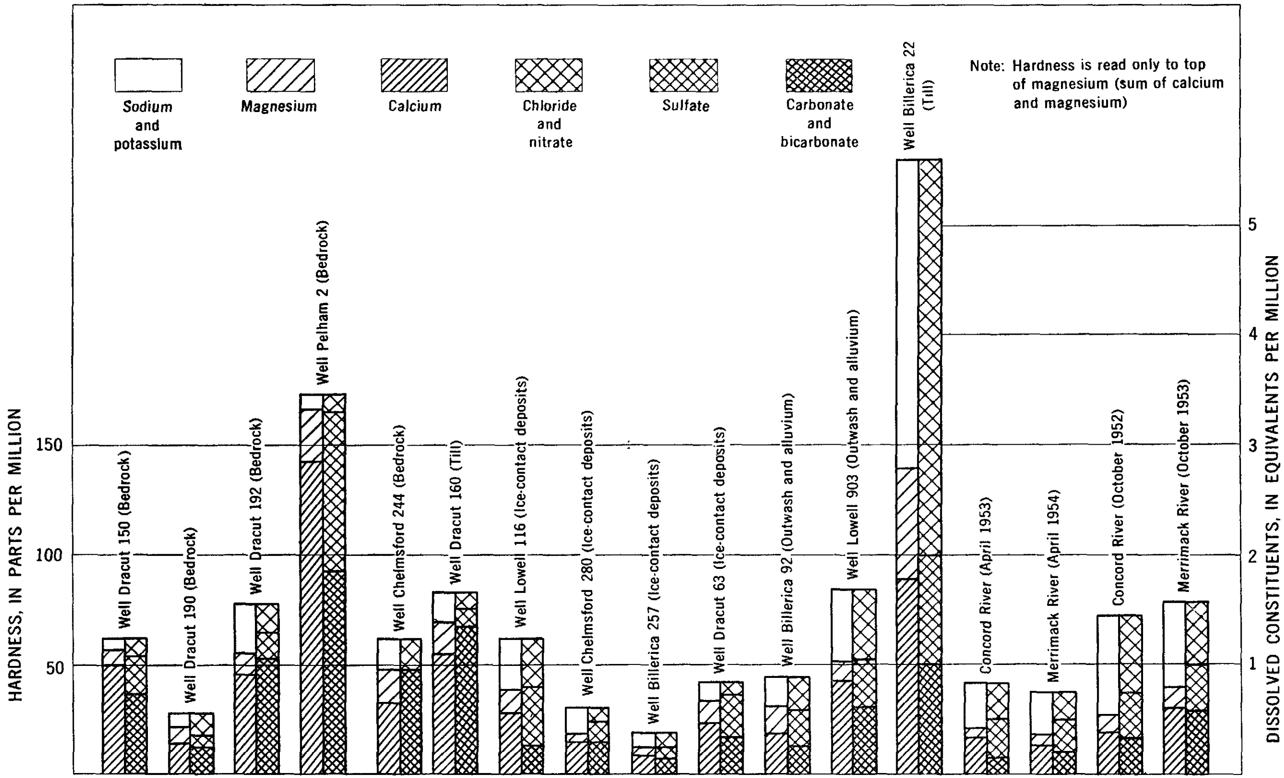

FIGURE 3.—Graphic representation of chemical analyses of ground water and surface water in the Lowell area, Massachusetts.

TABLE 1.—*Chemical analyses of water from wells*

[Chemical constituents, dissolved solids, and hardness

Well or river	Depth (feet)	Geologic unit	Date of collection	Temperature °F	Silica (SiO_2)	Aluminum (Al)	Iron (Fe)	Manganese (Mn)	Copper (Cu)	Zinc (Zn)
Billerica 22	23	Till	Jan. 12, 1955	46	14	0.0	0.32	0.00	0.00	0.34
92	36	Outwash and alluvium.	do	42	8.0	.0	2.0	.74	.00	.00
257	28	Ice-contact deposits	Mar. 5, 1954	54	8.7	.0	.13	.00	.05	.00
Chelmsford 244	73	Bedrock	June 16, 1954	54	17	-----	.78	.00	-----	-----
280	45	Ice-contact deposits	Jan. 12, 1955	50	14	.0	.05	.00	.00	.00
Dracut 63	35	do	Jan. 11, 1955	49	12	.0	.03	.00	.00	.00
150	173	Bedrock	June 16, 1954	54	9.8	-----	.34	.00	-----	-----
160	20	Till	Jan. 12, 1955	43	7.6	.1	.13	.00	.00	.22
190	105	Bedrock	June 11, 1954	53	7.4	-----	.41	.00	-----	-----
192	189	do	June 14, 1954	52	9.5	-----	.33	.01	-----	-----
Lowell 116	58	Ice-contact deposits	Jan. 11, 1955	49	14	.0	.84	.07	.00	.00
903	52	Outwash and alluvium.	do	51	16	.0	.15	.14	.00	.00
Pelham 2	250	Bedrock	June 14, 1955	49	8.1	-----	.24	.00	-----	-----
Concord River at Lowell.	-----	-----	Oct. 21, 1952	-----	5.2	-----	.51	-----	-----	-----
Do	-----	-----	Apr. 23, 1953	-----	1.5	-----	.19	.00	-----	-----
Merrimack River at Lowell.	-----	-----	Oct. 19, 1953	-----	7.1	-----	1.0	.00	-----	-----
Do	-----	-----	Apr. 30, 1954	-----	3.0	-----	.08	.00	-----	-----

[1] Residue on evaporation at 180°C.

alents per million are determined by dividing parts per million of each constituent by its equivalent (combining) weight. Theoretically, in a chemical analysis of water, the total equivalents of cations equal the total equivalents of anions. Thus, the two bars that express graphically the analysis of each water sample in figure 3 are of equal height. The plotting of analysis to show chemical combinations facilitates a comparison of water from different geologic units.

Table 2 lists the chemical constituents commonly found in ground water, the sources of these constituents, and the effects the constituents have on the use of water for ordinary purposes. Related data not listed in table 2 include the dissolved-solids content, hydrogen-ion concentration (pH), and hardness of water.

DISSOLVED SOLIDS

The dissolved-solids content refers to the residue left after evaporation of the water (at 180°C by Survey procedure) and, theoretically, consists of minerals dissolved by the water plus some organic matter and water of crystallization. It is not a measure of the total weight of dissolved constituents, however. According to standards set up by the U.S. Public Health Service (1961), water containing less than 500 ppm of dissolved solids is suitable for domestic and most industrial *and streams in the Lowell area, Massachusetts*

in parts per million. Analyses by U.S. Geol. Survey]

Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Lithium (Li)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Phosphate (PO_4)	Dissolved solids [1]	Hardness as $CaCO_3$: Calcium and magnesium	Hardness as $CaCO_3$: Noncarbonate	Specific conductance at 25°C (micromhos)	pH	Color [2]
36	12	24	56	2.3	61	47	56	0.0	127	0.00	444	140	90	644	7.5	5
7.8	2.7	6.1	1.4	.1	16	16	8.8	.0	2.6	.00	60	31	18	97	7.2	5
3.3	1.0	3.3	.8	.0	9.6	3.4	5.6	.0	.3	.00	33	13	5	44	6.4	2
13	3.8	6.1		-----	58	.5	9	.1	.3	-----	103	48	1	144	7.9	2
5.9	.8	3.4	1.0	.1	18	8.3	4.0	.0	.8	.00	43	18	3	66	6.8	3
9.4	2.6	3.1	1.6	.1	21	18	2.8	.0	2.7	.00	58	34	17	92	6.7	3
20	1.6	2.2		-----	44	17	5	.1	.4	-----	107	56	20	146	7.3	2
22	3.6	3.2	4.8	.2	81	8.5	1.5	.0	6.5	.00	99	71	4	162	7.8	3
5.5	.8	5.0		-----	15	5.6	5	.0	3.4	-----	49	17	5	69	7.1	2
18	2.3	11	------	-----	64	12	8	.1	1.8	-----	110	54	2	174	8.1	3
11	2.8	8.2	2.3	.2	16	25	14	.0	3.3	.00	87	40	26	137	7.0	5
17	2.3	11	3.2	.2	37	21	16	.0	12	.00	116	52	22	184	6.7	3
57	5.8	3.2		-----	112	70	3	.2	4.3	-----	239	166	74	375	8.2	2
7.6	2.0	18	3.0	-----	19	21	22	.5	2.9	-----	96	27	12	165	6.5	----
6.7	1.0	7.4	1.0	-----	9.3	17	10	.2	.9	-----	63	21	13	93	5.7	28
12	2.3	19	4.8	-----	36	19	16	.3	7.0	-----	133	40	11	190	6.7	42
5.9	.7	5.8	1.7	-----	12	14	7.8	.0	2.2	-----	61	21	11	83	6.1	20

[2] Color data were obtained by comparing color of water sample to the platinum-cobalt scale of Hazen (1892, p. 427–428).

use if the water is not hard or does not have excessive iron. None of the 13 samples of water from wells in this area contained as much as 500 ppm of dissolved solids. Water from well Billerica 22, which ends in till, had 444 ppm of dissolved solids, but the water is probably contaminated and not representative of water from till.

HYDROGEN-ION CONCENTRATION (pH)

The hydrogen-ion concentration, or pH, is an index of the acidity or alkalinity of water. Water with a pH of less than 7 is acidic, and water with a pH greater than 7 is alkaline. In this area, the water from bedrock and till is generally alkaline, and the water from ice-contact deposits and outwash and alluvium generally is acidic. Acidity greatly increases the capacity of water to dissolve minerals from the soils and rocks with which the water comes in contact and also renders it corrosive to pipes and plumbing.

HARDNESS

Hardness of water is of particular interest to the household consumer. Hard water requires a greater amount of soap to produce lather, and soap used with hard water forms a sticky, insoluble scum,

TABLE 2.—*Elements and substances commonly found in ground water* [1]

Constituent	Source	Significance
Silica (SiO_2)	Siliceous minerals—such as feldspars, pyroxenes, and amphiboles—in almost all formations.	Forms hard scale in pipes and boilers. Inhibits deterioration of zeolite-type exchange material in water softeners.
Iron (Fe)	The common iron-bearing minerals—such as pyroxenes, amphiboles, iron sulfides, and iron oxides—in most formations.	Oxidizes to a reddish-brown sediment (iron oxide). More than about 0.3 ppm in water solution stains laundry and utensils reddish brown and is objectionable for food processing and beverages; larger quantities impart taste and favor the growth of iron bacteria.
Manganese (Mn)	Manganese-bearing minerals, such as amphiboles and micas.	Rarer than iron; in general, has same objectionable properties; brown to black stain.
Calcium (Ca) and magnesium (Mg).	Feldspars, amphiboles, micas, limestone and dolomite. Gypsum also is a common source of calcium.	Cause most of the hardness and scale-forming properties of water; soap consuming.
Sodium (Na) and potassium (K).	Feldspars and other common minerals, ancient brines, sea water, industrial brines, and sewage.	Large amounts cause foaming in boilers and other difficulties in certain specialized industrial water uses.
Bicarbonate (HCO_3) and carbonate (CO_3).	Action of carbon dioxide in water on carbonate minerals.	In combination with calcium and magnesium form carbonate scale on application of heat and releases corrosive carbon dioxide gas.
Sulfate (SO_4)	Gypsum and from oxidation of iron sulfides. Common in water from coal-mining operations and many industrial wastes.	Sulfates of calcium form hard scale.
Chloride (Cl)	Sodium chloride deposits found in small to large amounts in all soils and rocks, natural and artificial brines, sea water, and sewage.	In large enough amounts can cause corrosion; objectionable for various specialized industrial uses of water.
Fluoride (F)	Fluorite (CaF_2) is principal source. Various complex minerals of widespread occurrence, such as apatite, hornblende, and the micas, in minute amount.	In excessive concentrations is undesirable in water used for drinking but as much as 1.0 ppm seems to reduce dental decay.
Nitrate (NO_3)	Decayed organic matter, sewage, nitrate fertilizers, nitrates in soil.	Values higher than the local average may suggest pollution. There is evidence that more than about 45 ppm NO_3—or about 10 ppm of nitrate expressed in terms of nitrogen (N)—may cause methemoglobinemia (infant cyanosis), which is sometimes fatal. Water of high nitrate content should not be used for baby feeding.

[1] California State Water Pollution Control Board (1952); Hem (1959).

which is difficult to remove from fabrics and containers. Hard water also forms scale when used in boilers.

Water that has less than 60 ppm of hardness is usually considered soft. Water that has 61 to 120 ppm of hardness is considered moderately hard and does not seriously interfere with the use of the water but does increase soap consumption. Hardness of 121 to 200 ppm is noticeable to nearly everyone, and—in many places—water containing more than 200 ppm of hardness is softened before using.

Hardness of ground water is not a serious problem in the Lowell area. Only three samples, one from a well in bedrock and two from wells in till, had a hardness of more than 60 ppm. Water from bedrock and till is harder than water from stratified deposits. In general, hardness of water in unconsolidated deposits is higher than that of water in bedrock.

IRON (Fe) AND MANGANESE (Mn)

Iron and manganese are the most objectionable chemical constituents in ground water in the Lowell area. Iron and manganese cause stains on textiles and fixtures if their combined concentration exceeds about 0.3 ppm. Precipitates that clog pumps, distribution systems, and fixtures may be formed if the iron concentration exceeds about 1 ppm. Sterling and Belknap (1932) reviewed the problem with respect to public water supplies in Massachusetts, and Barbour (1917) and S. M. Ellsworth (1942, written communication) [1] discussed the problem with particular reference to the municipal water supply for the city of Lowell. High concentrations of iron and manganese in the water was a critical factor leading to the abandonment by the town of Billerica and the city of Lowell of their wells as a principal source of water and to the construction of facilities to treat water drawn directly from the Concord and Merrimack Rivers.

The iron content of the 13 samples of ground water collected from wells in the Lowell area ranged from 0.03 to 2.0 ppm. The iron content in 9 samples of water from unconsolidated deposits ranged from 0.03 to 2.0 ppm and was more than 0.3 ppm in only 2 of the samples. The iron content in 5 samples of water from bedrock ranged from 0.24 to 0.78 ppm and was more than 0.3 ppm in 4 of the samples. Thus, on the basis of the 13 analyses, the iron content of water from unconsolidated deposits covers a wider range but is lower on the average than the iron content of water from bedrock.

Iron in ground water is derived from iron-bearing minerals in bedrock and mineral grains in the unconsolidated deposits. The principal sources of iron in the Lowell area are silicate minerals of dark-colored igneous rocks, such as pyroxenes, amphiboles, and dark ferromagnesium micas. Some iron is probably derived from sulfides, such as pyrite, and from oxides, such as magnetite.

Iron also may be derived from well screen, well casing, pump parts, pipes, storage tanks, and other iron objects that the water contacts. The amount of iron dissolved in water by contact with iron objects in the well or pumping equipment may be significant, but it is not of interest for geochemical interpretation. To obtain reliable information on the iron content of natural water, considerable care is necessary in sampling.

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[1] Ellsworth, S. M., 1942, Report on the Lowell water department: report to the city of Lowell (typewritten).

In its chemical behavior and its occurrence in natural water, manganese resembles iron, but the concentration of manganese in water is generally much less than the concentration of iron. The manganese content was 0.00 ppm in 9 of the 13 samples analyzed and ranged from 0.01 to 0.74 ppm in the remaining 4 samples.

TEMPERATURE

Ground water maintains a relatively constant year-round temperature, whereas surface-water temperature fluctuates widely from season to season in response to changes in air temperature. Ground-water temperatures, as indicated from single measurements at individual wells at the time they were inventoried, range from 42° to 62° F in wells in unconsolidated deposits and from 42° to 55° F in wells in bedrock. Because it is farther below the surface, water in bedrock is better insulated from effects of changing air temperatures than the water in unconsolidated deposits and therefore shows less temperature variation from well to well and season to season. Periodic measurements show that the annual temperature range of water in the Merrimack River at Lowell is from about 32° F in winter to about 75° F in summer.

USE OF GROUND WATER

In the Lowell area nearly all ground water withdrawn is for public water supplies. The development of ground water for public supplies began about the turn of the century: public supplies of the city of Lowell and the towns of Billerica, Chelmsford, and Dracut were drawn from wells. The quantity of ground water withdrawn was small at first, but it increased steadily over the years and in 1959 averaged about 10 mgd. Pumpage of ground water for public supplies for the period 1938–59 is given in table 3.

A relatively small amount of ground water is withdrawn from privately owned wells for industrial use. The amount of ground water withdrawn for industrial use in 1959 averaged only about 1 mgd. The water was used for cooling, processing, and washing.

Many privately owned wells supply ground water for domestic and stock purposes to families living in rural areas not served by municipal water supplies. Supplemental irrigation is practiced to only a small extent. Rural use of ground water is negligible compared to use for public and industrial water supplies.

TABLE 3.—*Pumpage of ground water for municipal supplies for Billerica, Chelmsford, Dracut, and Lowell, Mass., 1938–59*

[Compiled from municipal files and Massachusetts Department of Public Health files]

Year	Pumpage (millions of gallons)				
	Billerica	Chelmsford	Dracut	Lowell	Total
1938	127.6	124.5	74.4	1,918.7	2,245.2
1939	135.5	99.2	81.6	2,046.3	2,362.6
1940	118.4	105.3	88.0	2,057.4	2,369.1
1941	127.9	121.8	98.2	2,193.9	2,541.8
1942	113.1	117.3	73.1	2,459.0	2,762.5
1943	121.6	121.9	81.3	2,459.0	2,783.8
1944	128.6	144.2	81.2	2,596.9	2,950.9
1945	139.6	153.0	87.5	2,535.4	2,915.5
1946	153.9	160.9	108.4	2,688.4	3,111.6
1947	172.3	163.9	107.8	2,503.4	2,947.4
1948	178.9	178.3	128.4	2,478.5	2,964.1
1949	190.1	152.2	137.7	2,121.7	2,601.7
1950	208.3	175.0	155.0	2,530.2	3,068.5
1951	174.6	200.0	155.0	2,693.5	3,223.1
1952	191.8	230.3	156.6	2,780.6	3,359.3
1953	194.2	232.1	174.1	2,844.8	3,445.2
1954	208.1	217.6	189.0	3,013.6	3,628.3
1955	206.8	251.1	192.0	3,194.7	3,844.6
1956	(1)	280.3	188.0	3,006.7	3,475.0
1957	-----------	309.5	196.3	2,880.9	3,386.7
1958	-----------	322.1	238.0	2,916.3	3,476.4
1959	-----------	360 est	246.9	3,129.9	3,736.8
Total	2,891.3	4,220.5	3,038.5	57,049.8	67,200.1

1 Pumpage since Jan. 23, 1956, from Concord River.

APPRAISAL OF THE GROUND-WATER RESOURCES

Basically, three factors, singly or in combination—recharge, storage capacity, and the distribution of permeable materials—may limit the development of a ground-water reservoir. The following is a qualitative appraisal of the ground-water potentialities of the Lowell area in terms of these factors. For purposes of the appraisal three subareas are considered: (1) the Merrimack River watercourse,[2] (2) the Concord River watercourse, and (3) the abandoned valley of the preglacial Merrimack.

The Merrimack River watercourse occupies parts of Tyngsborough, Chelmsford, and Lowell. From the place where the Merrimack River enters the Lowell area to the mouth of Black Brook, the Merrimack River watercourse occupies the valley of the preglacial Merrimack. Under existing conditions the Merrimack River, a large perennial stream, is a potential source of continuing and almost unlimited recharge for its watercourse aquifer. The basic factor limiting the development of ground-water supplies from the watercourse aquifer is the distribution of relatively thick permeable materials through which wells can induce infiltration of water from the river.

2 In accordance with the usage of Thomas (1951, p. 136), the term "watercourse" is applied to a stream and its associated ground-water reservoir.

In this reach of the Merrimack River watercourse, the aquifer consists chiefly of outwash deposits which adjoin the river. Ice-contact deposits crop out along the periphery of the watercourse and wedge out beneath the outwash deposits toward the bottom of the preglacial Merrimack valley. In 1958, outwash deposits yielded water at the rate of about 4 mgd to municipal wells of Dracut and Lowell. Records of wells and test holes suggest that the outwash, which is traversed by the river, is relatively thick (at least 93 feet thick in test well Chelmsford 135) and moderately permeable at enough places to make substantial further development of ground water possible.

The surface reservoir formed above the dam across the Merrimack River at Lowell undoubtedly contributes considerable recharge to the watercourse aquifer. When the level of a stream is raised by a dam, the normal direction of ground-water movement toward the stream is reversed. Water from the reservoir formed behind the dam then moves into the aquifer and backs up ground water until the gradient of the water table is readjusted to the new level. Also, part of the streamflow is held back temporarily in the reservoir, thus providing greater opportunity for recharge from the stream.

Between the mouth of Black Brook and the eastern edge of the Lowell area, the Merrimack River watercourse aquifer consists chiefly of outwash. The available data suggest that the outwash in this part of the watercourse is relatively thin; therefore, substantial development is probably not possible.

The Concord River watercourse occupies parts of Bedford, Carlisle, Billerica, Chelmsford, Tewksbury, and Lowell. The Concord River is a potential source of continuing recharge for its watercourse aquifer. The basic factor limiting the development of ground-water supplies is the distribution of relatively thick permeable materials through which wells can induce infiltration of water from the river.

The watercourse aquifer consists chiefly of outwash deposits; ice-contact deposits crop out along the valley walls and wedge out beneath the outwash toward the bottom of the preglacial Concord River channel. Outwash deposits, which partly fill the channel of the preglacial Concord River, formerly furnished water at an average rate of 0.5 mgd to municipal wells of Billerica. Since 1956, however, the town of Billerica has obtained most of its water directly from the Concord River. The available data suggest that the stratified drift forming the watercourse aquifer of the Concord River is relatively thin; the greatest known thickness is about 43 feet (wells Billerica 93 and 97). The permeability of the ground-water reservoir materials is probably small to moderate, as inferred from the descriptions of the materials in drillers' logs and the specific capacity of 50 gpm per ft of well

Billerica 73. Thus, the quantity of water from the river that can be transmitted through the ground-water reservoir is limited by its relatively small saturated thickness and small to moderate permeability of the deposits. If further development in this area is warranted, wells should be placed as close to the river as possible to establish maximum hydraulic gradients during pumping. Furthermore, wells should be sufficiently dispersed to eliminate interference with each other, which would aggravate the already unfavorable situation of small permeability and small saturated thickness.

As pointed out earlier (p. Y13), if the preglacial Merrimack valley extends to the southeast from Lowell, the present Concord River must flow across the buried Merrimack channel. Thick deposits of permeable material should be found in the Concord River watercourse at this juncture. Therefore, further exploration may be justified in the Concord River watercourse between North Billerica and the mouth of River Meadow Brook in order to interpret the course of the preglacial Merrimack beyond well Lowell 96.

The abandoned valley of the preglacial Merrimack River extends from the watercourse of the Merrimack to the watercourse of the Concord River. The ground-water reservoir formed by the stratified drift in the abandoned valley underlies an area of about 7 square miles in Chelmsford and Lowell. It is formed chiefly of ice-contact deposits which, in 1958, yielded water at an average rate of more than 4 mgd to wells in Chelmsford and Lowell. This ground-water reservoir is traversed by Black Brook and River Meadow Brook. Information on the flow of Black Brook is lacking, but River Meadow Brook has never been known to go dry in the memory of some of the older residents in the area. Thus, annual recharge apparently is in excess of present ground-water withdrawal, and the surplus is discharged into the stream. Under this situation, ground-water withdrawals could be increased to at least the limit set by the low flow of the stream. If withdrawals are to be sustained at a larger rate, the additional water must be derived from storage.

If ground-water withdrawals were to be developed beyond the limit set by the low flows of the streams, and if the additional water were to be derived from ground-water storage, the distribution of thick permeable materials would be a critical problem. Over most of the reservoir area, the stratified deposits are thick enough to supply sufficient water for municipal use; the maximum thickness is 140 feet where they overlie the deepest part of the buried channel. Records of wells and test holes suggest that the stratified deposits, though variable in composition, contain permeable materials at enough places to permit dispersal of wells of at least moderate capacity in about 5 square miles of the reservoir area. Excluded are parts of the reservoir fringe where the deposits are thin. Also excluded are the part of the reservoir along the east side of River Meadow Brook about half a mile north of the Chelmsford-Lowell line and the part of the reservoir adjacent to Highway 110 between wells Chelmsford 278 and 265 where, on the basis of composition, these deposits are inferred to have a small permeability.

Knowledge of the hydrologic properties of ice-contact deposits and outwash and alluvium is too scanty to justify an accurate determination of the storage capacity of the ground-water reservoir. However, a crude estimate of the usable storage serves as a guide in determining whether use of the reservoir can be sustained or increased during long periods of no recharge. If the specific yield of the stratified drift were 20 percent (a conservative figure based on values of specific yield of similar deposits in nearby areas of northeastern Massachusetts), the dewatering of 4 feet of the ground-water reservoir over an area of 5 square miles would sustain an average withdrawal of at least 5½ mgd during a 5-month period.

For the part of the ground-water reservoir in the abandoned valley of the preglacial Merrimack River that is adjacent to the Merrimack River watercourse, the river is a potential source of continuing recharge. Under existing conditions, however, induced recharge to the reservoir from the Merrimack River is effectively prevented by the cone of depression around municipal supply wells Lowell 794, 795, 796, and 797, which are developed in the watercourse aquifer of the Merrimack River in the western part of Lowell. Also, between these wells and Highway 110 the reservoir is bounded on two sides by valley walls of till and bedrock which are relatively impermeable. Under these conditions, the drawdown in a heavily pumped well that is forced to draw water principally from ground-water storage during an extended dry period might lower the water level to the point where, by the end of an extended dry season, pumping could not be continued at the seasonal pumping rate. In order to sustain the yield during extended dry seasons, pumpage would have to be maintained at smaller rates from a larger number of wells carefully dispersed so as to avoid interference with each other.

For the part of the ground-water reservoir in the abandoned valley of the preglacial Merrimack River that may be adjacent to the Concord River watercourse, the Concord River is a potential source of continuing recharge. The problem is to locate the juncture of the preglacial Merrimack River valley and the Concord River (p. Y33) and then to locate areas where water could be induced from the river to wells.

Another factor that should be considered in the development of the ground-water reservoir in the abandoned valley of the preglacial Merrimack River is the possibility of artificial recharge. Should the reservoir be developed to the point where sustained withdrawals exceed the natural replenishment, water that under present conditions leaves the area by way of the Merrimack River might be diverted into recharge canals, basins, or wells to reduce the disparity. The feasibility of installing and managing artificial-recharge facilities should be carefully studied.

In addition to the three areas discussed, the watercourses of Stony Brook, Beaver Brook, and River Meadow Brook afford some potential for further development. The basic factors limiting the development of ground water in these watercourses is the rate at which withdrawals could be sustained during the seasonal period when little recharge from rainfall takes place and streamflow is lowest. Data are not sufficient to justify an appraisal of the ground-water potential in these three watercourses.

Development of the water resources at one place in a watercourse will affect the development or potential development at other places. For example, water diverted for water supply at a given point, whether from the ground-water reservoir or directly from a stream, would not be available for use downstream from that point unless it was returned to the watercourse. For this reason, the possible effects of development upstream from existing or potential water supplies should be carefully studied.

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