Geology and Ground-Water Conditions in the Wilmington-Reading Area Massachusetts

By JOHN A. BAKER, HENRY G. HEALY, *and* O. M. HACKETT

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1694

Prepared in cooperation with the Commonwealth of Massachusetts, Department of Public Works

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1964

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

The U.S. Geological Survey Library catalog card for this publication appears after the index.

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

CONTENTS

ILLUSTRATIONS

[Plates are in the pocket]

TABLES

GEOLOGY AND GROUND-WATER CONDITIONS IN THE WILMINGTON-READING AREA, MASSACHUSETTS

By JOHN A. BAKER, HENRY G. HEALY, and O. M. HACKETT

ABSTRACT

The Wilmington-Reading area, as defined for this report, contains the headwaters of the Ipswich River in northeastern Massachusetts. Since World War II the growth of communities in this area and the change in character of some of them from rural to suburban have created new water problems and intensified old ones. The purpose of this report on ground-water conditions is to provide information that will aid in understanding and resolving some of these problems.

The regional climate, which is humid and temperate, assures the area an ample natural supply of water. At the current stage of water-resources development a large surplus of water drains from the area by way of the Ipswich River during late autumn, winter, and spring each year and is unavailable for use during summer and early autumn, when during some years there is a general water deficiency.

Ground water occurs both in bedrock and in the overlying deposits of glacial drift. The bedrock is a source of small but generally reliable supplies of water throughout the area. Glacial till also is a source of small supplies of water, but wells in till often fail to meet modern demands. Stratified glacial drift, including ice-contact deposits and outwash, yields small to large supplies of water.

Stratified glacial drift forms the principal ground-water reservoir. It partly fills a system of preglacial valleys corresponding roughly to the valleys of the present Ipswich River system and is more than 100 feet thick at places. The ice-contact deposits generally are more permeable than the outwash deposits. Ground water occurs basically under water-table conditions.

Recharge in the Wilmington-Reading area is derived principally from precipitation on outcrop areas of ice-contact deposits and outwash during late autumn, winter. and spring. It is estimated that the net annual recharge averages about 10 inches and generally ranges from 5 inches during unusually dry years to 15 inches during unusually wet years. Ground water withdrawn largely by municipal wells supplies the towns of North Reading, Reading, and Wilmington. In 1957 the average daily withdrawal from these wells was about 2.5 million gallons, of which about half was used outside the Ipswich River drainage basin.

The chemical quality of the ground water is generally satisfactory except for local excessive concentrations of iron.

The storage capacity of the ground-water reservoir and recharge in the Wilmington-Reading area are large enough to sustain a total withdrawal of ground water at several times the current rate, but the use of the reservoir probably will be limited by the extent to which wells of moderate or large

capacity can be dispersed. This will depend upon the distribution of areas of thick permeable materials. Conditions in the Martins Brook-Skug River drainage basin seem generally favorable for increased development of water supplies. In the rest of the Wilmington-Reading area the chances of finding substantial bodies of thick permeable materials probably are small, but further exploration is desirable.

Measures proposed to drain swampland by deepening and straightening the Ipswich River and its tributaries will have some effect upon the ground-water conditions. Probably the most obvious effect will be a lowering of water levels in wells near improved reaches of channel. Also important will be the effect of changes in low streamflow conditions on wells that induce infiltration from streams and the effect on well yields of an improved hydraulic connection between streams and the ground-water body.

The Reading 100-acre well field, which derives part of its supply by inducing recharge from the Ipswich River, would be affected by the drainage measures. During a dry summer, such as that of 1957, the flow of the Ipswich is fully diverted by pumping at this well field, and drawdowns at some of the wells approach half the saturated thickness of the aquifer there. If the drainage measures are successful, the reduced flow of the stream during the dry period and the initially lower cone of depression, a consequence of the lower stream level in the improved channel of the Ipswich, will tend to decrease the capacity of this well field.

INTRODUCTION

LOCATION AND DESCRIPTION OF THE AREA

The Wilmington-Reading area includes about 43 square miles in northeastern Massachusetts. (See fig. 1.) Except for the east margin,

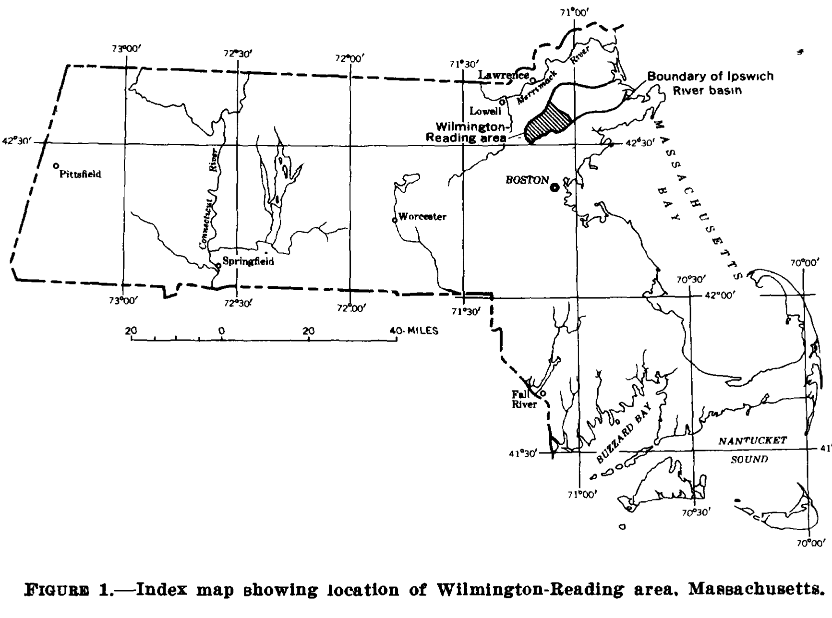

FIGURE 1.—Index map showing location of Wilmington-Reading area, Massachusetts.

which is in Essex County, the area is entirely within Middlesex County. It is about equally distant north of Boston, south of New Hampshire, and west of the seacoast. As defined for this report it consists of that part of the Ipswich River drainage basin above the Geological Survey stream-gaging station at South Middleton. (See pl. 1.)

Included in the area are large parts of the towns of North Reading and Wilmington, about half of Reading, small parts of Andover, Billerica, Burlington, Lynnfield, Middleton, and North Andover, and small parts of the cities of Peabody and Woburn. Before World War II most of the towns were rural in character. However, they are within ready commuting distance of Boston, Lowell, and Lawrence, and in sharing the general growth of the Boston area after World War II they have become increasingly suburban.

State Highway 28 connects the area with Boston, which is about 15 miles to the south, and Lawrence, which is about 5 miles to the north. Interstate Highway 93, under construction parallel to and 1 to 2 miles west of State Highway 28, will make Boston and Lawrence even more accessible and will offer a direct route northward into New Hampshire. State Highway 128, a circumferential highway around Boston, passes from southwest to northeast along the south edge of the area. In addition, an adequate network of paved highways makes the area readily accessible from surrounding communities.

PURPOSE AND SCOPE OF THE REPORT

This report covers the first phase of an investigation of water resources in the Ipswich River basin by the U.S. Geological Survey in cooperation with the Commonwealth of Massachusetts, Department of Public Works. The report has been prepared in response to the need for information on the water resources as a basis for solving present and future water problems.

The Wilmington-Reading area forms the upstream section of the Ipswich basin. The towns of North Reading and Wilmington derive their water supply from wells in this part of the basin. Also, the town of Reading, which is only partly within the Ipswich basin, derives its water supply from wells within the basin. The cities of Lynn and Peabody derive part of their water supply directly from the Ipswich River.

Since World War II the growth of the communities within the Wilmington-Reading area and expansion of the area to include communities once dominantly rural in character have created new water problems and intensified old ones. The suburban communities are confronted not only by the recurring problem of where to get new supplies of water to meet the increasing demand but also by the continuing problem of how to develop and manage the water resources most effectively. In addition, these communities face the two-fold problem of anticipating the effects of land-use changes upon the water resources and of resolving conflicts of interest in the uses of land and water resources.

This report deals principally with the geologic and hydrologic conditions controlling the occurrence of ground water in the Wilmington-Reading area and with the possibilities of increased development of the ground-water resources. The surface waters are discussed as they bear upon the development of ground-water supplies, but a description of the characteristics of the streams in the area is reserved for a subsequent report, which will cover the last phase of the Ipswich River basin study. At the request of the Massachusetts Department of Public Works a section of the present report describes the elements of hydrology that relate to a proposal by that department for the drainage of swampland in Wilmington, Reading, and North Reading; special attention is given to the probable effect of the proposed drainage measures upon the Reading municipal water supply. In an earlier paper, which was based principally on information gathered for this report, Baker (1960) identified some of the problems that need further study in order to clarify the role of wetlands or swamps in relation to water supply.

ACKNOWLEDGMENTS

This investigation was under the general direction of J. E. Upson and O. M. Hackett. Most of the fieldwork was done during the summers of 1955–57 by Henry G. Healy. Assisting with fieldwork were Richard J. Hecht, Jōan Canzanelli, and John K. Colby. Analyses of ground water were made by the Quality of Water Branch of the Geological Survey. Analyses of rock materials for particle size and hydrologic properties were made by the Hydrologic Laboratory of the Geological Survey.

Surface-water work in support of the investigation was performed by the Surface Water Branch of the Geological Survey. Miscellaneous measurements of streamflow were made by Richard A. Brackley and interpretations of base flow were by C. E. Knox.

Preliminary surficial geologic maps of the Wilmington and Reading quadrangles by Robert O. Castle and Robert N. Oldale, respectively, were furnished by the Geologic Division of the Geological Survey. The map of the Wilmington quadrangle has since been published (Castle, 1959). Seismic data gathered by the Geological Survey in Wilmington were interpreted by C. R. Tuttle of the Geologic Division.

The Massachusetts Department of Public Works furnished the results of seismic surveys made by the Weston Observatory for that department in support of the ground-water investigation in the Wilmington-Reading area.

The writers gratefully acknowledge the help of well owners, drillers, consultants, and owners and operators of public and industrial water-supply systems. Special acknowledgment is given to James T. Putnam, Superintendent of Public Works, Reading, Mass., and Edmund H. Sargent, Superintendent of the Wilmington Water Department, for their helpful cooperation in supplying data on the water supplies for their respective towns.

PREVIOUS INVESTIGATIONS

The geology of parts of the area and of adjacent areas has been discussed in several reports. A report by Emerson (1917) describes the geology of Massachusetts and Rhode Island and includes a map showing the distribution of bedrock formations in the two-state area. Reports on Essex County by Sears (1905) and Clapp (1921) include geologic maps of bedrock and of some glacial features. Reports by Robert O. Castle describe the surficial geology of the Wilmington quadrangle (Castle, 1959), which forms the western half of the area, and the surficial geology of the Lawrence quadrangle (Castle, 1958), which is adjacent to the Wilmington quadrangle on the north. A report by Mills (1903) describes the so-called Ballardvale delta plain about 1 mile northwest of the area, and a report by Chute (1960) describes the geology of the Mystic Lakes-Fresh Pond buried valley area south of the Wilmington-Reading area.

Two 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 Massachusetts Coastal Region. The other, by I. B. Crosby (1937), describes the occurrence of ground water in relation to buried valleys in northeastern Massachusetts.

METHODS OF INVESTIGATION

Fieldwork for the Wilmington-Reading area investigation included inventorying wells, test holes, and springs; collecting water samples for chemical analyses; collecting samples of rock materials for analyses of physical and hydrologic properties; exploring the subsurface geology by drilling and seismic methods; measuring water levels periodically in a network of observation wells; and making miscellaneous measurements of streamflow at several points along the Ipswich River and some of its tributaries.

The geologic map was compiled largely from a surficial geologic map of the Wilmington quadrangle by Castle (1959) and a preliminary surficial geologic map of the Reading quadrangle by Robert N. Oldale (written commun.). The small part of the area that lies in the South Groveland quadrangle was mapped by Henry G. Healy.

Basic data collected during this investigation but not incorporated in the report include records of about 680 wells or groups of wells and test holes, logs of 290 wells and test holes, periodic measurements of ground-water levels in 35 observation wells, and continuous records of ground-water levels in 4 wells. These data are included in a report by Baker and Sammel (1961). The locations of wells, test holes, and springs are shown on plate 1.

GENERAL FEATURES OF THE AREA

CLIMATE

The climate of the Wilmington-Reading area is humid and temperate and is characterized by fairly uniform monthly precipitation, warm summers, and cold winters. Based on records for the period 1931–55 at Lowell, which is about 7 miles northwest of the Wilmington-Reading area and is the nearest station where temperatures are recorded by the U.S. Weather Bureau, the coldest month is January with a mean temperature of 26.6° F, and the warmest month is July with a mean temperature of 73.7° F. The mean annual temperature is 49.8° F. The average growing season lasts about 165 days, from late in April to about the middle of October.

Precipitation is measured at stations in Reading and Wilmington. Data for these stations, compiled from records of the Massachusetts Department of Public Health, are given in table 1. For convenience in comparing precipitation and runoff later in this report the data are tabulated on a water-year (October 1–September 30), rather than a calendar-year, basis.

The average annual precipitation at Reading, which has the longer period of record, is 40.94 inches. The least annual precipitation, recorded for the 1957 water year, is 26.92 inches and the greatest, recorded for the 1938 water year, is 58.56 inches. Precipitation generally is distributed fairly evenly throughout the year; an average of 2.98 inches falls in October, the driest month, and an average of 3.81 inches falls in April, the wettest month. Based on records of precipitation at Lowell, Lawrence, and Middleton, the mean annual snowfall is in the order of 50 inches—equivalent to about 5 inches of water. Ordinarily more than three-fourths of the annual precipitation falls when the soil is frost-free.

TABLE 1.—*Monthly and annual precipitation, in inches, at stations in the Wilmington-Reading area, Massachusetts*

[Data from the Massachusetts Dept. Public Health]

Water year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Total
Reading, Mass. (waterworks pumping station). Lat 42°32′55″ N., long 71°07′55″ W. Alt 80 ft													
1899	-------	-------	-------	4.00	3.26	6.48	2.56	1.33	3.36	3.15	1.91	4.67	-------
1900	1.35	2.95	1.50	5.32	8.69	5.03	2.15	4.60	3.13	1.90	3.17	4.15	43.94
1901	3.31	5.05	2.44	1.33	1.08	5.88	9.59	7.19	1.74	4.65	2.66	3.59	48.51
1902	2.67	3.06	8.10	1.80	6.11	4.69	6.22	1.69	1.98	3.02	3.75	4.01	47.10
1903	4.91	.99	5.60	3.84	3.16	6.38	4.95	.48	8.91	3.40	3.42	2.29	48.33
1904	3.69	1.33	2.59	4.42	2.21	2.21	9.90	3.56	2.56	1.88	4.26	5.16	43.77
1905	2.02	1.80	2.25	5.44	1.47	2.92	2.59	1.39	6.11	1.19	3.30	7.87	38.35
1906	1.20	2.22	3.72	2.60	2.53	6.48	2.84	5.14	2.63	5.88	4.18	1.36	40.78
1907	2.38	3.31	3.08	3.97	2.10	2.04	3.21	2.89	3.80	3.58	1.33	7.90	39.59
1908	3.36	6.83	3.60	3.07	4.28	2.72	1.71	4.00	1.58	3.01	4.07	.86	39.09
1909	3.56	1.10	2.66	4.17	5.33	3.57	3.95	1.97	2.14	3.59	2.75	3.74	38.53
1910	1.23	4.06	3.60	4.54	3.14	1.58	2.32	1.19	4.36	1.98	2.61	2.45	33.06
1911	1.48	4.30	1.92	2.25	2.94	3.31	1.89	.60	3.90	4.79	3.30	2.94	34.12
1912	2.91	4.14	3.57	2.72	2.42	5.04	4.05	5.73	.29	6.44	2.02	3.02	42.35
1913	1.45	3.10	4.80	2.48	2.64	4.51	3.76	3.45	.93	1.68	3.47	3.66	35.93
1914	7.56	2.13	3.23	3.34	3.65	4.09	6.32	2.76	1.44	2.34	2.78	.23	39.87
1915	1.51	2.92	3.69	5.52	3.54	Tr.	2.72	1.68	1.70	11.66	6.66	.70	42.30
1916	2.80	2.93	5.47	1.22	5.37	3.37	5.14	4.59	5.86	3.13	2.30	3.11	45.29
1917	1.01	1.94	2.91	2.92	2.41	4.18	2.90	4.00	4.78	1.19	3.40	1.46	33.10
1918	5.76	1.39	2.66	2.92	3.02	2.02	4.10	.85	3.04	2.99	2.81	8.37	39.93
1919	1.02	2.24	2.06	3.68	3.61	4.01	2.46	5.44	.88	3.22	3.83	5.65	38.10
1920	2.63	6.20	1.53	2.75	6.46	4.18	5.75	3.27	5.27	1.94	2.02	4.27	46.27
1921	1.16	5.30	4.77	2.09	3.43	2.16	5.48	1.86	3.97	9.79	1.96	1.74	43.71
1922	1.53	6.43	2.28	1.77	2.72	4.27	1.37	5.08	11.27	4.88	3.29	3.68	48.57
1923	2.73	1.06	3.13	6.95	1.67	2.60	5.09	1.56	2.89	1.97	3.17	.82	33.64
1924	3.73	4.13	4.83	3.77	2.55	1.71	5.25	3.10	2.53	2.70	4.80	7.95	47.05
1925	.05	2.56	1.52	4.29	2.14	7.66	2.95	2.05	5.62	3.13	2.37	2.16	36.50
1926	4.66	3.94	5.53	2.53	4.41	2.83	2.26	2.19	1.80	2.08	3.30	1.32	36.85
1927	3.95	3.89	3.09	2.32	3.39	1.30	1.43	2.19	2.27	3.04	5.28	2.68	34.83
1928	4.10	4.18	4.65	2.10	3.37	1.45	5.13	2.77	6.63	3.65	3.84	4.18	46.14
1929	2.96	2.28	2.57	3.14	3.76	3.49	6.81	3.50	1.23	1.19	4.53	2.41	37.87
1930	2.49	2.88	3.63	2.48	2.05	3.29	1.90	3.38	2.19	4.07	2.77	.79	31.92
1931	4.45	3.69	2.20	3.27	2.72	4.94	3.07	3.53	6.70	3.76	4.11	1.97	44.41
1932	2.43	1.26	3.67	3.92	1.90	4.83	2.01	1.17	1.81	2.04	5.09	7.24	37.37
1933	7.26	5.25	1.29	2.27	3.46	7.22	6.51	2.70	1.27	1.47	4.41	9.97	53.08
1934	3.50	.96	3.47	3.17	3.29	5.13	3.09	2.52	4.00	1.25	1.73	6.43	38.54
1935	3.89	2.03	2.70	6.13	3.23	1.06	4.72	1.44	6.21	2.67	1.98	4.03	40.09
1936	.58	4.36	.90	6.60	3.09	7.23	3.01	2.05	2.73	1.75	4.49	4.15	40.94
1937	1.59	1.37	8.24	4.50	1.80	3.21	4.61	3.13	3.45	.97	3.91	3.04	39.82
1938	4.48	5.18	4.89	4.08	2.07	2.11	3.12	3.51	7.18	11.42	2.19	8.33	58.56
1939	2.93	1.86	2.85	2.08	3.48	4.00	4.47	2.02	2.77	.73	3.13	2.45	32.77
1940	4.66	.77	2.92	2.22	4.34	3.68	4.65	3.52	2.41	2.58	.80	4.59	37.14
1941	1.05	6.67	2.73	3.16	1.88	2.51	1.87	2.24	2.09	3.66	3.05	.58	31.49
1942	2.13	2.38	4.08	4.25	2.98	7.20	2.02	3.34	3.19	5.08	1.82	2.18	40.65
1943	2.99	4.72	5.61	3.09	1.03	3.57	2.60	5.54	2.09	4.79	1.35	.67	38.05
1944	5.84	4.45	1.02	2.63	2.26	4.22	3.84	.83	5.32	2.56	2.83	7.22	43.02
1945	2.65	6.03	3.18	2.60	4.40	1.79	2.85	4.28	5.90	3.07	3.07	1.19	41.01
1946	2.62	7.77	6.41	3.91	3.06	1.57	2.74	5.26	3.39	1.90	8.64	2.37	49.64
1947	.37	1.02	4.09	3.10	1.03	3.69	4.91	3.27	2.58	5.83	1.44	3.33	34.66
1948	9.44	6.24	4.05	4.33	2.11	2.84	2.63	5.38	4.63	4.83	1.08	1.00	39.56
1949	3.08	5.41	1.41	3.47	3.28	1.25	4.25	3.37	.84	1.78	5.05	4.28	37.47
1950	1.93	3.03	1.86	4.41	3.12	3.67	1.95	1.38	1.38	1.91	4.19	1.56	30.39
1951	3.27	6.31	3.53	3.33	3.79	4.76	1.87	4.74	3.47	4.72	2.11	1.77	43.67
1952	5.15	6.84	4.56	4.65	3.71	3.67	4.45	5.14	1.50	.93	8.85	1.83	51.28
1953	1.32	2.27	4.14	6.72	2.96	7.57	5.43	4.81	1.09	2.31	.61	1.46	40.72
1954	5.52	5.91	3.81	2.34	2.53	3.13	3.93	10.97	1.46	2.16	5.89	9.92	57.56
1955	1.61	5.27	5.25	.63	3.06	4.17	3.18	1.86	3.29	1.17	12.45	.47	42.41
1956	8.95	5.88	1.02	7.80	4.59	6.27	4.13	1.33	1.57	1.93	1.35	3.29	48.11
1957	3.06	4.09	4.73	1.83	1.22	2.32	3.10	2.49	.78	1.13	1.65	.52	26.92
58-yr. avg	2.98	3.64	3.47	3.48	3.13	3.73	3.81	3.20	3.28	3.24	3.46	3.45	40.94
Wilmington, Mass. (waterworks). Lat 42°34′55″ W., long 71°08′50″ W Alt 80 ft													
1934	-------	-------	2.68	2.92	3.59	4.77	3.05	2.58	4.88	1.20	1.85	5.69	-------
1935	3.38	2.60	2.37	6.16	2.56	1.55	4.06	1.22	5.81	1.83	1.22	4.13	36.89
1936	.58	4.66	.90	5.88	2.71	6.65	3.39	2.22	2.76	2.01	5.31	4.24	41.31
1937	1.93	1.27	7.92	4.23	1.85	3.25	3.88	2.86	3.31	.96	4.38	2.91	38.75

TABLE 1.—*Monthly and annual precipitation, in inches, at stations in the Wilmington-Reading area, Massachusetts*—Continued

Water year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Total
Wilmington, Mass.—Continued													
1938	4.34	4.86	4.07	3.79	1.94	1.86	2.67	3.48	6.54	11.49	2.73	8.38	56.15
1939	2.46	2.43	2.81	1.45	3.00	3.41	4.32	2.46	3.40	.47	3.49	3.05	32.75
1940	4.65	.96	2.94	1.98	3.34	3.29	4.44	3.56	1.92	2.31	1.05	3.59	34.03
1941	1.10	6.03	2.57	2.35	1.68	1.25	1.42	1.84	2.11	3.65	3.02	.15	27.17
1942	2.08	1.80	3.58	3.65	2.60	6.44	1.46	2.35	3.46	5.57	1.57	1.74	36.30
1943	3.01	4.13	5.38	2.56	.99	2.86	2.70	5.36	2.24	6.28	1.39	.39	37.29
1944	5.01	4.35	.92	2.68	2.07	3.82	3.16	.61	5.05	2.67	3.69	6.29	40.32
1945	1.85	5.59	2.63	2.36	3.23	1.59	2.39	3.94	6.21	3.07	2.84	1.39	37.09
1946	2.39	6.50	5.62	3.67	2.66	1.52	2.48	4.82	3.43	1.21	7.55	2.80	45.15
1947	.56	.98	3.55	2.57	.95	3.22	4.80	3.20	2.63	6.29	1.36	2.73	32.84
1948	.42	5.54	3.10	4.17	1.88	2.35	2.67	5.03	5.13	3.17	1.33	.98	35.77
1949	2.60	5.30	1.46	3.45	3.02	1.12	3.75	3.75	.81	1.79	5.46	4.61	37.12
1950	1.92	2.69	1.72	4.34	2.71	3.51	2.20	1.52	1.98	2.60	4.02	1.20	30.41
1951	3.20	6.43	3.24	3.04	3.36	4.59	2.47	4.69	3.09	5.07	2.36	1.91	43.45
1952	5.22	7.00	3.78	4.22	2.61	2.84	4.31	5.17	2.28	1.71	6.74	2.01	47.89
1953	1.50	1.79	3.57	4.86	3.32	8.16	5.47	3.99	2.09	3.94	3.06	1.43	42.18
1954	5.42	6.06	4.12	2.33	3.06	3.08	4.80	10.69	2.24	3.05	7.32	9.63	61.80
1955	2.12	4.57	5.28	.63	2.81	3.51	3.54	2.18	3.33	.92	13.48	2.76	45.13
1956	9.67	5.00	.96	6.14	3.88	4.35	3.05	2.52	2.18	3.02	1.43	3.69	45.89
1957	3.68	3.54	4.68	2.22	1.08	1.91	2.87	3.22	1.24	1.66	2.94	.89	29.93
23-yr. avg	3.00	4.09	3.35	3.42	2.49	3.31	3.31	3.50	3.18	3.22	3.81	3.08	39.80

TOPOGRAPHY AND DRAINAGE

The Wilmington-Reading area lies within the Seaboard Lowland section of the New England physiographic province (Fenneman, 1938, p. 370–373). The Seaboard Lowland is a relatively long, narrow coastal border region that extends for a distance of about 300 miles from eastern Connecticut to the Maine-New Brunswick border. In northeastern Massachusetts it is about 50 miles wide, poorly drained, and has low to moderate relief.

The topography of the Wilmington-Reading area is characterized by rounded hills or groups of hills and relatively broad lowlands. The summits of most of the hills are at altitudes of about 200 feet. However, Holt Hill and Boston Hill in the northern part of the area rise to altitudes of 420 feet and 385 feet respectively. The lowlands, which include terraces and terracelike features interspersed with extensive swamps, range in altitude from about 60 to 140 feet. The maximum relief of the area is 370 feet. The highest point is the crest of Holt Hill; the lowest point, altitude 50 feet, is where the Ipswich River leaves the area at South Middleton. Local relief is generally less than 100 feet.

The area is drained by the Ipswich River system (pl. 1). The Ipswich heads in Wilmington, flows eastward across the area, and thence northeastward to the Atlantic Ocean. The principal tributaries joining the Ipswich River from the north are Lubber Brook and Martins Brook; the latter is joined at Martins Pond by the Skug

River. The principal tributaries joining the Ipswich River from the south are Maple Meadow Brook and Bear Meadow Brook. The stream gradients generally are low—the gradient of the Ipswich River averages about 6 feet per mile. Swamps form about one-fourth of the area. They border most of the streams and at places extend across poorly defined divides into adjacent drainage basins. There are a few small ponds and lakes, of which the largest are Martins Pond, Pond One, and Silver Lake.

SOILS AND LAND COVER

According to the soil survey of Middlesex County (Latimer and Lanphear, 1929) the soils of the Wilmington-Reading area, except those of the swamps, are classified principally in the Gloucester, Merrimack, and Hinckly series. These soils are described as having formed on glacial drift, but it is probable that at many places in the Wilmington-Reading area they were formed on a thin veneer of wind deposits. Wind deposits were noted by Castle (1959) and Oldale (oral commun.) during recent geological investigations. In general, however, the Gloucester soils occupy areas of glacial till and the Hinckly and Merrimack soils occupy areas of stratified glacial drift. Soils in the swamps are classified principally as peat and muck but include some meadow soils.

The soils of the Wilmington-Reading area, except those of the swamps, are sandy and well drained. The Soil Conservation Service, which classifies soils into four general groups with respect to infiltration and runoff potential (U.S. Dept. Agriculture, 1957, p. 3.7–1 to 3.7–11) places the Hinckly soils in the highest group with respect to infiltration (lowest surface runoff potential) and the Merrimack and Gloucester soils in the next lower group.

Land-cover types in Massachusetts have been mapped by the University of Massachusetts in cooperation with other agencies from aerial photos taken in 1951–52 (MacConnell, 1957). On the basis of the land-cover maps for the Wilmington and Reading quadrangles and a statistical summary of land-cover types for the towns in Middlesex County (Massachusetts Cooperative Wildlife Research Unit, 1959), it is estimated that about 70 percent of the Wilmington-Reading area is forested, about 10 percent is open land, about 5 percent has a cover typical of wetland, and about 15 percent is urban. The forest cover includes both hardwoods and softwoods but hardwoods predominate. Most of the swampland is forested but about one-fifth (about 5 percent of the total Wilmington-Reading area) is wetland from the standpoint of distinctive cover, which according to MacConnell (1957, p. 160–161) includes fresh-water meadow commonly identified by the reed Juncus, shallow fresh-water marsh marked by cattails, deep fresh-water marsh, shrub swamp, and open water. The open land consists principally of agricultural land and abandoned fields now reverting to forest; it also includes a few orchards.

SUMMARY OF GENERAL HYDROLOGY AND WATER SUPPLY

The source of water in the Wilmington-Reading area is precipitation within the area. This, except for small amounts returned to the atmosphere by evaporation, either flows overland to streams, ponds, or swamps within the area or infiltrates the soil. Of the water that enters the soil, part is stored temporarily as soil moisture and is subsequently returned to the atmosphere by evaporation or by transpiration from plants; the remainder percolates downward through the porous rock materials to the water table where it joins the ground-water body.

Ground water, as defined by Meinzer (1923, p. 21–22), is the water stored in the zone of saturation—a zone in which the rocks are saturated with water under hydrostatic pressure. A water table is the upper surface of a zone of saturation except where that surface is formed by an impermeable body.

Storage as ground water is temporary because ground water moves slowly downgradient under the force of gravity from the interstream areas toward the streams, ponds, and swamps. Enroute some of it is evaporated or transpired to the atmosphere. The remainder seeps into streams or other bodies of surface water. During times of bank-full stage or flood the direction of ground-water movement adjacent to streams or ponds or in the swamps may be reversed temporarily and surface water then may recharge—that is, replenish—the ground-water body.

Regardless of the devious paths followed by the precipitation after reaching the ground, water ultimately is disposed of in two ways: (1) it is returned to the atmosphere by evapotranspiration (a composite term for evaporation and transpiration), or (2) it drains from the area, principally as runoff. The part of the precipitation that is returned to the atmosphere by transpiration plays a significant role in the growth processes of plants, but it cannot be used directly by man nor have techniques yet been devised to alter or control substantially the discharge of water by evapotranspiration. The part of the precipitation that drains from the area is subject to recovery and use by man. In this sense it constitutes his manageable water supply.

Runoff is defined (Langbein and Iseri, 1960, p. 17) as that part of the precipitation that appears in surface streams. It is the same as streamflow unaffected by artificial diversions, storage, or other works of man in or on the stream channels. On the basis of how soon runoff appears after rainfall or melting snow, it may be classified as direct runoff, which is directly associated as to time with causitive rainfall or melting snow, and base runoff, which is the sustained, or only flow, in fair weather. Base runoff continues also during times of direct runoff. On the basis of source, runoff may be classified as (1) surface runoff, which travels over the soil surface to the nearest stream channel, (2) ground-water runoff, which is derived by seepage from the main ground-water body, and (3) storm seepage, which is derived by seepage from shallow, perched ground water above the main ground-water body. Direct runoff ordinarily consists of surface runoff and storm seepage. Base runoff consists largely of ground-water runoff but may also include surface runoff. For example, in the Wilmington-Reading area the base runoff at times consists only of ground-water runoff, but at other times it may include surface runoff from swamp storage (surface water temporarily stored on the swamps).

Except for water diverted to other drainage basins, nearly all water draining from the Wilmington-Reading area is measured as streamflow at the Geological Survey gaging station on the Ipswich River at South Middleton. Beginning with the 1939 water year, records of runoff at this gaging station, which measures almost all the outflow from the Wilmington-Reading area, have been published annually in Water-Supply Papers of the Geological Survey. This report includes estimates of runoff at South Middleton for the period 1930–38; these estimates are based on a comparison of runoff at South Middleton with that at the stream-gaging station on the Ipswich River near Ipswich, near the mouth of the river. The mean annual runoff at South Middleton is a measure of the net manageable water supply for the Wilmington-Reading area. The gain or loss in ground-water, soil-moisture, swamp, or pond storage is not included in the runoff figure. However, over a period of years the annual gains and losses approximately balance out, and the net gain or loss is insignificant in comparison with the total runoff from which the mean is computed. Also, some unmeasured water leaves the area as underflow at the gaging station or may enter or leave the area wherever swamps lie athwart the drainage divide at the border of the basin. Because of the low gradient of the river and the small cross-sectional area of saturated permeable rock material underlying or adjacent to the channel the quantity of underflow at the gaging station is small—estimated to be less than 0.1 cfs (cubic feet per second). The quantity of water enter-

718-172 O—64——2

ing or leaving the area through the swamps is small too because of the low hydraulic gradients there. In comparison with the runoff the quantity of unmeasured water entering or leaving the area is insignificant.

For a 30-year period—water years 1930–59—the mean annual runoff was 21.96 inches (about 16 billion gallons of water per year). The least annual runoff was 10.52 inches (about 8 billion gallons per year), and the most annual runoff was 35.28 inches (about 26 billion gallons per year). During the same period the mean annual precipitation as computed on the basis of records at Reading, Wilmington, Middleton, and North Andover was 41.18 inches. The difference between mean annual runoff and precipitation, 19.22 inches, is a reasonable measure of the mean annual discharge of water by evapotranspiration.

The largest annual withdrawal—by withdrawal is meant the removal of water from the ground or its diversion from a stream or lake for use—from the Wilmington-Reading area during the period 1930–59 was 3.56 billion gallons, or 4.72 inches, in 1944. This figure is about 22 percent of the average annual runoff and about 45 percent of the least annual runoff. On the average, about 10 percent of the water withdrawn was returned to the drainage basin and became available for further use; most of the remainder was diverted to other drainage basins. Figure 2 compares the largest annual (1944) withdrawal with the gross natural supply, represented by the mean annual precipitation during the period 1930–59, and the net natural supply, represented by the mean annual runoff during the same period.

The data cited above indicate that the Wilmington-Reading area has an abundance of water and a substantial annual surplus. However, most of the surplus drains from the area during the late autumn, winter, and spring. Consequently, the usable water supply is basically limited by the rate at which water is available during the summer and early autumn.

The summer and early autumn include a critical period of varying duration when, at the current stage of water-resources development, streamflow is nearly all utilized and much of the water withdrawn from wells is derived from ground-water storage. This critical period, on the basis of runoff at South Middleton, occasionally has lasted more than four months—from late in June until some time in November. If a higher rate of water use is to be sustained, the additional water during the critical period must come from storage also—whether from the ground-water reservoir or from surface storage facilities—and the draft replaced by surplus water that drains from the area during the winter and spring. Indeed, during periods of high streamflow, usually in the winter, Peabody and Lynn divert

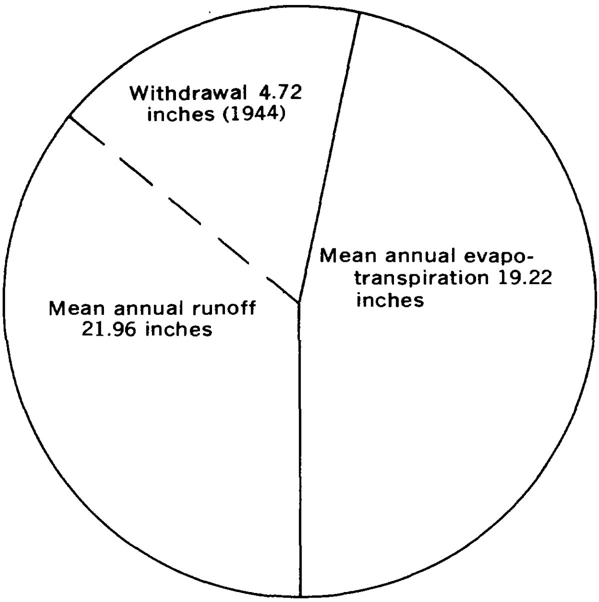

FIGURE 2.—Precipitation, runoff, and withdrawal in the Wilmington-Reading area, Massachusetts

water directly from the Ipswich River to surface reservoirs, where it is stored for use later in the year.

GEOLOGIC UNITS AND THE OCCURRENCE OF GROUND WATER

Rocks having common or closely related characteristics are grouped by the geologist into units. The occurrence of ground water is determined principally by the distribution, extent, thickness, structure, and properties of these units. A water-bearing unit that yields enough water to be a source of supply is called an aquifer or ground-water reservoir. The significant properties of rocks with respect to ground water are porosity, specific yield, and permeability.

Porosity, which is the property of containing void spaces (also called pores or interstices), enables a rock or soil material to contain water. It may be expressed quantitatively as the ratio, usually given as a percentage, of the volume of the void spaces to the total volume of the rock. Porosity determines the maximum capacity of a rock to store water.

Because some water adheres to the walls of the voids, a rock yields only part of its stored water to wells. The quantity of water that a fully saturated rock will yield by gravity drainage is called specific yield. This is defined as the ratio, expressed as a percentage, of the volume of water yielded by gravity to the total volume of the rock. The complement of specific yield is specific retention, which is the quantity of water that a fully saturated rock will retain against gravity drainage. This is defined as the ratio, expressed as a percentage, of the volume of water retained to the total volume of rock. Together the specific yield and the specific retention equal the porosity.

The permeability of a rock determines its capacity to transmit water under pressure. The coefficient of permeability, as defined by Meinzer (Stearns, 1927, p. 148) and used by the Geological Survey, is the rate of flow of water in gallons per day through a cross-sectional area of 1 square foot under a hydraulic gradient of 100 percent at a temperature of 60° F. For field use the temperature is neglected and the field coefficient expresses the flow of water under prevailing field conditions.

Perhaps more useful than permeability in evaluating an aquifer is its transmissibility, which is the capacity of the aquifer to transmit water. The coefficient of transmissibility as used by the Geological Survey is the rate of flow of water in gallons per day through a vertical strip of aquifer 1 foot wide, extending the full saturated thickness of the aquifer, under a hydraulic gradient of 100 percent at the prevailing water temperature (Theis, 1935). It is equal to the product of the field coefficient of permeability and the saturated thickness of the aquifer. Transmissibility determines the ability of an aquifer to serve as a distribution medium. It affects the specific capacity (yield per unit of drawdown) of a well and the area from which the well can draw water—that is, the higher the transmissibility the higher the specific capacity of the well and the larger the radius of its cone of depression, if all other factors remain equal. Also, the drawndown of water level at any point on the cone of depression would be smaller with larger transmissibility.

The storage capacity of an aquifer often is expressed in terms of a coefficient of storage. This is defined as the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change of head normal to that surface. For an aquifer under water-table conditions the coefficient of storage is approximately equal to the specific yield.

Water-table conditions exist where the water at the top of an aquifer is under atmospheric pressure. When a well is drilled into a water-table aquifer, water stands in the well almost at the level at which it is first struck.

Artesian or confined conditions exist where the water in an aquifer occurs under hydrostatic pressure. If a well is drilled into an artesian aquifer, the water will rise in the well above the level at which it is first struck to a point above the top of the aquifer (but not necessarily to or above the land surface). The imaginary surface formed by connecting levels to which ground water would rise in an infinite number of tightly cased wells penetrating an artesian aquifer is called a piezometric surface.

The occurrence of water under artesian or under water-table conditions has significant implications with respect to the spacing of wells and the manner of developing an aquifer. An artesian aquifer is completely saturated from bottom to top and will remain so until the hydrostatic pressure has been lowered so as to dewater part of the aquifer. The withdrawal of water from an artesian aquifer results in a decline of the hydrostatic pressure at the point of withdrawal the diminishing effects of which are quickly transmitted to considerable distances.

An aquifer under water-table conditions generally is not saturated for its full thickness. The withdrawal of water results in a lowering of the water table at and near the point of withdrawal and an actual removal of water from storage in the aquifer there. The effect is transmitted slowly to other parts of the aquifer because it involves dewatering and the actual movement of water through the aquifer before the levels at remote points can be lowered.

The rocks in which ground water occurs in the Wilmington-Reading area are divided into two main categories: the consolidated rocks, hereafter referred to as bedrock, and the unconsolidated deposits.

BEDROCK

Distribution and characteristics.—The bedrock formations in the Wilmington-Reading area consist of igneous and metamorphic rocks. As described by Emerson (1917) the principal rock types are granite, gneiss, diorite, gabbro, and quartzite. Subordinate rock types include schist, syenite, and pegmatite. According to Emerson these rocks range in age from Precambrian to late Carboniferous. It is noted, however, that Jahns (1941) and Currier and Jahns (1952) assigned ages ranging from middle or late Paleozoic to Triassic to similar rocks in the nearby Lowell area. The bedrock formations have been fractured and folded and at places faulted. The general structural trend is northeast. In general, the water-bearing properties of the several bedrock formations are similar and they are considered as a single unit in this report.

Bedrock is mantled discontinuously by unconsolidated deposits. It crops out principally on hills and ridges but also protrudes through the unconsolidated deposits in places in the valleys.

Ground water in the bedrock occurs chiefly in joints or fractures. These are narrow planar openings, some of which extend for long distances. They are variously spaced and dip at all angles from horizontal to vertical. In general, joints intersect each other and may be interconnected over a considerable area. They occupy only a very small part of the total volume of the bedrock. As a result the porosity, specific yield, and permeability of the bedrock, although differing greatly from place to place, are low.

Water in the bedrock.—The bedrock is a source of generally small but reliable supplies of ground water throughout the area. Because of its low porosity and correspondingly low storage capacity, bedrock is of little importance as a reservoir; rather, the joints in the bedrock serve principally as conduits and transmit water from recharge areas to the wells that intersect the joints. Some joints tap ground water in storage in overlying unconsolidated deposits. Saturated unconsolidated deposits overlie the bedrock in most of the area; therefore, most wells in bedrock are assured a reliable source of water. These wells yield water at small rates determined either by the permeability of the bedrock or the permeability of overlying deposits, whichever is smaller. Other joints are isolated or are connected only to an exposed bedrock surface or to dry unconsolidated deposits. If a well were to penetrate such joints only, it would fail after the small quantity of ground water stored in the joints was exhausted.

The ground water in the bedrock commonly occurs under artesian conditions. Ordinarily the walls of the joints serve as the confining layers, but at some places impermeable unconsolidated deposits overlie the bedrock surface and serve as a confining layer. Less commonly the ground water occurs under water-table conditions. Water-table conditions are most likely to exist near the surface of the bedrock if the bedrock is highly fractured.

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 and water levels in bedrock wells are at greater depths below the land surface in wells situated on the hills than in wells in the valleys. The greatest reported depth to water in the Wilmington-Reading area was 153 feet in well North Andover 61. This well is situated at the summit of Boston Hill, one of the highest points in the area. In contrast, some wells in the valleys, Tewksbury 119 for example, overflow at the land surface. The water level in a completed well is no index to the depth at which a nearby well will first intersect a water-bearing joint. One well may intersect such a joint only a few feet below land surface, whereas a nearby well may be drilled to a depth of many feet before doing so.

Because of the great variety in size, spacing, and attitude of the joints, neither the depth nor the yield of wells in bedrock can be predicted accurately. However, most wells yield at least a few gallons per minute, enough for domestic use, at depths less than 150 feet. In the Wilmington-Reading area, the reported yields of 25 wells for which data were available ranged from half a gallon per minute to 60 gpm (gallons per minute). The median yield was 10 gpm. In addition, five wells (well group Reading 107 and well 108), which formerly supplied part of the municipal water supply for the town of Reading, reportedly were pumped as a group at the rate of 300,000 gpd (gallons per day) or about 200 gpm. The depths of 60 wells for which data were available ranged from 10 to 750 feet. The median depth was about 80 feet.

As a well is drilled it intersects an increasing total number of joints and may produce an increasing total quantity of ground water. For example, well North Reading 78 was tested at 42, 65, 80, and 88 feet and at these depths reportedly yielded 1½, 4, 7, and 18 gpm respectively. The increase in yield is not, however, proportional to depth. Some geologists—Cushman, Allen, and Pree (1953) and Ellis (1909) for example—have concluded that in crystalline rocks, such as those found in the Wilmington-Reading area, the joints decrease in number and size with depth. Cushman, Allen, and Pree (1953, p. 95) also concluded that if no water-bearing fractures were struck by the time a well reached a depth of 300 feet, the chances of success would be improved by abandoning the well and moving to a new location and drilling another well. Ellis (1909, p. 94) stated that "if a well has penetrated 250 feet of rock without success, the best policy is to abandon it and sink in another location."

No information on drawdown versus yield was available for the bedrock wells in the Wilmington-Reading area. However, because of the low permeability of the bedrock large drawdowns are to be expected whenever wells are pumped at a high rate. The specific capacities probably are correspondingly low.

The bedrock surface and buried valleys.—The configuration of the bedrock surface is a significant factor in controlling the occurrence of ground water in the overlying unconsolidated deposits. Relief and configuration of the bedrock surface determine in part the thickness of the unconsolidated deposits, and the bedrock surface acts as a barrier to the downward movement of ground water from those deposits. The principal features of the bedrock surface in the

Wilmington-Reading area are valleys cut by preglacial streams. Because these valleys are the loci for the thicker saturated deposits from which the larger ground-water supplies in the Wilmington-Reading area are derived, knowledge of the preglacial drainage pattern serves as a guide to systematic exploration for favorable ground-water areas.

The old stream channels along the bottoms of the buried valleys, where the overlying deposits should be thickest, are effectively masked. The existing streams flow on unconsolidated deposits in channels whose positions are controlled by the shape of the postglacial land surface. As a result these streams do not furnish a reliable clue to the positions of the buried channels—the present streams may parallel the buried channels closely at some places but may diverge widely from them at other places. For these reasons the buried channels can be located precisely only by detailed test drilling or by geophysical exploration.

Despite the difficuties in locating the buried channels, a generalized picture of the buried valley system may be inferred from the surface and subsurface data collected for this report. These data suggest that a preglacial ancestor of the Ipswich River drained much the same area as the existing stream system. Outcrop areas of till and bedrock (pl. 3) are assumed to mark positions on the divides between the valleys of the preglacial stream system. The bottoms of the principal preglacial valleys may be approximately traced from seismic data and well and test-hole data. (See pls. 2–5 for locations of seismic traverses and selected wells and test holes.) The postulated traces of the principal preglacial valleys are shown on plate 2 and are discussed below.

From the vicinity of the Geological Survey stream-gaging station at South Middleton westward to Wilmington the main preglacial valley apparently coincides closely with the present valley of the Ipswich. Records of test holes show that within this reach the bottom of the preglacial valley is below sea level (at least 22 ft below sea level at test well North Reading 202 and more than 32 ft below sea level at test well Reading 125). Seismic line d near West Village in North Reading indicates that the bottom of the old valley may be as much as 165 ft below sea level. At no other place in the area do the subsurface data suggest so great a depth for this valley. If the interpretation of the seismic data along line d is correct, then either the preglacial valley is generally deeper than indicated by test-well or seismic data at other places, or locally the preglacial valley was deepened greatly by glacial erosion.

West of the Wilmington-Reading town line the preglacial drainage pattern is poorly defined. In the central and west-central parts of Wilmington widespread unconsolidated deposits mantle the preglacial valleys and divides indiscriminantly. W. O. Crosby (1899, p. 302) suggested that the preglacial Merrimack River passed through this area and flowed into Boston harbor by way of the present Mystic valley. This hypothesis was accepted by I. B. Crosby (1937, p. 221; 1939, p. 375–376), who also suggested an alternate course for the preglacial Merrimack, across Wilmington and eastward towards Salem. LaForge (1932, p. 79) and Chute (1960, p. 190) questioned the views of both 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 pre-glacial Merrimack River may have flowed southeastward through the Billerica and Wilmington quadrangles (Crosby, 1939, p. 375–377; Lee and others 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 the current investigation support the conclusions of LaForge and Chute and cast doubt on I. B. Crosby's suggestion, which was supported by Castle, of an alternate route for the preglacial Merrimack eastward toward Salem by way of Wilmington. The bottom of the Mystic or Fresh Pond buried valley is below sea level at least as far inland as Mishawam Lake, just south of Wilmington, and the bottom of the Ipswich buried valley is below sea level at least as far inland as the eastern part of Wilmington. Thus, if the preglacial Merrimack, whose channel is at or below sea level near Lowell (I. B. Crosby, 1939, p. 375–376; Lee and others, 1940, p. 37–40), were to connect with either of these, its channel would lie below sea level where it crosses Wilmington. The distribution of bedrock outcrops indicates that this channel could pass into Wilmington only in the west-central part of the town north of Silver Lake. This area was explored by seismic methods along a line parallel to the Boston and Maine railroad tracks north of the village of Wilmington. (See pls. 2 and 3.) The line was carried from a point 0.3 mile north of highway 38 northward to the junction of the Boston and Maine tracks 0.7 mile south of Wilmington Junction. The line was virtually continuous, with major breaks only in areas of bedrock outcrops. The lowest point on the bedrock surface was about 25 feet above sea level, thereby indicating that no major preglacial channel crosses the line. The distribution of bedrock outcrops makes passage of a major preglacial channel around either end of the line seem improbable. Lending support to the results of the seismic exploration is the fact that except near the eastern margin of Wilmington no wells or test holes are known to reach bedrock at an altitude below about 35 feet above sea level.

From the above information it is 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. It is further concluded that the preglacial Ipswich basin was separated from adjacent drainage basins by divides at roughly the same positions as the existing divides. The courses of the headwater streams of the preglacial Ipswich and the positions of the buried divides separating them cannot be located accurately on the basis of existing data. At places the present streams may flow over the buried divides. The most likely courses of the preglacial headwater streams are shown on plate 2; these necessarily are approximate.

Subsurface data for the area southwest of Martins Pond show that one or two major tributary valleys extend into this area. Bedrock is more than 4 feet below sea level at the Wilmington pumping station on Salem St. (pl. 2, well Wilmington 389) and is 25 feet below sea level where a small northeast-flowing tributary joins Martins Brook about 0.6 mile southeast of the pumping station (pl. 2, line q). The alinement of Martins Pond and Fosters Pond suggests that they may occupy part of a preglacial valley also. The deepest wells near these ponds penetrated to points 10 feet and 3 feet above sea level without reaching bedrock (North Reading 186 and 136, respectively). Unconsolidated deposits conceal the relationships of the several points cited above with respect to the preglacial drainage system. Two paths are suggested by which this area may have drained to the preglacial Ipswich: (1) A valley coinciding roughly with the lower course of Martins Brook; (2) a valley marked by the northwest-trending undrained lowland that is parallel to and about 1 mile west of the lower course of Martins Brook. Either or both of these buried valleys may exist, and both are shown on plate 2. If only one exists, a branch must extend across the area enclosed by the U-curve of Martins Brook.

The preglacial Ipswich had several minor tributaries. Principal among these are one extending into the area occupied by Cedar Swamp and one extending into the area drained by Revay Brook. The buried valley of the Cedar Swamp tributary probably extends no farther south than the head of Bear Meadow Brook where seismic line a (pl. 2) indicates that the bedrock surface is generally no lower than 60 feet above sea level. Little is known of the Revay Brook buried valley, but the altitude of bedrock near the head of Revay Brook is lower than 25 feet above sea level (well Reading 187).

The overall picture provided by subsurface data and the positions of bedrock outcrops suggests that the buried walls of the Ipswich valley have moderate slopes and that the valley floor is fairly narrow. Where the valley of the preglacial Ipswich intersects the present surface, it ranges in width from about 200 feet to at least 2,000 feet as indicated by the distribution of bedrock outcrops and by well data. There is no clear evidence in the Wilmington-Reading area of an inner gorge cut into the floor of an older, broader valley floor as suggested by Crosby (1945, p. 393) and Chute (1960, p. 189) for other areas in Massachusetts.

UNCONSOLIDATED DEPOSITS

The unconsolidated deposits in the Wilmington-Reading area include glacial drift (a general term for all deposits of glacial origin) and wind-laid (eolian) deposits of Pleistocene age, and swamp deposits and alluvium of Recent age. The glacial drift includes glacial till (ice-laid drift) and stratified drift (water-laid drift). The stratified drift is subdivided further into ice-contact deposits and outwash.

A brief summary of the Quaternary history serves to explain the classification used here and to describe the general relationships of the several geologic units. In common with the rest of Massachusetts the Wilmington-Reading area may have been glaciated by continental ice sheets several times during the Pleistocene epoch ("ice age"). However, the recognized glacial deposits in Massachusetts generally are attributed to the last (Wisconsin) major advance and retreat of the ice (Flint, 1953, p. 900–901).

The ice moved south across the area and picked up soil and rock, which were spread unevenly across the land surface to form a blanket of till.

With the waning of the ice age the ice sheet melted and shrank. For a while tongues of ice remained in the valleys, then melted into isolated masses. In the meantime sediments released from the melting ice and possibly derived in part from the till were picked up and transported by the meltwater streams. These streams deposited their load in channels along the valley walls marginal to the ice and in channels, crevasses, and holes in, on, or beneath the ice. The deposits thus formed, in an environment of wasting ice, are called ice-contact deposits.

As the ice masses continued to melt, the streams built ice-contact deposits at lower and lower levels and progressively nearer the middles of the valleys, where the last small ice blocks remained. Finally, after the valleys were virtually free of ice, the meltwater streams partly filled them with sediments, burying bedrock, till, and low-lying ice-contact deposits. Here and there, where the streams were temporarily ponded, they poured their load into lakes. The meltwater deposits that were formed in ice-free valleys beyond the glacier terminus are called outwash.[1]

With the disappearance of the ice sheet and the transition in time from Pleistocene to Recent, the last meltwater streams gradually became the smaller modern streams. Meanwhile a thin blanket of windborne material was deposited across the area and swamp deposits accumulated slowly in low-lying poorly drained places. From place to place the streams eroded the older deposits, picking up and transporting the materials so derived, then redepositing them as alluvium (modern stream deposits) along the stream courses.

For details of the history of the Wilmington quadrangle the reader is referred to a report by Castle (1959).

The unconsolidated deposits, as the above description indicates, cannot everywhere be classified precisely. Locally, till and ice-contact deposits are intimately associated and difficult to distinguish from each other. The youngest ice-contact deposits grade into the oldest outwash, and the youngest outwash grades into the alluvium. Nevertheless, at most places the unconsolidated deposits differ from each other in form, physical characteristics, and water-bearing properties.

Ground water in the unconsolidated deposits occurs in the intergranular openings (voids between the constituent particles). The porosity of the rock materials depends principally on the shape and arrangement of the constituent particles and the degree of sorting. The permeability depends on the size, shape, and interconnection of the openings. Fine-grained materials, such as clay and silt, have many very small openings. Consequently they have a large porosity but are almost impermeable and have a very low specific yield. In contrast, coarse-grained materials, such as sand and gravel, have large well-connected openings, but these are small in number compared to the openings in clay and silt. As a result the permeability and specific yield of sand and gravel commonly are high, but the porosity may be lower than that of silt and clay.

The several classes of unconsolidated deposits are described below in the following order: till, ice-contact deposits, outwash, wind deposits, swamp deposits, and alluvium. The extent and distribution of

[1] The term "outwash" is used here in a restricted sense and not, as is common, as a general term to include all fluvial deposits of glacial origin.

till, ice-contact deposits, outwash, and swamp deposits are shown on the geologic map (pl. 3), and the subsurface relations of these units, based on geologic mapping and interpretation of drillers' logs, well cuttings, and seismic data, are shown in sections (pls. 4 and 5). The wind deposits, which are thin and superficial, are not shown. Alluvium is not a significant water-bearing unit; it is not differentiated on the map but is included with the older deposits with which it is associated.

TILL

Distribution and characteristics.—Till overlies the bedrock surface nearly everywhere. It commonly forms a thin sheet of varying thickness called ground moraine, but it also forms a few rounded, elongate hills called drumlins. It is exposed in nearly half the area (pl. 3), principally on hills and ridges. In the valleys and along the flanks of many of the hills it is buried by younger unconsolidated deposits.

Till ranges in thickness from less than 1 foot to at least 208 feet. Till in ground moraine commonly is less than 20 feet thick. Till ordinarily is much thicker in drumlins than in ground moraine; the largest known thickness of till, 208 feet, was recorded in the log of well Andover 61, which penetrated the drumlin known as Boston Hill.

Till is characterized by a wide range in particle size, a lack of stratification, and little or no sorting; also, it may be difficult to dig or drill into. The poor sorting and wide range in particle size are illustrated by table 2 and by a particle-size distribution curve (fig. 3) that represents the average composition of six samples of till from

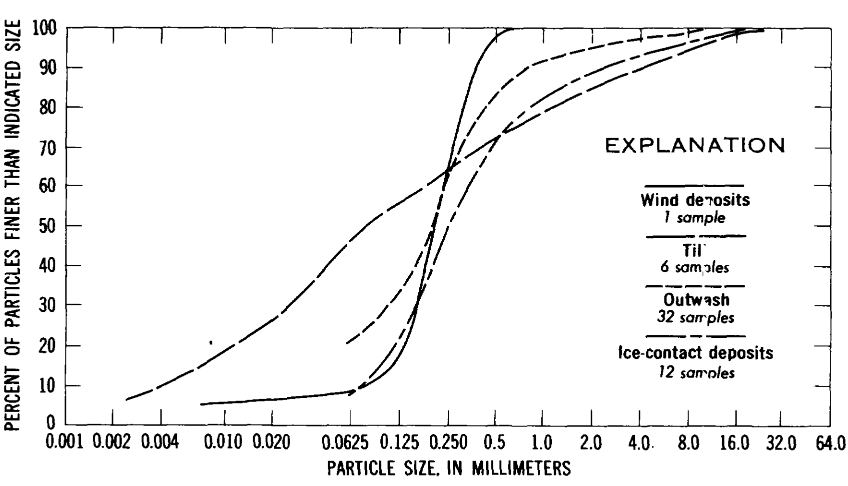

FIGURE 3.—Particle-size distribution curves representing the average composition of samples of till, ice-contact deposits, outwash, and wind deposits in the Wilmington-Reading area, Massachusetts. (See table 2.)

the Wilmington-Reading area. Because of the difficulty in collecting samples containing gravel and boulders these samples represent the till matrix only.

TABLE 2.—*Particle-size distribution, by percent, in samples of unconsolidated deposits in the Wilmington-Reading area, Mass.*

[Samples collected from test pits at surface unless otherwise noted]

Field No.	Clay	Silt	Sand					Gravel			
	<0.004 mm	0.004–0.0625 mm	Very fine 0.0625–0.125 mm	Fine 0.125–0.25 mm	Medium 0.25–0.5 mm	Coarse 0.5–1.0 mm	Very Coarse 1.0–2.0 mm	Very fine 2–4 mm	Fine 4–8 mm	Medium 8–16 mm	Coarse 16–32 mm
Till											
3	9.7	30.4	11.1	9.7	9.0	7.5	6.2	5.7	6.0	4.7	----
4	11.0	25.7	11.7	15.0	13.8	11.4	5.5	3.7	2.2	----	----
6	15.0	84.2	.4	.2	.2	----	----	----	----	----	----
7	9.8	14.0	7.4	10.0	10.0	10.6	9.4	8.0	7.3	6.5	7.0
10	6.9	55.3	11.1	9.1	8.2	6.1	2.6	.7	----	----	----
11	5.4	14.6	6.8	9.3	9.0	8.7	8.0	9.2	10.5	18.5	----
Ice-contact deposits											
28	0.2		6.0	60.9	30.5	1.4	0.8	0.1	0.1	----	----
29	.6		5.0	37.1	49.6	6.6	.8	.2	.1	----	----
30	2.4		14.1	43.2	32.8	5.1	1.6	.6	.2	----	----
35	31.0		49.3	18.8	.4	.2	.2	.1	----	----	----
36a	.2		.8	6.2	22.2	22.2	9.9	8.0	11.2	13.3	6.0
36b	8.8		24.6	54.5	10.8	.8	.4	.03	.07	----	----
37	2.6		22.2	66.4	8.0	.4	.2	.1	.1	----	----
42 [1]	.3		2.5	20.4	29.4	17.3	8.6	5.5	5.8	6.9	3.3
43 [1]	.5		1.5	2.9	5.8	9.5	12.9	24.7	25.6	16.6	----
44 [1]	4.6		6.4	15.8	33.3	28.3	6.7	1.1	.4	1.9	1.5
45 [1]	45.6		12.8	10.5	13.0	12.5	4.3	1.0	.3	----	----
46 [1]	9.6		5.1	10.1	22.3	26.2	17.7	5.6	2.1	1.3	----
Outwash											
1	2.1		12.5	42.1	32.9	9.1	1.0	0.2	0.1	----	----
2	5.8	8.4	25.5	31.2	19.7	7.4	1.8	.2	----	----	----
12	31.9		34.4	28.6	4.9	.2	----	----	----	----	----
13	3.5	4.1	18.2	47.6	24.1	2.4	.1	----	----	----	----
14	2.2		4.2	68.0	25.4	.2	----	----	----	----	----
15	3.7		10.6	74.8	9.7	.8	.2	.1	.1	----	----
16	3.5	7.1	13.0	23.8	33.3	14.9	2.8	.8	.8	----	----
19	1.8		7.1	29.9	59.3	1.2	.4	.2	.1	----	----
20	1.5	1.5	5.0	20.5	51.8	7.6	5.2	3.5	2.0	1.4	----
21	----	----	.4	10.4	35.2	37.7	11.0	5.0	.3	----	----
22	2.4		2.8	23.0	52.4	14.2	4.4	.7	.1	----	----
23	1.2		.2	1.9	21.6	37.6	25.1	7.4	3.0	2.0	----
24	1.8		2.0	7.4	33.6	21.2	13.2	8.2	6.0	4.7	1.9
25	3.0	.6	6.2	43.2	31.6	11.0	4.4	----	----	----	----
26	1.0		2.0	10.6	54.4	26.0	6.0	----	----	----	----
27	1.7		1.6	13.3	20.0	17.7	17.0	16.2	11.4	1.1	----
31	2.6		2.2	5.1	14.4	15.5	12.8	14.5	13.7	19.2	----
32	.4		2.0	24.9	34.0	20.7	8.6	5.0	3.8	.6	----
33	74.7		20.3	3.2	1.4	.3	.1	----	----	----	----
34	6.3	66.9	19.8	4.0	2.4	.6	----	----	----	----	----
38 [1]	15.0	75.2	6.0	2.0	1.0	.6	.2	----	----	----	----
39	1.6		12.0	72.8	13.0	.2	.2	.1	.1	----	----
40 [1]	5.3	56.9	30.8	6.6	.2	.1	.1	----	----	----	----
41	45.0		40.6	13.4	.6	.2	.2	----	----	----	----
47 [1]	.2		1.0	46.4	49.7	1.6	.4	.4	.3	----	----
48 [1]	2.4		14.1	58.8	22.7	1.0	.4	.6	----	----	----
49 [1]	9.8		30.8	53.4	5.6	.2	.2	----	----	----	----
50 [1]	3.5	2.4	3.0	34.2	40.0	9.5	4.5	2.5	.4	----	----
51 [1]	4.2	1.5	2.3	58.0	30.4	2.2	.8	.6	----	----	----
52 [1]	5.0	52.8	23.6	11.8	5.7	.6	.2	.1	.2	----	----
53 [1]	6.0	65.7	24.9	2.4	.4	.2	.2	.1	.1	----	----
54 [1]	7.0	81.3	10.2	.8	.2	.2	.2	.1	----	----	----

[1] Sample from well cuttings.

TABLE 2.—*Particle-size distribution, by percent, in samples of unconsolidated deposits in the Wilmington-Reading area, Mass.*—Continued

Field No.	Clay	Silt	Sand					Gravel			
	<0.004 mm	0.004–0.0625 mm	Very fine 0.0025–0.125 mm	Fine 0.125–0.25 mm	Medium 0.25–0.5 mm	Coarse 0.5–1.0 mm	Very Coarse 1.0–2.0 mm	Very fine 2–4 mm	Fine 4–8 mm	Medium 8–16 mm	Coarse 16–32 mm
Wind deposits											
8	5.2		12.3	56.1	24.7	1.7	------	------	------	------	------
9	5.3	2.5	10.0	51.8	28.4	2.0	------	------	------	------	------
Swamp deposits											
107	10.0	20.9	15.6	23.2	18.6	8.5	2.2	0.5	0.5	------	------
111	59.5	39.9	.4	.2	------	------	------	------	------	------	------

There are two types of till in the area. One is compact and contains a large proportion of silt and clay. In some places it is massive, but in other places it has nearly horizontal closely spaced parting planes. In fresh exposures it is gray to bluish gray; in weathered exposures it is light gray, yellowish brown, or tan. The other type is loose and distinctly sandy and is generally structureless. In fresh exposures it is gray or gray green; in weathered exposures it is tan, brown, or olive brown. Both types contain boulders and lenses of stratified materials, but boulders are more numerous in the loose till than in the compact till. The relation of the two tills is imperfectly known. The loose till rests on the compact till in the few exposures where both were seen.

Because of poor sorting and large range in particle size, the porosity, specific yield, and permeability of the till were expected to be low. These properties were determined in the laboratory for six undisturbed samples (table 3). The coefficient of permeability ranged from very low to low (0.1 to 220 gpd per sq ft). On the other hand the porosity, which ranged from 22.1 to 40.6 percent, and the specific yield, which ranged from 19.6 to 31.2 percent, were much higher than expected. With one exception the till that was sampled was the loose, sandy type, which probably has a much higher porosity and specific

TABLE 3.—*Hydrologic characteristics of till from the Wilmington-Reading area, Mass.*

[Analyses by U.S. Geol. Survey]

Sample	Depth (ft)	Orientation of undisturbed sample	Specific retention (percent)	Specific yield (percent)	Porosity (percent)	Coefficient of permeability (gpd per sq ft, meinzer units)
3	6.0	Horizontal	5.9	30.8	36.7	11
4	5.0	Vertical	5.4	29.1	34.5	2
6	3.5	do	12.6	28.0	40.6	.1
7	7.0	Horizontal	2.5	31.2	33.7	220
10	7.0	do	5.8	29.8	35.6	5
11	2.5	Vertical	2.5	19.6	22.1	2

silt and clay." Twelve samples of ice-contact deposits analyzed in the laboratory (table 2) average 12 percent gravel, 38 percent medium to very coarse sand, 41 percent very fine to fine sand, and 9 percent silt and clay (fig. 3). Size-sorted materials occur in discontinuous layers. The contacts between adjacent layers generally are sharp, and abrupt changes in grain size in both horizontal and vertical directions are common. Bedding is horizontal to steeply dipping, and some deposits are crossbedded. In general the materials are not cemented, but hard layers, consisting of either fine or coarse-grained materials cemented with iron oxide, occur from place to place.

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. They may contain small bodies of till. These deposits commonly form ice-channel fillings and kames. At the other extreme, the deposits are well stratified and moderately well sorted. These deposits commonly form kame terraces and kame plains. Many deposits are intermediate in character between the extremes. A feature of some of the deposits forming kame plains and terraces is a horizontal cap of gravel. In many of these deposits this cap conceals sand, which makes up the bulk of the deposits.

The predominance of sand and gravel suggests that in general the porosity and specific yield of the ice-contact deposits are moderate to high, probably ranging from 15 to 40 percent. The wide variation in the composition and sorting of the individual deposits suggests that some of them have moderate or high permeabilities, probably from several hundred to more than 1,000 gpd per sq ft, and others have low permeabilities (in the order of a few tens of gallons per day per square foot).

Ground water in the ice-contact deposits.—The ice-contact deposits yield small to large quantities of ground water to wells. In the Wilmington-Reading area the reported yields of 138 wells ranged from 2½ to 500 gpm. The reported yields of 3 large-diameter gravel-packed wells were 320, 350, and 500 gpm; the yields of 130 small-diameter wells ranged from 6 to 150 gpm; and the yields of 5 dug wells ranged from 2½ to 45 gpm.

Most wells in the more permeable ice-contact deposits can be expected to have specific capacities in the order of 10 to 100 gpm per ft of drawdown. Such specific capacities may be considered to be moderate to large. The specific capacities of the few wells for which yield and drawdown data were available supported this conclusion. Ten wells, which were pumped for periods ranging from 4 to 26 hours, had specific capacities that ranged from 12 to 124 and averaged 42 gpm per ft of drawdown. The median specific capacity, which probably is more representative than the average, was 32 gpm per ft of drawdown.

Coefficients of transmissibility were estimated from the specific capacities of nine of the wells noted above. They ranged from about 8,000 to 70,000 and averaged about 40,000 gpd per ft. The median was about 30,000 gpd per ft. Data from a pumping test were used to compute the coefficients of transmissibility and storage for ice-contact deposits penetrated by one of the wells. The coefficient of transmissibilty was about 100,000 gpd per ft, and the coefficient of storage was about 0.003. For this well the coefficient of transmissibility estimated on the basis of the specific capacity was about 70,000 gpd per ft.

OUTWASH

Distribution and characteristics.—Outwash underlies low terraces and swamps in the lowlands throughout the area. It forms a continuous body extending along the valleys and spreading out where the valleys widen. It is especially widespread in Cedar Swamp in Reading and along the headwater streams of the Ipswich River system in Wilmington (pl. 3). The outwash overlies older unconsolidated deposits and bedrock. (See pls. 4 and 5.) In the swamps and along the streams it is overlain by a thin layer of swamp deposits or alluvium. Along the margins of many of the swamps the outwash crops out in the form of scattered low terraces and plains. Some of the low terraces and plains in the Wilmington quadrangle mapped by Castle (1959) include adjacent kame terraces and kame plains. However, the available subsurface data suggest that the deposits forming these features generally are similar to and continuous with outwash underlying the adjacent swamps. In this report they are classified as outwash and are so shown on plate 3. Also, where streams traverse the outwash thin deposits of alluvium are included with the outwash.

The thickness of the outwash may range from less than 1 foot to about 200 feet. The greatest known thickness, 102 feet, was reported in the log of well North Reading 131, but seismic traverses suggest that the maximum thickness may be about 200 feet. One traverse (line v, pl. 2), north of the Ipswich River about a quarter of a mile west of Highway 28, indicates a maximum depth to bedrock of about 160 feet. Another traverse (line d, pl. 2), south of the Ipswich River about half a mile west of Highway 28, indicates a maximum depth to bedrock of about 235 feet. The outwash, which underlies the land surface along the parts of both traverses where bedrock is lowest, probably extends downward to or nearly to bedrock.

The outwash is thickest where is overlies the channels of the preglacial Ipswich River and its tributaries. From these channels it thins laterally toward the sides of the valleys and pinches out along the mapped contact with either bedrock or the older unconsolidated deposits. South of Cedar Swamp and in the headwaters area of the Ipswich in Wilmington, the outwash also thins across buried divides on the bedrock surface.

The outwash consists principally of sand but includes small amounts of gravel, silt, and clay, and scattered boulders. The bedding commonly is horizontal or gently dipping. In the drillers' logs collected for this report about 15 percent of the materials interpreted by the authors as outwash are listed as "gravel" or "sand and gravel," about 50 percent are listed as "sand," about 30 percent are listed as "sand with silt and clay," and about 5 percent are listed as "silt and clay." Thirty-two samples of outwash analyzed in the laboratory (table 2) averaged 5 percent gravel, 35 percent medium to very coarse sand, 39 percent very fine to fine sand, and 21 percent silt and clay. (See fig. 3.) The outwash generally contains a larger proportion of fine-grained materials, is better sorted, and is more homogeneous than the ice-contact deposits.

The outwash differs in texture from place to place depending chiefly on the manner and environment of deposition. Stream-laid deposits predominate. They consist mostly of sand but certain lenses and layers of gravel. Deposits of probable lacustrine origin—thought to have formed in temporarily ponded streams—occur from place to place. The largest known body of these deposits occurs in the valley of the Ipswich River. The full extent of this body is not known. As mapped by Oldale (written commun.) it extends from West Village in North Reading to the Middleton town line and up the valley of the unnamed stream draining Eisenhoures Pond. It probably also extends into the area occupied by Cedar Swamp. The deposits consist principally of very fine to fine sand and silt but include some gravel, medium to coarse sand, and clay.

The porosity and specific yield of the outwash are fairly high. The porosity of 17 samples (see table 4), collected at 12 locations in the Wilmington-Reading area, ranged from 31.6 to 44.8 percent; the average was 39.1 percent and the median was 39.4 percent. The specific yield of the same set of samples ranged from 22.4 to 44.0 percent; the average was 36.0 percent and the median was 36.3 percent. These few samples do not provide an index to the full range of values, but on the basis of field observations the samples probably are sufficiently typical to give values of porosity and specific yield of the order of magnitude to be expected generally.

TABLE 4.—*Hydrologic characteristics of outwash from the Wilmington-Reading area, Mass.*

[Analyses by U.S. Geol. Survey]

Sample	Depth (ft)	Orientation of undisturbed samples	Specific retention (percent)	Specific yield (percent)	Porosity (percent)	Coefficient of permeability (gpd per sq ft, meinzer units)
1	4.5	Horizontal	1.1	35.7	36.8	220
2	4.5	Vertical	1.0	38.6	39.6	48
12	11.0	Horizontal	.5	41.4	41.9	91
13	13.0	Vertical	.5	44.0	44.5	290
14	5.0		.5	41.5	42.0	480
15	4.0	Horizontal	1.7	43.1	44.8	330
16	4.0	Vertical	2.7	36.3	39.0	110
19	5.0	Horizontal	.6	41.1	41.7	590
20	5.0	Vertical	.6	37.4	38.0	500
33	3.0	Horizontal	5.5	29.7	35.2	1
34	3.0	Vertical	4.7	33.9	38.6	3
24	3.5		1.6	32.3	33.9	850
25	3.5		2.9	36.5	39.4	250
26	3.0		1.5	35.2	36.7	560
27	3.0		2.6	29.0	31.6	190
38	32		18.6	22.4	41.0	.3
40	40.0		6.2	34.3	40.5	7

From the composition of the outwash it is inferred that the permeability is generally low but ranges from very low to moderate. The large amount of silt and very fine sand in the deposits of lacustrine origin suggests that they have very low to low permeabilities. In contrast, the stream-laid deposits, which contain a much smaller amount of silt and very fine sand, probably have a low to moderate permeability. The general conclusion is supported by the results of the sampling program. The coefficient of permeability of 17 samples of outwash, from 12 locations, ranged from 0.3 to 850 gpd per sq ft; the average was 266 and the median was 220 (table 4). These values probably do not represent the full range of values of permeability to be expected from the outwash but probably include the common range of values. No significant differences appear to exist between the permeabilities of a group of 6 disturbed samples and those of a group of 11 undisturbed samples. In order to examine the effect of stratification upon the permeability, five pairs of undisturbed samples were taken, each consisting of one sample oriented in the horizontal plane and one sample oriented in the vertical plane. (See table 4.) However, because a comparison of grain-size analyses for each pair of samples shows large differences in composition and sorting, conclusions as to the effect of the stratification do not appear to be justified.

Ground water in the outwash.—The outwash stores a large amount of ground water, which is transmitted slowly. The outwash provides supplementary storage to adjacent or subjacent ice-contact deposits.

It furnishes a large share of the water forming the base flow of the streams and thereby contributes water indirectly to wells that are placed so as to induce recharge from the streams. Also it is sufficiently permeable at some places to yield small to moderate quantities of water to wells.

At most places wells in the outwash probably will produce enough water for domestic use, and it is possible that groups of wells if properly dispersed in the areas of coarser grained (stream-laid) deposits and if carefully screened and developed, could yield enough water for commercial or municipal use. The reported yields of seven wells in outwash ranged from 3 to 90 gpm. The median yield was 40 gpm. These wells ranged in depth from 11 to 67 feet.

Drawdown and yield data were available for only two wells. The specific capacities of these wells were 9 and 11 gpm per foot of drawdown, and the estimated coefficient of transmissibility for the outwash at both wells was about 8,000 gpd per ft.

WIND DEPOSITS

Wind deposits form a thin discontinuous mantle on bedrock and glacial drift throughout the area and occur as poorly formed dunes (Castle, 1959) at a few places. These deposits consist chiefly of fine-grained sand and silt (table 2 and fig. 3) apparently derived from drift and deposited by the wind soon after the disappearance of the last ice sheet. They are characterized by a lack of stratification, by excellent sorting, and by the presence of scattered ventifacts. According to Castle the wind deposits in the Wilmington quadrangle average between 1 and 2 feet in thickness and generally are not more than 4 feet thick.

Throughout most of the Wilmington-Reading area the wind deposits lie above the water table and therefore are not a source of ground water. However, they are sufficiently permeable to permit water to percolate freely from the surface to the underlying deposits. The wind deposits were sampled at only one site. The coefficient of permeability was 240 gpd per sq ft in a horizontal direction and 250 gpd per sq ft in a vertical direction.

The wind deposits are not shown on the geologic map (pl. 3) because they are thin and widespread and would mask the distribution of the principal water-bearing units of the area.

SWAMP DEPOSITS

Distribution and characteristics.—Swamp deposits are exposed in about one-fourth of the Wilmington-Reading area (pl. 3). They are widespread along the floors of the valleys and occupy scattered small depressions in the uplands. They commonly overlie outwash in the lowlands and till or bedrock in the uplands. Cedar Swamp, the largest swamp in the area, occupies about 2 square miles in the eastern part of Reading.

The swamp deposits range in thickness from less than 1 foot to about 55 feet but ordinarily are less than 5 feet thick. The maximum known thickness, 55 feet, was reported in the log of test boring Wilmington 252, in the valley of Martins Brook. The deposits in the uplands ordinarily are thinner than those in the lowlands.

The swamp deposits consist of peat and muck interbedded, or intermixed in some places, with sand or silt. The peat in this area is a spongy, fibrous mass of poorly decomposed plant remains. It is generally brown. The muck is a fine-textured, nonfibrous mass of well-decomposed plant remains. It is generally dark brown. The sand and silt probably were deposited during recurrent flooding of the swamps.

Hydrologic properties were determined in the laboratory for six samples of the swamp deposits (table 5), which were collected at three points. The samples included four of peat (sample Nos. 103–106) and two of muck (sample Nos. 107–108). The porosity ranged from 54.7 to 83.3 percent, the specific yield from 42.3 to 76.4 percent, and the coefficient of permeability from 1 to 1,960 gpd per sq ft. The lowest values were for the muck. The six samples were paired, each set consisting of one oriented in a horizontal plane and the other oriented in a vertical plane. For the peat the vertical permeabilities were notably lower than the horizontal permeabilities. The few data on the permeabilities of peat and muck in the Wilmington-Reading area are consistent with the data from a few analyses of peat and muck elsewhere in eastern Massachusetts. These data indicate that swamp deposits have very low to low vertical permeabilities.

TABLE 5.—*Hydrologic characteristics of swamp deposits from the Wilmington-Reading area, Mass.*

[Analyses by U.S. Geol. Survey]

Sample	Depth (ft)	Orientation of sample	Moisture content (percent)		Specific retention (percent)	Specific yield (percent)	Porosity (percent)	Coefficient of permeability (gpd per sq ft, meinzer units)
			Natural	Oven dried [1]				
103	1.5	Vertical	103.4	118.9	7.7	75.3	83.0	53
104	1.5	Horizontal			6.9	76.4	83.3	870
105	1.5	Vertical	159.4	65.8	8.5	69.1	77.6	28
106	1.5	Horizontal			6.1	75.8	81.9	1,960
107	.5	Vertical	96.0	46.3	15.6	50.1	65.7	2
108	.5	Horizontal			12.4	42.3	54.7	1

[1] *Moisture content after dried samples were wetted by capillary action.*

Ground water in the swamp deposits.—The swamp deposits do not yield water to wells but may be important with respect to ground-water recharge and discharge. The very low to low vertical permeabilities suggest that these deposits retard the movement of water between the surfaces of the swamps and the more permeable deposits, such as the outwash, which underlie the swamp deposits in most of the area. Field observations indicate that from time to time water may be perched on or within the swamp deposits or confined in the materials beneath the swamp deposits. The confining effect is shown by the hydrographs for a pair of observation wells 10 feet apart. (See fig. 4.) During the period of record the water level in the deeper well (Wilmington 447), which was finished in the outwash, remained higher than the water level in the shallower well (Wilmington 448), which was finished in the swamp deposits overlying the outwash.

The swamp deposits are highly absorbent when their moisture content is low, and they can store large quantities of water as they again become wetted. However, the laboratory data on moisture content (table 5) suggest that if saturated swamp deposits were fully dried and then rewetted, they would regain their initial moisture content slowly.

Organic compounds derived from the organic material in the swamp deposits may impair the quality of water as it percolates through them. In particular, ground water that has passed through these deposits may be highly colored, high in iron content and strongly odorous.

ALLUVIUM

A thin layer of alluvium occurs along the streams of the area. It rests indiscriminately on the older geologic units traversed by the streams, and in many places it is interbedded or intermixed with swamp deposits.

The alluvium consists principally of sand and silt, but at places in some of the stream channels gravel predominates. The alluvium is generally similar in physical characteristics and water-bearing properties to the outwash. It does not form a distinct water-bearing unit. It has not been differentiated on the geologic map (pl. 3) but is included with the older deposits with which it is associated.

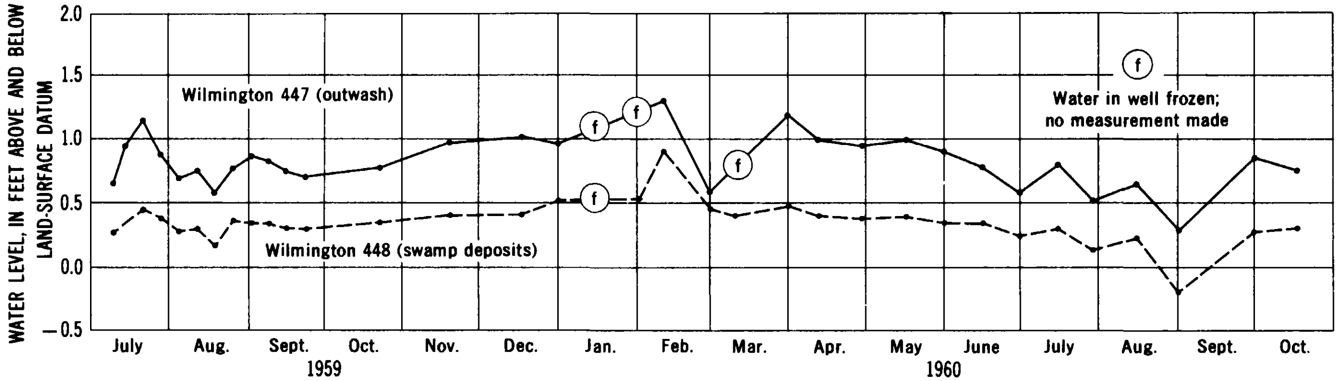

FIGURE 4.—Hydrographs showing water-level fluctuations in paired wells in swamp deposits and in confined beds in outwash in the Wilmington-Reading area, Massachusetts.

GROUND-WATER CONDITIONS

THE GROUND-WATER RESERVOIR

The principal ground-water reservoir in the Wilmington-Reading area consists of the deposits of stratified drift that partly fill the valleys of the preglacial Ipswich River and its tributaries. The reservoir underlies about 21 square miles, or about 50 percent of the area. The saturated thickness of the stratified drift is estimated conservatively to average at least 30 feet but is substantially greater along the bottoms of the buried valleys. The maximum known thickness, on the basis of well data, is 102 feet. If it is assumed that the specific yield of the stratified drift is between 20 and 40 percent (the common range of values of specific yield for materials such as those forming the ice-contact deposits and outwash), the reservoir stores between 30 and 60 billion gallons of ground water.

Although a large volume of water is stored by the ground-water reservoir, individual wells can produce large quantities of water only from the more permeable saturated materials. In general these materials are included with the ice-contact deposits.

Generally, the ground water in the stratified drift occurs under water-table conditions. Locally, however, where the more permeable materials, such as sand and gravel, are interbedded with or overlain by less permeable materials, such as silt or clay, the water in the more permeable materials may be confined or semiconfined. Also, where the stratified drift is overlain by swamp deposits the water in the reservoir may be confined occasionally.

Depths to water are shallow. In the swamps the water table is at or near the land surface throughout the year. In most of the area mapped as outwash (see pl. 3) the depth to water usually is less than 10 feet and in many places it is less than 5 feet. In most of the area mapped as ice-contact deposits the depth to water usually is less than 20 feet. Levels of water in streams or swamps are a rough index to the ground-water levels to be expected in adjacent ice-contact deposits or outwash.

Under natural conditions the range of seasonal fluctuations of the water table in the stratified drift is small, usually less than 5 feet.

THE GROUND-WATER RESERVOIR IN RELATION TO THE HYDROLOGIC SYSTEM

The area underlain by the ground-water reservoir is traversed by the Ipswich River and its tributaries, and about half the area of the reservoir is overlain by a cover of semipermeable swamp deposits. Within this complex environment the ground water, soil moisture, and surface water are intimately associated, and for the swamp environment in particular the distinction between them is at times obscure. In effect the reservoir, the swamps, and the streams function together as interdependent components of a single major hydrologic system. A description of the operation of this system during a typical water year follows.

In October, at the beginning of the water year, the surfaces of the swamps usually are dry or nearly dry, and the water table at most places stands in the swamp deposits or possibly in the outwash beneath them. Streamflow is low and is derived principally from the ground-water reservoir. Vegetation is discharging water from the swamps either from soil-moisture storage or from ground-water storage. With the first killing frost the discharge of water by vegetation ceases. The first appreciable precipitation thereafter is accompanied by recharge of the swamp soils and the ground-water reservoir, a rise in the water table, and an increase in runoff, including an increase in the ground-water runoff. From late autumn throughout the winter the water table remains at or near land surface in the swamps. Ponded water is present during most of this time on the swamp surfaces. Some of this water comes directly from precipitation, some comes from streams by overbank flooding, and possibly some comes from upward seepage of ground water derived from the stratified deposits near the periphery of the reservoir. In the spring the melting snow and the spring rains assure a high water table, a full ground-water reservoir, and saturated swamp soils. Water remains ponded on the swamps. The rate of runoff of the Ipswich and its tributaries is high.

The growing season begins. Water is discharged from the swamps to the atmosphere by evaporation and transpiration. The ground-water reservoir continues to discharge to the streams, but there is very little if any recharge to the ground-water body. For a time runoff is sustained by surface runoff from swamp storage—that is, water temporarily stored on the swamp surfaces—as well as by effluent ground water. Finally the swamp surfaces dry up and streamflow is sustained principally by ground water. If the summer is unusually dry, the antecedent moisture conditions in the swamp soils may be generally unfavorable to surface runoff except after heavy extended rains. These conditions remain to the end of the water year.

In this part of the Ipswich basin the towns of Reading, North Reading, and Wilmington draw their water supplies from wells. Also, water is diverted directly from the Ipswich River by the cities of Lynn and Peabody (see fig. 8), which are outside the Wilmington-Reading area.

Some wells may draw water principally from ground-water storage in their immediate vicinity. Others not only draw water from ground-water storage locally but also induce recharge from nearby streams during at least part of the year. During periods of no surface runoff the flow of these streams consists of ground-water runoff, and, in effect, some of the water from wells that induce recharge is imported by way of the streams from upstream parts of the ground-water reservoir.

RECHARGE

Ground water in the Wilmington-Reading area is derived from precipitation within the area, principally by the direct infiltration of rain or snowmelt but partly by the infiltration of surface water. Because some of the precipitation is lost by evapotranspiration and some runs off directly to streams, only part of it is available for ground-water recharge. Nevertheless, under existing conditions the annual precipitation, which on the basis of past records averages about 41 inches and is at least 26 inches even in a dry year, is sufficient to recharge the ground-water body to approximate capacity each year.

Recharge follows an annual cycle. During the growing season (see p. 6) most rainfall is retained in the soil to replenish the more or less continuing soil-moisture deficiency that results from losses by evapotranspiration. Consequently, except during an unusually wet late spring or summer, recharge occurs infrequently and usually only in small amounts. Ordinarily most of the annual recharge occurs during the remainder of the year, from about the middle of October to April, which period may therefore be considered as the annual recharge season. During this period the soil-moisture conditions generally are favorable with respect to recharge, and except when frost impedes or prevents infiltration an appreciable part of the rain or snowmelt on the intake areas may percolate to the water table.

The intake (recharge) areas are determined chiefly by geologic and topographic conditions. For example, places underlain by permeable deposits that have ample room to store ground water are favorable for recharge. Also favorable is flat or gently sloping land because surface runoff is minimal and the opportunity for infiltration, maximal. In contrast, places underlain by relatively impermeable deposits or by deposits that are fully saturated so as to afford no room for additional water are unfavorable for recharge. Places where slopes are steep and the rate of surface runoff is correspondingly high are likewise unfavorable.

The principal intake areas in the Wilmington-Reading area are the outcrop areas of outwash and ice-contact deposits. These deposits are sufficiently permeable to absorb water readily. At most places and at most times they have enough storage capacity to accept all potential recharge. Also, the landforms typical of these deposits generally have flat surfaces which afford maximum opportunity for recharge whenever rain or snowmelt occur. Under natural conditions the infiltration of rain or snowmelt is the main source of recharge in these areas, but the infiltration of runoff from adjacent hills may be a source of recharge locally.

Outcrop areas of till and bedrock also are intake areas, but the quantity of recharge per unit area is comparatively small owing to the low permeability and storage capacity of till and bedrock and the relatively steep slopes of the land surface. The only source of recharge in these areas is direct precipitation.

The significance of the lowland swamps as intake areas is uncertain. As noted earlier the permeability of the swamp deposits is low enough to impede the movement of water between the surfaces of the swamps and the outwash beneath the swamp deposits. Nevertheless, despite their retarding effect, it is unlikely that swamp deposits prevent recharge entirely. At times when the difference in head between the water in the swamp deposits and the water in the underlying outwash permits downward movement of water from the swamp deposits, even very slow leakage from the swamp deposits would total an appreciable volume of recharge over an area of swampland as large as that in the Wilmington-Reading area.

The flat, poorly drained swamp surfaces afford maximum opportunity for recharge. In addition to direct precipitation they gather runoff from adjacent higher land, and commonly they are flooded intermittently each year, usually at times during the recharge season and early part of the growing season, by the overflow of streams. The streams overflow their banks under existing conditions whenever the discharge at the gaging station at South Middleton exceeds approximately 125 cfs (Commonwealth of Mass., 1955, p. 6). Figure 5 shows the annual distribution of discharge in excess of 125 cfs at South Middleton. During the period 1938–57, the authors calculate that the swamps were flooded by the streams an average of 9 weeks each year. During the period 1938–52 the swamps were flooded an average of 7 weeks each year (Commonwealth of Mass., 1955, p. 6). (See p. 59.) The apparent disparity is due to the difference in the periods of record used in deriving the averages; the period 1952–57 was one of greater than average precipitation (table 1) and therefore also was a period of higher than average runoff (table 6). The actual duration of ponding on the swamps is unknown but is appreciably longer each year than the duration of overbank flooding. Especially significant is the fact that each year some flooding took place in April or May, during the early part of the growing season.

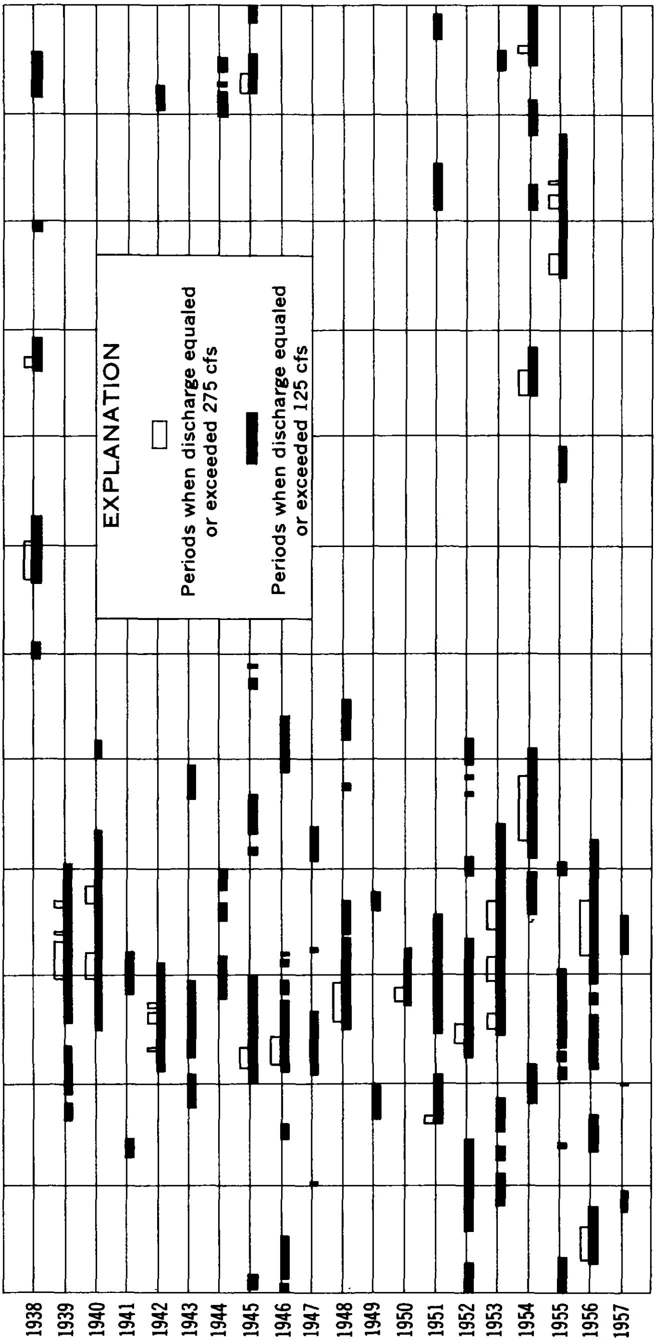

FIGURE 5.—Graph showing times during 1938–57 when discharge of the Ipswich River at South Middleton equaled or exceeded 125 cfs and equaled or exceeded 275 cfs.

During much of the recharge season and the early part of the growing season water is ponded in the swamps, and the water table is at or near swamp surface. These conditions indicate that the potential recharge rate in the swamp area exceeds the rate at which water can move through the underlying materials and that much of the available recharge is therefore rejected. It should be noted, however, that so long as water remains ponded on the swamps replacement or some or all of the water discharged from the ground-water body is assured. During the latter part of the growing season, when the deposits underlying the swamps are not fully saturated, flooding seldom occurs and most direct preciptation is retained by the swamp soils. Thus, despite the favorable position of the swamps, substantial recharge in the swamp area probably occurs only infrequently. Recharge in the swamp areas is most likely to accompany precipitation and flooding at the beginning of the recharge season after the swamp soils have been primed but before the underlying outwash has been fully saturated again. Recharge also may accompany unusually high rainfall and flooding during the growing season if the water table is low; for example, recharge probably occurred in the swamp areas in the late summers of 1954 and 1955 as an aftermath of hurricanes that crossed southern New England.

DISCHARGE

Ground water is discharged both naturally and artificially. It is discharged naturally through springs and by evaporation, transpiration, and effluent seepage, and it is discharged artificially by wells and artificial drains.

Natural discharge.—Ground water is discharged by seepage where the water table intersects the land surface or is intersected by effluent (gaining) streams. In the Wilmington-Reading area some ground water may be discharged to the swamps when the water table is high—at times during the spring, winter, or late autumn. Some ground water also is discharged to the few ponds in the area, but most of it is discharged to the Ipswich River and its tributaries. Except in the vicinity of major ground-water developments—such as that at the Reading 100-acre well field—these streams usually are effluent, although with the decline of the water table during an unusually dry summer the upper reaches of the headwaters sometimes cease to flow in the late summer or early autumn.

Springs also discharge ground water, but in the Wilmington-Reading area springs are few and the quantity of water discharged from them is small. Only two springs were inventoried during this investigation, both in the town of Lynnfield. Sagamore Spring, at the

Sagamore Golf Club in Lynnfield, is unused; Pocahontas Spring, located at the head of Wills Brook about 0.4 mile south of Sagamore Spring, yields about 150 gpm. The water is bottled and sold for drinking water.

During the recharge season, particularly in the early part of the spring season, numerous small seepage springs form in low places, but these are unimportant with respect to water supply. Small seepage springs form also at points of contact between bedrock and overlying unconsolidated deposits. Small fracture springs are especially noticeable along road cuts during the winter. The few springs that are developed, such as Sagamore and Pocahontas Springs, are difficult to classify as the natural openings have been enlarged and encased.

Transpiration of ground water occurs where the roots of plants penetrate the capillary fringe (a belt overlying the zone of saturation and containing capillary interstices, some or all of which are filled with water that is continuous with the water in the zone of saturation but is held above that zone by capillarity acting against gravity) or the water table. Evaporation of ground water occurs where the capillary fringe or water table is near or at the land surface. The swamps are the principal areas of ground-water discharge by evapotranspiration.

No determination of the amount of ground water discharged by evapotranspiration was made by this report. For the Pomperaug Basin, a glaciated area in Connecticut, the ground-water evaporation computed for a 3-year period averaged 6.27 inches annually or about 27 percent of the total evaporation (Meinzer and Stearns, 1929, p. 139). This included transpiration of ground water and evaporation from springs, seepage areas, and streams. If the ratio of ground-water evapotranspiration to total exapotranspiration were about the same for both the Pomperaug Basin and the Wilmington-Reading area, the ground-water evapotranspiration for the latter would average about 5 inches annually. However, because the ratio of swampland (which has a high potential for the evapotranspiration of ground water) to total area is much larger for the Wilmington-Reading area than for the Pomperaug Basin, the average annual ground-water evapotranspiration for the Wilmington-Reading area probably exceeds 5 inches.

A small quantity of ground water, less than 0.1 cfs or 65,000 gpd, is discharged from the area as underflow through outwash and ice-contact deposits along the Ipswich River at the east edge of the Wilmington-Reading area. (See p. 11.)

In contrast to recharge, which is intermittent, discharge is continuous. During the recharge season—generally October to April—

the rate and amount of ground-water runoff are large, and in comparison the amount of discharge by evapotranspiration is small; during the growing season the rate and amount of ground-water runoff usually are small, but in comparison the rate and amount of discharge by evapotranspiration are large.

Artificial discharge.—In the Wilmington-Reading area nearly all the ground water discharged artificially is from wells of the municipal water-supply systems in the towns of North Reading, Reading, and Wilmington. The quantity of water discharged by privately owned wells is negligible. In 1957 the average daily discharge from wells is estimated to have been about 2.5 million gallons.

Nearly all the ground water withdrawn by the town of Reading, about half of the total annual withdrawal for the area, is discharged outside of the Ipswich River drainage basin. Except for a small quantity of water actually consumed, the water withdrawn by North Reading and Wilmington is discharged within the area and eventually becomes available for further use within the drainage basin.

Ground water is discharged by effluent seepage to artificial drains in the same manner as to streams. Some artificial drainage has been undertaken in the area, mostly by way of open ditches, but the amount of ground water discharged thereby probably is small. Additional drainage is contemplated (see p. 59).

ESTIMATES OF EFFECTIVE RECHARGE

Under natural conditions recharge ultimately is disposed of in two ways: It is returned to the atmosphere by evapotranspiration, or it is discharged to streams, where it forms the ground-water runoff. The component of recharge represented by ground-water runoff is subject to recovery and use by man; it is termed "effective recharge." Effective recharge cannot be measured directly. However, by applying hydrologic principles and knowledge of the characteristics of the Wilmington-Reading area to the analysis of precipitation and runoff data, limits for effective recharge were set, and these limits, in turn, furnished a basis for estimating effective recharge.

Values of base runoff ordinarily closely approximate ground-water runoff and therefore provide a good measure of effective recharge. In the Wilmington-Reading area, where base runoff contains some surface-water runoff from swamps, these values cannot be so used; however, they set an upper limit for effective recharge and furnish an index for changes in effective recharge from year to year. Estimates of the base runoff for the water years 1931–59 were made for the Wilmington-Reading area by C. E. Knox of the Geological Survey from a study of stream discharge at South Middleton during rainless

718–172 O—64——4

periods (see table 6). During the period 1931–59, the estimated annual base runoff ranged from 7.15 inches in 1941 to 19.40 inches in 1956; the median was 12.21 inches, and the average was 11.69 inches. During 5 consecutive years, 1940–44, the annual base runoff was less than the median, and during another period of 5 consecutive years, 1947–51, it was less than or did not exceed the median. It is significant that the annual base runoff was less than 8 inches for 2 consecutive years, 1949–50. Figure 6 is a graph showing the frequency of annual

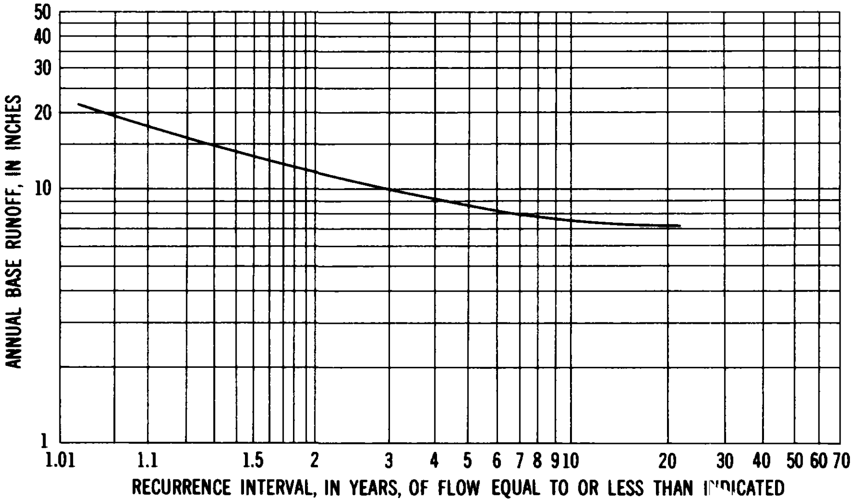

FIGURE 6.—Frequency curve of annual base runoff from the Wilmington-Reading area for the period 1931–59 based on records of streamflow of the Ipswich River at South Middleton, Mass.

TABLE 6.—*Yearly runoff and estimates of base runoff based on records of streamflow of the Ipswich River at South Middleton, Mass.*

Water year	Adjusted runoff [1] (in.)	Estimated base runoff [2] (in.)	Water year	Adjusted runoff [1] (in.)	Estimated base runoff [2] (in.)
1931	[3] 21.50	11.82	1946	27.14	14.93
1932	[3] 15.00	8.25	1947	16.49	9.07
1933	[3] 32.20	17.70	1948	23.20	12.21
1934	[3] 22.90	12.60	1949	13.47	7.41
1935	[3] 23.90	13.15	1950	14.10	7.76
1936	[3] 22.60	12.42	1951	20.77	11.42
1937	[3] 20.55	11.30	1952	28.77	15.82
1938	[3] 32.05	17.65	1953	23.94	13.17
1939	24.71	13.59	1954	30.09	16.55
1940	19.44	10.69	1955	26.59	14.62
1941	13.00	7.15	1956	35.28	19.40
1942	16.19	8.90	1957	14.03	7.72
1943	20.35	11.19	1958	28.90	16.44
1944	15.67	8.62	1959	21.07	11.59
1945	24.51	13.48			

[1] Runoff adjusted for diversions for municipal supplies of Reading, Lynn, and Peabody.
[2] Includes adjustment for diversion of ground water withdrawn by municipal water-supply systems of Reading.
[3] Estimates based on comparison of runoff at South Middleton with runoff at gaging station near Ipswich.

base runoff during the period 1931–59. This shows, for example, that on the average the recurrence interval of base runoff of 8 inches or less is once in 7 years.

By a careful choice of assumptions it is possible to arrive at a set of values that purposely err on the low side and therefore set a lower limit for effective recharge. These assumptions are: (1) Recharge occurs only in the outcrop area of ice-contact deposits and outwash; and (2) the rate of runoff for the whole area may be used as a conservative estimate of the rate of effective recharge for the areas underlain by the ice-contact deposits and outwash. Calculations were made using as assumed rates of effective recharge for the ice-contact and outwash deposits, the average annual runoff (22 in.), the greatest annual runoff (35 in.), and the least annual runoff (13 in.) for the period 1931–59. Then, the size of the outcrop area (13½ sq mi) of the ice-contact and outwash deposits was multiplied by the assumed rate of effective recharge for these deposits and the product was divided by the size of the whole area. The results represent, for the Wilmington-Reading area as a whole, a lower limit for average annual effective recharge (7 in.), the greatest annual effective recharge (11 in.), and the least annual effective recharge (4 in.) for the period 1931–59. The basis for adjudging these values to err on the low side is discussed in the following paragraphs.

The first assumption—that recharge occurs only in the outcrop area of ice-contact deposits and outwash—imparts to the calculations an error on the low side because recharge also occurs in till and bedrock areas and probably in swamp areas. The second assumption—that the rate of runoff for the whole area may be used as a conservative estimate of effective recharge for the areas underlain by ice-contact deposits—also introduces an error on the low side. The basis for this assumption and its validity are examined below.

Runoff for the Wilmington-Reading area, which is computed on the basis of streamflow records for the Ipswich River at South Middleton, represents an integration of runoff from all types of terrane within the area. Likewise, water loss (evapotranspiration), which is computed as the difference between runoff and precipitation, represents an integration of losses from all types of terrane. It is reasonable to assume that the swamps, which occupy about one-fourth of the area, sustain water losses at a rate higher than the upland parts of the area where water is not constantly exposed to the atmosphere and to the roots of plants. From this it follows that the remaining three-fourths of the area, including places underlain by ice-contact deposits and outwash, sustains water loss at a rate lower than that for the area as a whole and therefore must have a potential rate of runoff higher than for the area as a whole.

For reasons cited on page 38 there is little surface runoff from places immediately underlain by ice-contact deposits and outwash. In these places most of the water percolates downward and is transmitted to streams as ground-water runoff. As suggested in the preceding paragraph, the potential rate of runoff from the ice-contact deposits and outwash is probably larger than the rate of runoff computed for the area as a whole. If this is so, the rate of runoff for the whole area may be used as a conservative estimate of the rate of effective recharge for the areas underlain by the ice-contact deposits and outwash.

The actual rate of effective recharge should lie somewhere between the upper and lower limits established in the paragraphs above. For purposes of computation later in this report a set of values halfway between the extremes is arbitrarily chosen as the best estimate of effective recharge. On this basis the annual effective recharge in the Wilmington-Reading area during the period 1931–59 ranged from about 5 inches (10 mgd) to about 15 inches (30 mgd) and averaged about 10 inches (20 mgd).

It should be noted that nearly all the effective recharge for the entire area is available to the ground-water reservoir because, regardless of where the recharge occurs, most of the ground water so derived passes through the reservoir or the overlying swamp deposits on the way to the streams.

FLUCTUATIONS OF WATER LEVELS AND CHANGES IN GROUND-WATER STORAGE

Water-level fluctuations are an index to seasonal and long-term changes in ground-water storage. A rising water table reflects net recharge and an increase in the amount of ground water in storage; conversely, a declining water table reflects net discharge and a decrease in the amount of ground water in storage. These fluctuations are illustrated by hydrographs for seven wells (fig. 7). Long-term records of ground-water levels in six wells (Reading 1, Wilmington 10, 29, 56, 58, and 78) shown in figure 7 have been published in annual water-level reports for the years 1939–57 (U.S. Geol. Survey, 1940–60).

The hydrographs show a marked seasonal fluctuation. At the end of the growing season, in September or October, the water table usually is at its lowest position. Thereafter, the first appreciable amount of precipitation is accompanied by a sharp rise in the water table as the ground-water body is replenished. Throughout the winter

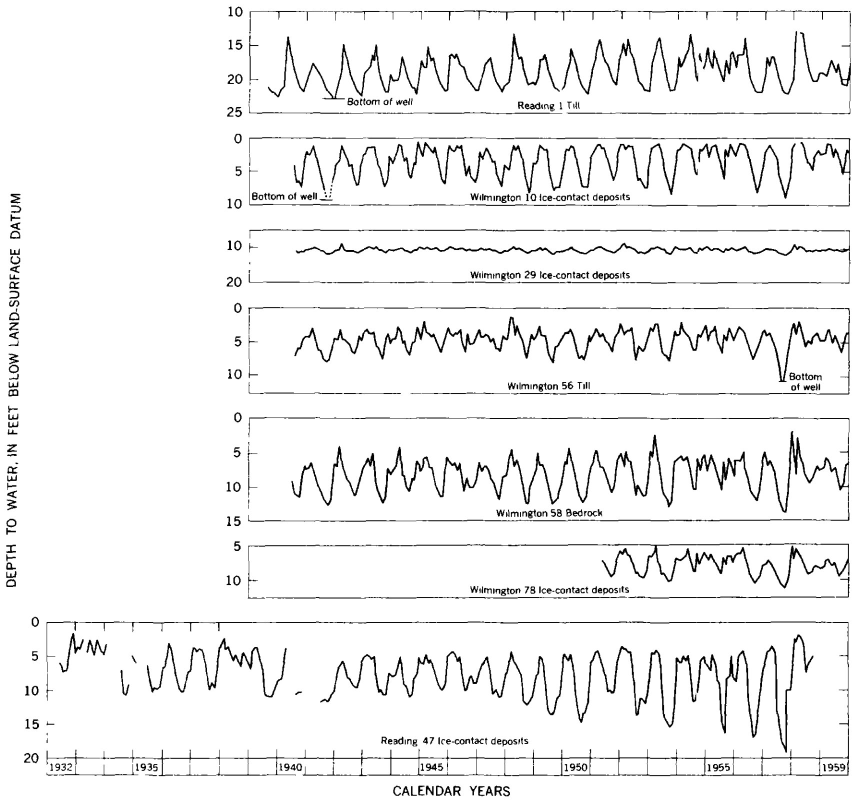

FIGURE 7.—Hydrographs of selected wells in the Wilmington-Reading area, Mass. Record for well Reading 47, 1932–56, based on lowest monthly water levels measured by town of Reading. Record for 1957–58 based on monthly measurements by U.S. Geological Survey.

months the water table may remain high, with recharge and discharge roughly in balance. On the other hand, during cold winters when most precipitation is stored as snow the water table sometimes declines in midwinter; later on it rises as a result of thawing ground, snowmelt, and rainfall in late winter or early spring. The water table usually is at its highest position in late winter or early spring. Then, usually in March or April, with the advent of the new growing season and the consequent increased loss of water by evapotranspiration, the frequency and duration of periods of recharge decrease and the water table declines sharply. Throughout the summer, discharge exceeds recharge, and the water table continues to decline as the ground-water body is depleted. Finally, after the growing season, the water table rises as the cycle begins again.

In response to the many variations in the frequency, rate, and amount of recharge and discharge local fluctuations of water level are superimposed upon the general seasonal trends. Some of the more significant short-term fluctuations are recorded by the monthly hydrographs. For example, owing to the appreciable amount of recharge from the rainfall that accompanied hurricanes "Carol" and "Edna" in August and September 1954 and hurricanes "Connie" and "Diane" in August 1955, a large unseasonable rise of the water table was recorded near the end of the summer in each of those years.

The hydrographs show no long-term trend even in the vicinity of the Reading well field (see hydrograph of well Reading 47, fig. 7), where withdrawals are relatively large and have increased progressively from year to year. Only the fall low water levels show a progressive decline in this well field. (See p. 69.) During the period of record, the water level in each well reached nearly the same peak for that well each year. Withdrawals from the parts of the groundwater body whose fluctuations are shown by wells Wilmington 10, 29, 56, 58, 78, and Reading 1 are not large; the hydrographs therefore represent natural conditions. They are the basis for the statement, made earlier, that under natural conditions the gound-water body is replenished fully each year. (See p. 38.) Were the yearly peak water levels to show a progressive decline, it would indicate that the average annual rate of withdrawal exceeds the average annual rate of replenishment.

USE OF GROUND WATER

In the Wilmington-Reading area nearly all ground water withdrawn is used for public water supplies. The locations of the municipal water supply facilities are shown in figure 8. The development of ground water for public supplies began about the turn of the century. The quantity of ground water withdrawn was small at first, but over the years it increased and in 1946 it averaged about 1 mgd (million gallons per day). From 1947 to 1957 the annual withdrawal more than doubled, and in 1957 it averaged about 2.5 mgd. Pumpage (for water years) by the towns of North Reading, Reading, and Wilmington for the period 1930–57 is given in table 7.

Records of the Massachusetts Department of Public Health show that the town of Reading installed a municipal water-supply system in 1890. The water was obtained from a filter gallery near the Ipswich River about half a mile west of Highway 28. High iron content of water from the filter gallery necessitated installation of treatment facilities in 1910. Five bedrock wells (well group Reading 107 and well Reading 108) were drilled in the area adjacent to the

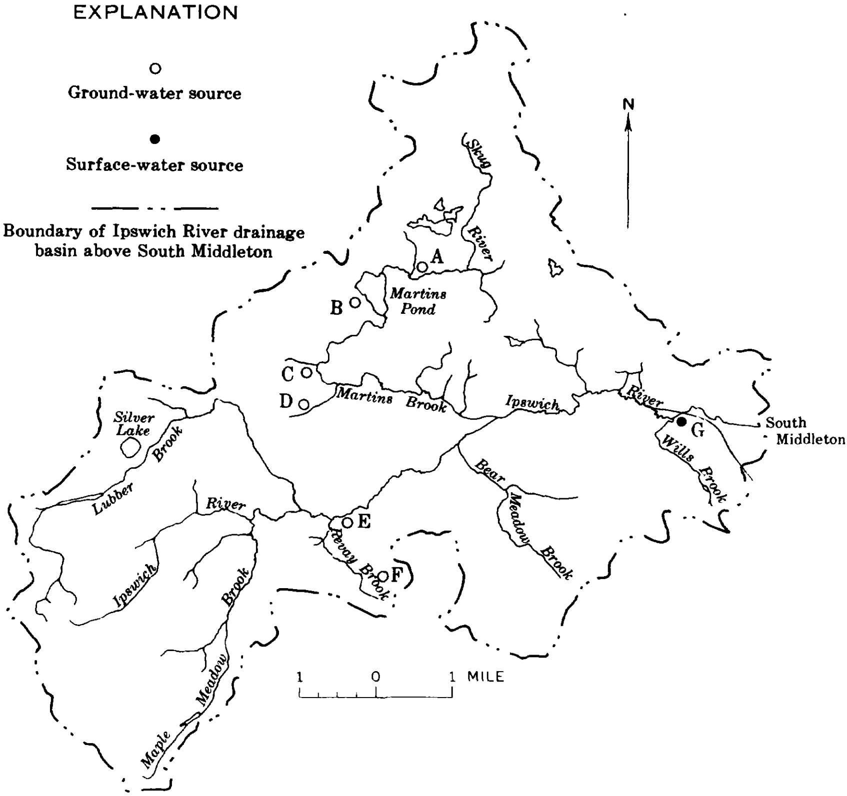

FIGURE 8.—Map of the Wilmington-Reading area showing location of municipal pumping stations. A, North Reading Skug River well field; B, North Reading Martins Pond well; C, Wilmington Salem Street well field; D, Wilmington Woburn Street well field; E, Reading 100-acre well field; F, Reading Revay Brook well field; G, Lynn-Peabody (Ipswich River).

filter gallery in 1915–17 to augment the supply from the filter gallery which had become inadequate. In 1931 the filter gallery and the five bedrock wells were abandoned, and the 100-acre well field, near the Ipswich River about half a mile east of the Wilmington-Reading town line (see Area A, pl. 1), was developed. The 100-acre well field consists of more than one hundred 2½-inch diameter driven wells and one 8-inch and three 24-inch gravel-packed wells. The wells reportedly range in depth from 28 to 68 feet. To augment the supply from the 100-acre well field, two 24-inch gravel-packed wells were installed in the Revay Brook area in 1958 and 1959. These wells reportedly are 51 and 37 feet deep.

The water supply for the town of Wilmington is obtained from two well fields. The older well field includes 61 driven wells, which

TABLE 7.—*Pumpage of ground water, in millions of gallons, for municipal supplies for North Reading, Reading, and Wilmington, Mass.*

[Compiled from records of town water departments and Massachusetts Dept. Public Health]

Water year	North Reading		Reading		Wilmington		Total	
	Annual	Avg. daily	Annual	Avg. daily	Annual	Avg. daily	Annual	Avg. daily
1930					23.9	0.065		
1931			236.1	0.65	28.9	.079	265.0	0.73
1932			160.4	.44	37.9	.10	198.3	.54
1933			170.2	.47	39.1	.11	209.3	.57
1934			208.3	.57	60.2	.16	268.5	.73
1935			243.6	.67	56.1	.15	299.7	.82
1936			258.2	.71	70.1	.19	328.3	.90
1937			211.1	.58	83.9	.23	295.0	.81
1938			212.4	.58				
1939			239.8	.66	99.0	.27	338.8	.93
1940			250.4	.69	80.7	.22	331.1	.91
1941			242.6	.67	96.7	.26	339.3	.93
1942			230.4	.63	90.3	.25	320.7	.88
1943			226.2	.62	88.8	.24	315.0	.86
1944			243.7	.67	108.5	.30	352.2	.97
1945			229.9	.53	99.6	.27	329.5	.90
1946			254.8	.70	130.3	.36	385.1	1.1
1947			263.0	.72	206.7	.57	469.7	1.3
1948			282.1	.77	255.7	.70	537.8	1.5
1949			323.1	.89	268.1	.74	591.2	1.6
1950			327.8	.90	285.6	.78	613.4	1.7
1951			320.6	.88	252.1	.69	572.7	1.6
1952			347.1	.95	295.1	.81	642.2	1.8
1953			383.3	1.1	324.1	.89	707.4	1.9
1954	66.0	0.18	378.2	1.0	327.3	.90	771.5	2.1
1955	114.1	.31	399.3	1.1	291.9	.80	805.3	2.2
1956	104.0	.28	424.4	1.2	326.6	.89	855.0	2.3
1957	135.4	.37	466.8	1.3	326.9	.90	929.1	2.5

were installed in 1925 and 1947 in the Martins Brook drainage area 0.7 mile northeast of the junction of Salem Street and Highway 62; this well field is referred to in this report as the Salem Street well field. The newer well field includes 30 driven wells installed in 1957 about 0.8 mile south of the original well field; the newer well field is referred to in this report as the Woburn Street well field. At both places the wells are 2½ inches in diameter. The reported depths of the wells at the Salem Street well field range from about 39 to about 84 feet. The reported depths of wells at the Woburn Street well field are on the order of 30 feet.

Part of the water supply for the town of North Reading is obtained from Wilmington. The remainder is obtained from a group of 10 driven wells and 1 gravel-packed well near the Skug River about half a mile east of Martins Pond and from 1 gravel-packed well on the west shore of Martins Pond.

No inventory of ground-water pumpage for privately owned domestic and industrial water supplies in the Wilmington-Reading area was made for this report, but the amount probably is less than 5 percent of the amount withdrawn for public-water supplies.

QUALITY OF WATER

Ground water in the Wilmington-Reading area is of suitable chemical quality for most uses. Chemical analyses were made of eight samples collected from wells tapping water in unconsolidated deposits and of two samples collected from wells tapping water in bedrock. The analyses of water from these wells are shown in table 8. Chemical constituents commonly found in ground water, and their significance with respect to the use of the water, are shown in table 9.

There appear to be no significant differences in the quality of the water from the unconsolidated deposits. The dissolved solids ranged from 37 to 92 ppm (parts per million) ; the hardness ranged from 17 to 41 ppm; and the pH ranged from 5.7 to 7.0. Water with a pH lower than 7.0 is on the acid side of the pH scale, though within the range of 5.7 to 7.0 free acid is not present. The iron content of the eight samples analyzed ranged from 0.14 to 2.1 ppm and the manganese content ranged from 0.00 to 0.26 ppm.

The dissolved-solids contents of the two samples of water from bedrock were 94 and 127 ppm; the hardness values were 56 and 82 ppm; and the pH values were 7.7 and 7.9. The iron contents were 0.08 and 0.50 ppm, and the manganese contents were 0.00 and 0.01 ppm.

The analyses indicate that water from the unconsolidated deposits generally has a lower dissolved-solids content, is softer, and has a lower pH than water from the bedrock. Iron is the most common objectionable constituent of water from both the unconsolidated deposits and the bedrock.

Iron in excess of about 0.3 ppm is objectionable because it stains fabrics, utensils, and fixtures and may impart an unpleasant taste to the water. (See table 9.) The concentrations of iron exceed 0.3 ppm in four of the eight samples of water from unconsolidated deposits and in one of the two samples of water from bedrock. High concentrations of iron in the water caused the town of Reading to abandon a filter gallery in the Ipswich River valley about half a mile west of Highway 28 and to construct treatment facilities for the removal of iron from water obtained at the 100-acre well field.

The factors controlling the concentration of iron in the water cannot be determined from the few data available. The data suggest that water from the stratified deposits has the highest concentrations of iron, but the iron concentrations vary widely from place to place.

TABLE 8.—*Chemical analyses, in parts per million, of water from selected wells in the Wilmington-Reading area, Mass.*

[Analytical results in parts per million except as indicated]

Well	Depth of well (ft)	Geologic unit	Date of collection	Temperature (° F)	Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na) and potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (residue on evaporation, dried at 180° C)	Hardness as $CaCO_3$: Calcium, magnesium	Hardness as $CaCO_3$: Noncarbonate	Specific conductance (micromhos at 25° C)	pH
Lynnfield 60	180	Bedrock	May 3, 1957	46	17	0.08	0.00	14	5.0	8.5	60	0	18	4.4	0.2	0.0	94	56	7	147	7.7
North Reading 67	19.1	Outwash	May 2, 1957	51	11	.42	.01	11	2.7	11	24	0	19	10	.1	12	92	39	19	146	6.0
70	14	Till	May 3, 1957	52	9.8	.24	.00	5.6	1.0	5.3	11	0	12	3.7	.1	3.0	45	18	9	65	6.1
73	32	Ice-contact deposits.	do	51	22	2.1	.26	10	2.0	6.4	41	0	8.1	4.7	.2	.1	73	33	0	97	7.0
110	18.9	do	do	57	11	.36	.00	14	1.3	7.8	29	0	21	3.8	.1	7.4	83	41	17	127	6.5
Reading 114	37	do	May 1, 1957	45	14	.14	.12	11	2.2	7.6	25	0	19	7.7	.1	2.1	82	37	16	118	6.2
Wilmington 19	8.6	Till	May 6, 1957	47	4.8	.14	.00	7.5	1.0	3.9	9	0	10	4.5	.0	8.0	47	23	15	72	6.2
102	9.9	Outwash	May 1, 1957	48	7.0	.64	.00	5.8	.5	4.1	10	0	12	3.0	.1	.6	37	17	9	56	5.7
113-31, 332-47, 368-94	26-84	Ice contact deposits	do	52	15	.14	.06	8.2	1.8	6.0	22	0	13	5.7	.2	1.3	62	28	10	90	6.3
183	125	Bedrock	May 2, 1957	49	11	.50	.01	23	5.8	15	109	0	16	5.3	.4	.1	127	82	0	216	7.9

TABLE 9.—*Elements and substances commonly found in ground water (after Price, 1956, table 2)*[1]

Constituent	Source	Significance
Silica (SiO_2)	Siliceous minerals present in nearly all formations.	Forms hard scale in pipes, boilers. Inhibits deterioration of zeolite-type exchange material in water softeners.
Iron (Fe)	The common iron-bearing minerals present in most formations.	Oxidizes to a reddish-brown sediment. More than about 0.3 ppm stains laundry and utensils reddish brown, is objectionable for food processing and beverages; larger quantities impart taste, and favor the growth of iron bacteria.
Manganese (Mn)	Manganese-bearing minerals	Rarer than iron; in general same objectionable features; brown to black stain.
Calcium (Ca) and magnesium (Mg).	Minerals that form limestone and dolomite and occur in some amount in most formations. Gypsum also 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.	In 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 forms carbonate scale on application of heat and releases corrosive carbon dioxide gas.
Sulfate (SO_4)	Gypsum, iron sulfides and other rarer minerals, common in waters from coal mining operations and many industrial wastes.	Sulfates of calcium and magnesium form hard scale.
Chloride (Cl)	Found in small to large amounts in all soils and rocks; natural and artificial brines, sea water, sewage.	In large enough amounts may give salty taste, objectionable for various specialized industrial uses of water.
Fluoride (F)	Various minerals of widespread occurrence, in minute amounts.	Fluoride in excessive concentrations is undesirable in waters 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), sometimes fatal. Waters of high nitrate content should not be used for baby feeding.

[1] Based on data in reports of California State Water Pollution Control Board (1952) and Hem (1959).

Ground-water temperatures at the Reading 100-acre well field and surface-water temperatures in the Ipswich River at a nearby point were measured weekly during the period from July 9, 1956 to May 2, 1957. The ground-water and surface-water temperatures are plotted in figure 9. For comparison, air temperatures at Lowell are also shown in this figure. The average ground-water temperature was about 48° F, which is approximately the mean annual air temperature. The ground-water temperature ranged from 44° F in the spring to 53° F in the autumn. The high and low ground-water temperatures lagged behind the high and low air and surface-water temperatures during the year.

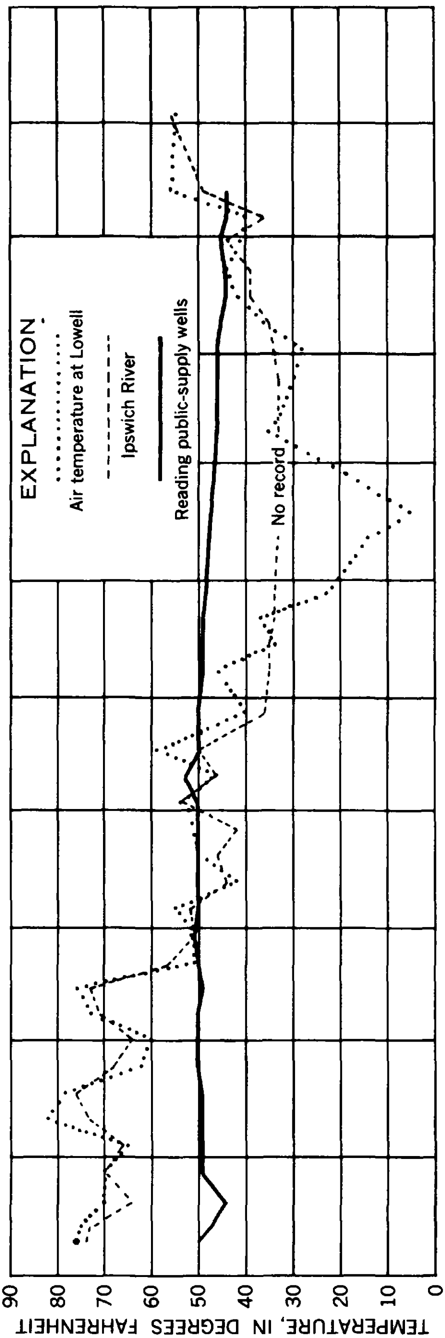

FIGURE 9.—Graphs showing temperatures of ground water, surface water, and air from July 1956 to May 1957.

UTILIZATION OF THE GROUND-WATER RESERVOIR

Basically the usable water supply of the Wilmington-Reading area is limited by the rate at which the use of water can be sustained from storage, whether in surface reservoirs or the ground-water reservoir or a combination of both, during the summer and fall seasonal period—lasting more than 4 months—when streamflow is nearly all utilized and little recharge from precipitation takes place. (See p. 12.) Utilization of the ground-water reservoir as the storage medium is discussed below in terms of potential recharge, storage capacity, and feasibility of withdrawing the ground water.

Recharge sets the upper limit of the sustained or so-called perennial yield of a ground-water reservoir, just as inflow to a surface reservoir determines its yield. On the basis of the best estimate of average annual effective recharge (see p. 46), a total withdrawal from the ground-water reservoir in the Wilmington-Reading area could be sustained at a rate of about 10 inches (20 mgd) providing the reservoir were large enough to store the surplus water during wet years for use during dry years. If storage were insufficient to carry over surplus water from year to year but large enough to satisfy the demand during the summer and early autumn, the sustained yield would be governed by the least recharge to be expected in a single year; this, on the basis of the best estimate of least annual effective recharge, would average about 5 inches (10 mgd). In either situation surface runoff is a potential source of additional recharge wherever wells can induce infiltration from streams.

The storage capacity of a ground-water reservoir determines the length of time the yield can be sustained without recharge or with less than normal recharge. For instance, a reservoir with a large storage capacity can sustain some withdrawal for a limited period without any recharge; conversely, a very small reservoir must be recharged at a rate more or less equal to that of the withdrawal. The ground-water reservoir in the Wilmington-Reading area was estimated to store between 30 to 60 billion gallons. (See p. 36.) Wells probably can dewater only a small part of the volume for which storage was estimated, but an average of only a few feet of saturated material need be dewatered during the annual critical period in order to sustain a rate of withdrawal equal to the average rate of least annual effective recharge (about 10 mgd). For example, the dewatering by wells of an average of only 1 foot of saturated material over the area of the ground-water reservoir, assuming a specific yield of 20 percent, a conservative value, would provide about 1 billion gallons, which over a period of 150 days averages about 7 mgd.

From the above discussion it is apparent that both recharge to the ground-water reservoir and the storage capacity of the reservoir are sufficient to sustain a total withdrawal of ground water from the Wilmington-Reading area at several times the 1957 rate of about 2½ mgd. Therefore, the feasibility of withdrawing the ground water is the critical problem.

Because of the low permeability of most of the outwash and the low permeability or small saturated thickness of some of the ice-contact deposits, a large part of the ground-water reservoir can yield only small amounts of water to individual wells. To utilize directly the storage in this part of the reservoir would require a wide distribution of numerous small-capacity wells—an impractical measure. Thus, it is concluded that the factor limiting the development of the reservoir is the distribution of areas of relatively thick permeable materials capable of yielding moderate or large amounts of water to individual wells. A qualitative appraisal of the potentialities of this part of the reservoir is made in the following paragraphs in this section. For purposes of the appraisal the Wilmington-Reading area is divided into three subareas: (1) The Ipswich valley above Martins Brook, (2) the Ipswich valley below Martins Brook, and (3) the Martins Brook-Skug River drainage area. The boundaries of the subareas are shown in figure 10.

Most of the ground-water reservoir in the Ipswich valley above the mouth of Martins Brook is in the town of Wilmington. The available data indicate that in the Ipswich valley above Martins Brook the reservoir consists principally of outwash and a few small bodies of ice-contact deposits. Records of wells and the relationships of outcrops of till and bedrock to the ice-contact deposits suggest that most of these deposits have a small saturated thickness. Also, some of the ice-contact deposits are relatively fine textured and probably are no more permeable than the outwash. This part of the subarea has not been fully explored, and it is possible that permeable ice-contact deposits are concealed by the outwash. The chances of finding relatively thick saturated deposits appear best east and north of the village of Wilmington where, according to the sparse subsurface data and the distribution of a few scattered outcrops of bedrock, the buried channel of the preglacial Ipswich may bend northwestward roughly parallel to the lower course of Lubber Brook (see p. 20 and p. 2). In the rest of the Ipswich valley above Martins Brook, in Reading and North Reading, the reservoir consists principally of a complex of ice-contact deposits. This part of the reservoir is undergoing intensive development by the town of Reading, by means of wells at the 100-acre well field and near Revay Brook.

The ground-water reservoir in the Ipswich valley below the mouth of Martins Brook occupies parts of Reading, North Reading, and Lynnfield. Along the Ipswich River the reservoir consists principally of outwash of lacustrine origin, whose permeability is generally low (see p. 31). Parts of this body of outwash extend from the main valley northward along the small unnamed brook draining Eisenhoures Pond and southward into the areas drained by Wills Brook and probably into Cedar Swamp. Small bodies of ice-contact deposits were mapped along the periphery of Cedar Swamp and near Wills Brook, but the relationships of outcrops of till and bedrock to these deposits suggest that they have small saturated thicknesses. The logs of test holes indicate that the chances of finding buried permeable materials are remote. Several test holes near the Ipswich River have been drilled to depths between 50 and 100 feet without penetrating permeable materials. Nevertheless, because most of these test holes were drilled only to refusal, the absence of permeable materials near the bottom of the preglacial valley has not been demonstrated conclusively. Some further exploration near the river may, therefore, be justified. The interior of Cedar Swamp has not been explored.

The ground-water reservoir in the Martins Brook-Skug River drainage basin underlies an area of about 8 square miles in Wilmington and North Reading. The reservoir is formed principally of ice-contact deposits, which in 1957 furnished water at an average rate of 1.3 mgd to the municipal wells of Wilmington and North Reading. These deposits partly fill one or two buried channels. If, as postulated earlier (p. 20), the buried channel or channels lead to the Ipswich valley, the unconsolidated deposits along whatever route is followed must be more than 85 feet thick between well Wilmington 389 and the Ipswich valley and more than 65 feet thick between well North Reading 186, at Martins Pond, and the Ipswich valley. Records of wells and test holes coupled with field observations suggest that the ice-contact deposits, although highly diverse, contain enough permeable materials to yield water in moderate quantities to wells at many places.

From the existing information it appears likely that several properly placed wells of moderate or large capacity could draw water directly from at least half of the Martins Brook-Skug River reservoir area. Excluded is the part of the reservoir in the upper two-thirds of the Skug River basin, where the ice-contact deposits appear to be thin and to have low permeabilities. Also excluded are parts of the reservoir fringe, where the deposits also appear to be thin. If it is assumed that the reservoir materials have a specific capacity of at least 20 percent, the dewatering by wells of 4 feet of the reservoir over an area of 4 square miles would sustain an average withdrawal of at least 4½ mgd during a 5-month period. Nearly all recharge in the Martins Brook-Skug River drainage basin, which covers about 13 square miles, is potentially available to the ground-water reservoir here. Using the value for least annual effective recharge derived earlier (p. 46), 5 inches, the potential recharge in this area is sufficient to sustain an annual withdrawal of at least 3 mgd. This estimate is conservative because the drainage basin in the Martins Brook-Skug River area has a higher proportion of permeable surficial materials favorable to recharge than does the Wilmington-Reading area as a whole, and because the surface runoff is a source of additional recharge wherever and whenever wells can induce infiltration from streams.

In summary, based on the available data, the chances of finding thick permeable materials in the part of the ground-water reservoir in the Martins Brook-Skug River drainage basin appear good; the chances of finding substantial bodies of thick permeable materials in the ground-water reservoir elsewhere in the Wilmington-Reading area probably are small, but the deeper parts of the preglacial valleys have not been fully explored.

Another factor that should be given attention in considering the use of the ground-water reservoir is its response to water and land developments within the drainage basin. Those parts of the reservoir where withdrawals of ground water depend or are likely to depend partly upon induced recharge are particularly sensitive to developments that effect changes in the streamflow from upstream areas. For example, water diverted for water supply in the headwaters area of the Ipswich—whether from the ground-water reservoir or directly from a stream—could not for some time contribute to the streamflow from that area, even if the diverted water were to be ultimately returned to the drainage basin. The potential of the Ipswich as a source of induced recharge downstream would be changed accordingly. Other developments, such as artificial drains, changes in land cover, and major construction, also may change the operation of the hydrologic system and, as a result, may affect the use of the reservoir. The effects of developments in general are beyond the scope of this report, but the potential effects of specific measures proposed by the Massachusetts Department of Public Works to drain swampland in the upper part of the Ipswich River drainage basin are discussed in the section that follows.

THE EFFECTS OF DRAINAGE ON GROUND-WATER CONDITIONS

In 1953 the Commonwealth of Massachusetts authorized and directed the Department of Public Works "to make a study and investigation of the Ipswich River, and to determine particularly the necessary improvements of said river for the purpose of draining the swamp areas in the town of Wilmington * * *." (Commonwealth of Mass., 1955, p. 1.) The purpose of the drainage project is to permit a wide range of land uses in the area to be drained. The swamplands cover an area of 4.3 square miles in Wilmington. Because the channels necessary to drain the swamps in Wilmington would extend into Reading and North Reading, 1.4 additional square miles of swamp adjacent to the Ipswich River and Martins Brook in the latter two towns would be drained. About 1.5 square miles of nearby swamp probably would be partly drained.

Subsequently, the Department of Public Works received numerous requests for information as to the effect of the drainage on the water table and the ground-water supplies in the area. Particular concern was expressed as to the effect of the drainage on the municipal supply of the town of Reading. At the request of the Department of Public Works the Geological Survey agreed, as part of a water-resources investigation in the Ipswich River basin, to define and describe the elements of the geology and hydrology that bear on the relationship of the Reading public-water supply to the Ipswich River—the results to serve as a basis for indicating more specific investigation of that particular problem if necessary.

To provide the necessary background for discussion of the drainage problem, pertinent parts of a special report by the Department of Public Works (Commonwealth of Mass., 1955, p. 5–9) are quoted below. The extent of the proposed channel improvements is shown in figure 10.

Under the existing conditions the channels of the Ipswich River and Martins Brook (a tributary which drains swamps in the northeasterly part of Wilmington) meander through swamp lands in Wilmington, Reading and North Reading. There are intermittent reaches where the Ipswich River flows in a well-defined channel with no swamps bordering the stream. The stream banks and bordering swamps generally have a heavy growth of trees and brush which seriously impedes flood flows.

In the swamp areas of Wilmington, Reading and North Reading the streams overflow their banks when the discharge at the South Middleton stream gaging station exceeds a discharge of approximately 125 cubic feet per second. During the period between June, 1938, and September, 1952, the swamps were flooded seven weeks per year on the average. The period that these swamps have been flooded has varied from two weeks in dry years to fifteen weeks

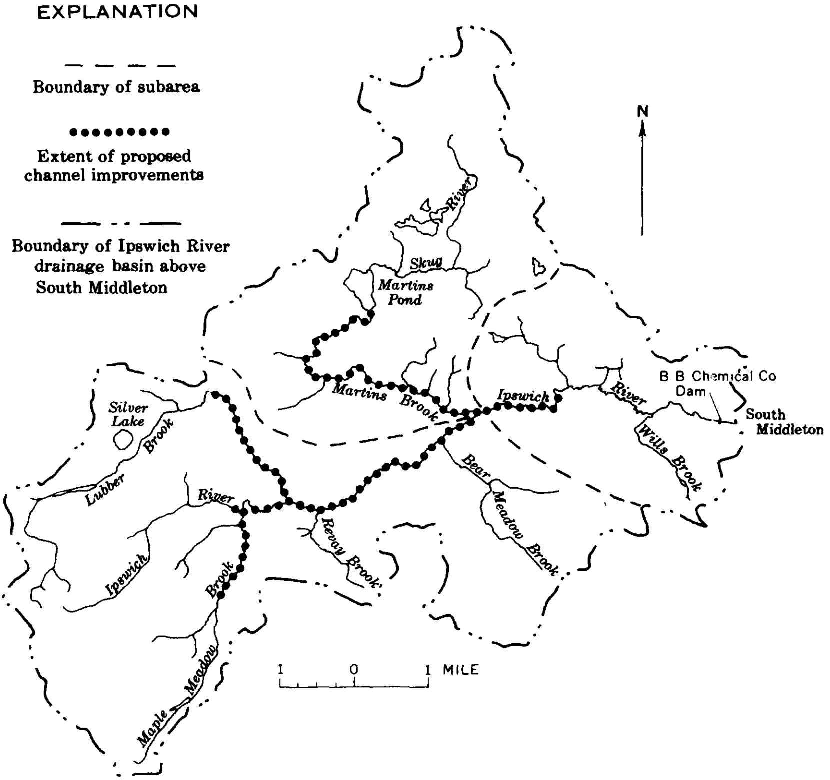

FIGURE 10.—Map of Wilmington-Reading area showing boundaries of subareas and extent of proposed channel improvements. (Modified from Commonwealth of Massachusetts, 1955, fig. A.)

in wet years. The peak flow since the South Middleton gaging station was established (June. 1938) was 646 cubic feet per second on March 21, 1948. The median yearly peak flow between June, 1938, and September, 1954, is approximately 350 cubic feet per second.

A minor flood computed by the Kinnison-Colby formula is 1,100 cubic feet per second, and for the purpose of design one half of this computed discharge was used for the main outlet channel in North Reading and a discharge computed separately for the tributary streams. It is pointed out that this design figure will provide adequate land drainage channels which will not, however, handle large flood discharges. The swamps would occasionally be flooded, but the flooding would be of short duration.

* * * * * * *

In order to adequately drain the swamps of Wilmington which lie on the Ipswich River, Lubber Brook and Maple Meadow Brook, the required channel work should begin in the vicinity of Washington Street in the town of North Reading and extend into Wilmington.

From Washington Street to the junction of Martins Brook near Chestnut Street, a new channel for the Ipswich River, having a bottom width of 40 feet and a depth of 5 feet, would be required. In this reach of the river new bridges would be required at Haverhill Street, Central Street and Chestnut Street because the proposed river bed will be below the bottom of the abutments and it is not considered feasible to under pin these abutments.

From the junction of Martins Brook in North Reading to the junction of Lubber Brook near Woburn Street in Wilmington, a channel for the Ipswich River, having a bottom width of 35 feet and a depth of 5 feet, would be required. A new bridge would be required at Mill Street in the towns of Reading and North Reading. A new bridge will be necessary at Woburn Street in the town of Wilmington.

A new channel for the Ipswich River from Lubber Brook to Maple Meadow Brook, having a bottom width of 35 feet and a depth of 5 feet, will be required.

A new channel for Lubber Brook from the Ipswich River upstream to the Boston & Maine Railroad (at a point southerly from Salem Street), having a bottom width of 15 feet and a depth of 4 feet, will be required.

Maple Meadow Brook from the Ipswich River to the Boston & Maine Railroad southerly from South Main Street in Wilmington will require a channel having a bottom width of 15 feet and a depth of 5 feet.

Martins Brook from its junction with the Ipswich River in North Reading to Salem Street in Wilmington will require a channel having a bottom width of 35 feet and a depth of 4 feet.

Other minor ditches may be required to drain some of the swamp lands distant from the main channels. It is probable that a new bridge will be necessary at Salem Street, Wilmington, and new culverts at Concord Street and Wildwood Street.

* * * * * * *

From an examination of hydrographs with discharges from 250 to 300 cubic road southerly from South Main Street in Wilmington will require a channel improvements are completed, the same flood would produce discharges of approximately 500 c.f.s. to 600 c.f.s. It is apparent that for discharges greater than 550 c.f.s. (the design capacity of the proposed channel below the junction of Martins Brook) flood water would again begin to store on the swamps. Although all discharges in the new channels would be greater than under existing conditions, the greatest increase would occur for approximately the annual flood. For large floods the new channels would not have much effect. These estimates disregard the storage in the new channels which cancels part of the loss of swamp storage.

* * * * * * *

It is pointed out that some minor corrections in the channel downstream from North Reading may be found to be necessary after the swamps of Wilmington have been drained.

GENERAL EFFECTS

Two principal effects of drainage bear on the ground-water situation: (1) An increase in the effectiveness of evapotranspiration as an agent of drainage in the swamp areas; (2) an increase in the ability of the ground-water reservoir to discharge water to streams.

The first effect—an increase in the effectiveness of evapotranspiration as an agent of drainage in the swamp areas—is implicit in the purpose of the program. Under existing conditions ponded water is available during part of the growing season to replace soil moisture and ground water discharged from the swamp area by evapotranspiration. If the swamp surfaces are drained at an earlier time each growing season and flooding is virtually eliminated during the growing season, the ponded water will no longer be available, and the period of net discharge of soil moisture and ground water by evapotranspiration will be extended accordingly. The total quantity of water discharged from the area, whether derived from surface water, soil moisture, or ground water by evapotranspiration may be smaller than under existing conditions and the runoff from the area will be increased correspondingly. However, the volume of earth materials actually dewatered by evapotranspiration will be larger.

The second effect—an increase in the ability of the ground-water reservoir to discharge water to the streams—is implicit in the means whereby drainage is to be accomplished. That is, the deepening, straightening, and widening of stream channels so as to increase their capacity to discharge water will be accompanied by a general lowering of stream levels. This, in effect, will lower the base level to which the water table adjacent to a functioning stream grades and will permit larger hydraulic gradients to develop within the ground-water reservoir. Furthermore, wherever dredging increases the area of effluent seepage, removes relatively impermeable mud and silt from the channels, or cuts more deeply into outwash or ice-contact deposits a better hydraulic connection will be established between the streams and the ground-water reservoir; as a consequence the rate of seepage to the streams will be increased. It is assumed that periodic maintenance of the improved channels will prevent excessive silting, which otherwise would reduce the permeability of the streambed.

If it is assumed that the objectives of the drainage program will be accomplished successfully by the methods proposed and with the general effects noted above, several tangible results may be predicted with a fair degree of assurance. These results are described below, in relationship, first, to the recharge season, and second, to the growing season.

The net change in ground-water conditions during the recharge season probably will be minor. Draining the swamp surfaces and reducing the frequency and duration of flooding will reduce the potential recharge available in the swamp areas and will eliminate swamp storage as a significant contributor to the base flow of the streams. There will be some lowering of the water table in the immediate vicinity of improved stream channels and supplemental drains, but for the area in general, it is probable that ground water moving into the subjacent deposits from peripheral areas and intermittent recharge from rain and snowmelt directly on the swamps will assure a high water table and a full or nearly full ground-water reservoir. Also, the Massachusetts Department of Public Works (p. 61) expects that floods that now produce discharges of 250 to 300 cfs will continue to cause some flooding of the swamps. For purpose of illustration the figure 275 cfs is used (fig. 5). The base flow from the area will be reduced as a consequence of the loss of much of the swamp storage increment. However, this reduction may be partly compensated for by an increase in ground-water runoff as a consequence of the increased capacity of the ground-water body to discharge water to streams.

During the growing season the proposed drainage measures will prolong and intensify drought conditions. Net discharge of soil moisture and decrease in ground-water storage will commence earlier in the growing season and will continue for a longer period of time than under present conditions. This, coupled with the more rapid discharge of water from the ground-water reservoir to the streams after recharge ceases, will result in an earlier beginning of the seasonal decline of the water table, a longer period of decline, an increased rate of decline, and a larger total decline. Thus, at any given time during a dry summer the stage of the water table in the area to be drained will be lower under the new conditions than it would have been under existing conditions. As a further consequence of the drainage measures, low-flow conditions in the streams will prevail earlier in the season, and will last longer; also, low flows will be smaller. Under existing conditions the uppermost reaches of the Ipswich River and some of its headwaters become dry during summer droughts, such as that of 1957, as shown by miscellaneous measurements of discharge (fig. 11 and table 10). Where improved channels extend into these reaches the new conditions will tend to aggravate this situation. Under the present proposed plan only Maple Meadow Brook is likely to be so affected.

The information on the proposed channel improvements for the Ipswich River and its tributaries provides a basis for roughly indicating the lower limits of water-table decline.

The proposed channel improvements are designed specifically to discharge water from the area to be drained at a higher rate than under present conditions. Implicit in the accomplishment of this objective is an increased rate of stream discharge at any given stream stage or, conversely, a lowered stage at any given rate of discharge. From this, providing the drainage measures are successful, it follows that: (1) There will be general lowering of water levels along all improved stream channels above the point where the level of the

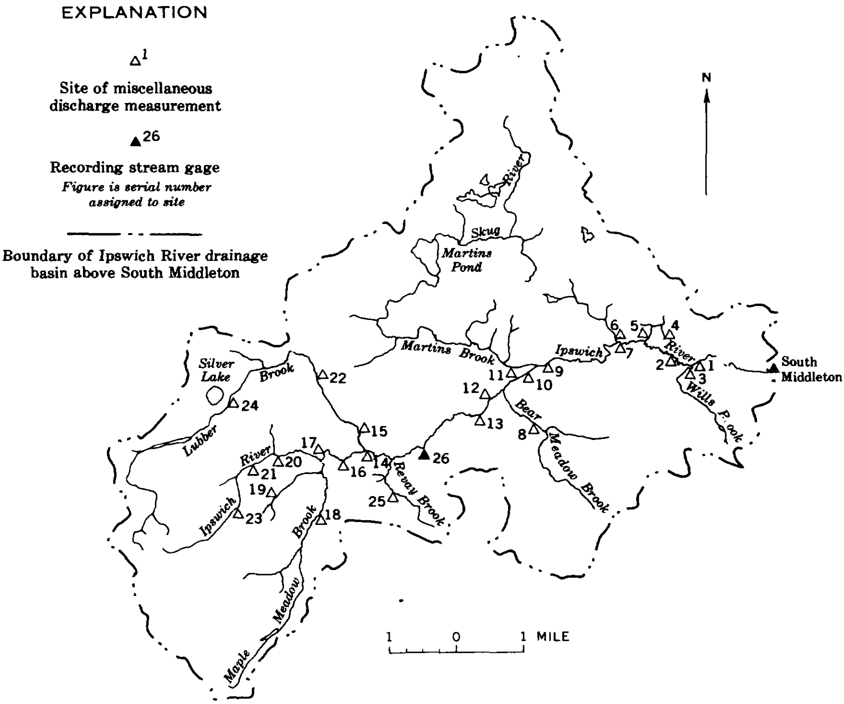

FIGURE 11.—Map of the Wilmington-Reading area showing discharge measurement sites.

Ipswich River is controlled by the dam of the B.B. Chemical Co. (fig. 10); (2) where a channel is deepened the water level will be lower, for any given discharge, by at least the amount of the deepening. The base level to which the water table grades along a functioning reach of stream will be lowered accordingly.

At most places the channel will be deepened only 2 or 3 feet, and nowhere will it be deepened more than about 4½ feet. Thus, immediately adjacent to the improved reaches the water table at most places will decline no more than 2 or 3 feet and nowhere will it decline more than about 4½ feet. The amount of decline will decrease progressively away from each channel and will vary with the duration of each period of dry weather. If supplementary drains are not dug, the area of significant decline of the water table may be restricted to the vicinity of the streams. If supplementary drains are dug, the extent of the area of significant decline will increase with the increase in drain density.

Besides the general effects described in the foregoing paragraphs, drainage may be accompanied by various secondary effects, such as changed rates of erosion and sedimentation and land subsidence. For

TABLE 10.—*Miscellaneous measurements of discharge, in cubic feet per second, of the Ipswich River and selected tributaries in the Wilmington-Reading area, Massachusetts*

[Records from Surface Water Branch, Geol. Survey]

NV, no velocity; NF, no flow; D, dry; SF, some flow; P, ponded; e, estimated; P-D, ponded below and above measuring point at bridge or culvert and dry at measuring point.

Station			Drainage area above station (sq mi)	Name of stream	Aug. 28, 1956	June 26, 1957	July 17, 1957	Sept. 4, 1957	Sept. 25, 1957
Tributary from north	Main stream	Tributary from south							
	1		42.22	Ispwich River	P	NV	P	P	P
		3	1.18	Wills Brook	0.08	0.2	D	NF	D
	2			Ipswich River	P	NV	P	P	P
4				Unnamed tributary	NF	NF	D	D	D
5				do	D	D	D	D	D
6			2.31	do	D	.06e	D	D	D
	7		37.70	Ipswich River	.48	2.18	0.08	0.06	0.03
		8	4.47	Bear Meadow Brook	NF	P	NF	D	D
	9		36.60	Ipswich River	.37	P	D	NF	D
	10		36.42	do	.24	2.05	.07	.02	.01e
11			13.16	Martins Brook	.34	1.07	.09	.02	D
	12			Ipswich River	NF	P	P	P	P
	13		17.87	do	NF	.92	D	P-D	D
	26		15.59	do	D	.55	D	D	D
		25	.52	Revay Brook	D	.02e	D	D	D
	14		13.74	Ipswich River	.67	1.10	.11	.01	.002
15			4.82	Lubber Brook	SF	NV	NV	.29	.05
22			4.25	do	.49	.98	.33	.47	.16
24			2.40	do	.18	.52	.23	.08	.14
	16		8.70	Ipswich River	.06	.41	.04	P-D	P-D
	17		8.32	do	.04	.48	.01	P-D	P-D
		18	4.47	Maple Meadow Brook	NF	.09	D	P-D	P-D
		19	.42	Unnamed tributary	D	D	D	D	D
	20		2.56	Ipswich River	.04	.08	.08	.02	.01
	21		1.81	do	D	.02	D	D	D
	23		1.06	do	D	D	D	D	D

instance, Latimer and Lanphear (1929, p. 55) noted that subsidence of peat and muck lands had occurred at places in Middlesex County where these lands were drained and cultivated. The factors involved in this type of problem are discussed by Stephens (1955, p. 541) and Roe (1943, p. 6–11) among others. The treatment of secondary effects is beyond the scope of this report. However, it is emphasized that such effects will tend to alter the conditions upon which the original plan for drainage was based. For example, land subsidence—were it to occur in a drained area—would be accompanied by changes in the grade relation between the drains and the land surface and by changes in the hydrologic properties of the swamp soils. Changes of this sort would, in turn, be followed by a change in the performance of the drains and by further changes in the general water situation.

EFFECTS OF DRAINAGE UPON GROUND-WATER SUPPLIES

Wells in the area to be drained generally will be affected by changes in the ground-water conditions. Probably the most obvious effect will be a lowering of water levels. This will be greatest in wells immediately adjacent to improved channels and may be almost insignificant in wells some distance away. Less obvious but not less important will be the effect of changes in low streamflow conditions on the yields of wells that induce infiltration from streams and the effect of an improved hydraulic connection between streams and the ground-water body on the yields of some of these wells. The magnitude and direction of the net effect will differ from place to place and from time to time. Consequently, with respect to the effect of drainage upon ground-water supplies, each locality requires individual study.

As an example of the potential effects of drainage upon a water supply, the Reading 100-acre well field is discussed below. A probable consequence of the drainage program, if it were undertaken, would be a decrease in the yield of this well field during drought periods. The reasoning leading to this conclusion is presented after the hydrologic setting and the existing situation at the 100-acre well field have first been described.

The Reading 100-acre well field is located on the present valley floor near the Ipswich River. (See area A, pls. 1 and 3.) The drainage area of the Ipswich River above the well field is about 17 square miles. The well field consists of over 100 small-diameter (2½-in.) driven wells and one 8-inch and three 24-inch gravel-packed wells. The reported depths of the wells range from 28 to 68 feet.

The logs of wells and test holes and the general geologic relations indicate that most of the wells are finished in ice-contact deposits. (See pls. 3 and 4.) These deposits crop out south and east of the Ipswich River. They lie along the south side of the preglacial Ipswich valley, which here seems to bend east-northeastward. The maximum known thickness of the deposits is 64 feet. To the southeast they pinch out against till or bedrock of the preglacial valley wall. Elsewhere along the mapped periphery of these deposits ice-contact slopes appear to dip beneath younger unconsolidated deposits. The extent of the buried part of the ice-contact deposits is unknown.

The younger unconsolidated deposits that overlie the ice-contact deposits consist of outwash mantled in most places by swamp deposits. The outwash thickens toward the middle of the preglacial valley. Its maximum known thickness is 75 feet. The swamp deposits range in thickness from less than 1 foot to about 20 feet.

The subsurface contact between the ice-contact deposits and the outwash is not clearly defined. The ice-contact deposits generally are coarser in texture than the outwash, but in logs of many wells the differences in texture are not great and the contact between the two units cannot be positively identified.

Most of the well field is situated in the swamp, and most of the wells pass first through a few feet of swamp deposits and associated alluvium, next through several feet of outwash, and are finished in the ice-contact deposits. Some of the shallow wells may be finished in the outwash, and a few wells penetrated ice-contact deposits without passing through outwash.

The ground water in the ice-contact deposits and outwash occurs as a single ground-water body under unconfined, or water-table, conditions. This conclusion is supported by the hydrographs of two pairs of wells in the well field. (See fig. 12.) The deeper well of each pair

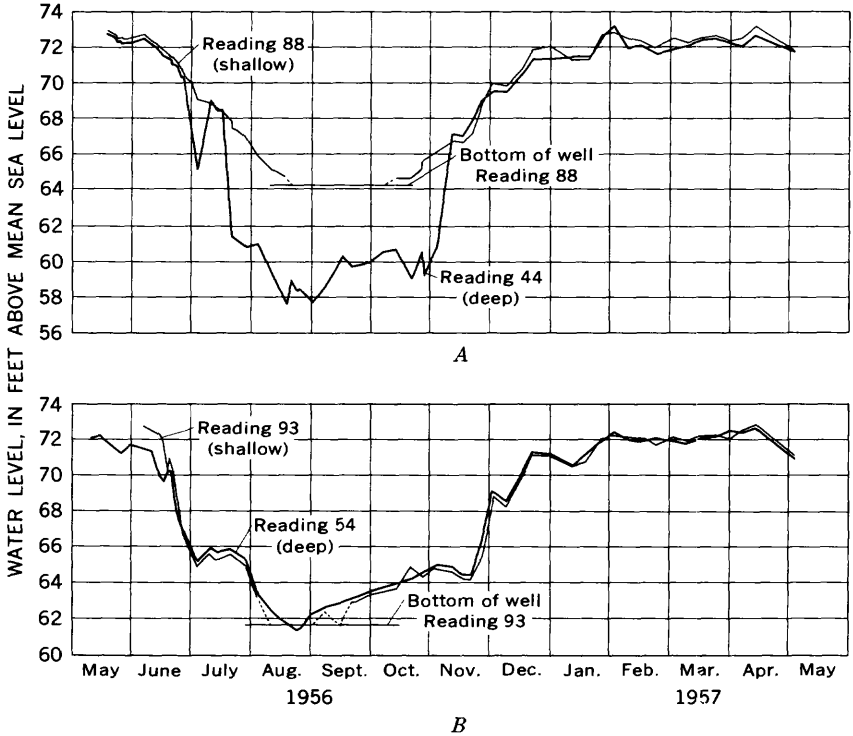

FIGURE 12.—Hydrographs showing fluctuations of water levels in paired shallow and deep wells at the Reading 100-acre well field in the Wilmington-Reading area, Mass. *A*, wells Reading 44 (deep) and 88 (shallow); *B*, wells Reading 54 (deep) and 93 (shallow).

is finished in ice-contact deposits; the shallower well is finished in the outwash overlying the ice-contact deposits. Except for the period July–November 1958, when well Reading 44 was being pumped and water levels in the well did not reflect the water level in the aquifer, the hyrdographs for each pair of wells are nearly alike. The close similarity shows that ground water can move relatively freely from the outwash to the ice-contact deposits.

The water withdrawn from the well field is derived in part from the stream and in part from the ground-water reservoir. The relative proportion from each source varies from season to season and year to year; it cannot be determined from the available data.

Observations of the Ipswich River during 1956 and 1957 offer convincing evidence of the hydraulic continuity between the stream and the ground-water body. From August 13 to September 17, 1956 and from July 28 to November 4, 1957 the Ipswich River was dry near the well field but was flowing at points upstream and downstream. It is reasonable to assume that the dry streambed was a result of seepage induced from the stream by the pumping of the Reading wells. The magnitude and rate of rise of the ground-water level in November 1957 when the stream, which had been dry in the vicinity of the well field, began to flow again is also suggestive of the interrelation between the stream and the ground-water body. The flow of the stream began in response to heavy rainfall during the few days preceding November 4, and as the growing season had ended, precipitation after November 4 was sufficient to maintain the flow of the stream past the well field. Figure 13 compares the water level in the well field, as recorded

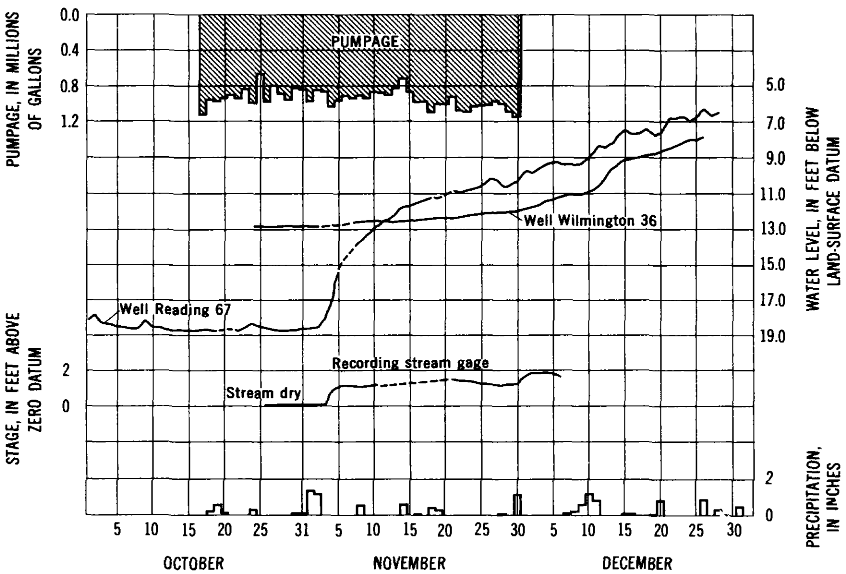

FIGURE 13.—Graphs showing pumpage, precipitation, ground-water levels, and stream stage at the Reading 100-acre well field in October–December, 1957.

at a gage on well Reading 67, with the stream stage, as recorded at a stream gage adjacent to the well field. Also graphed are records of precipitation and pumpage at the well field, and the water level at well Wilmington 36, which was unaffected by pumping and is situated so as to respond to recharge by precipitation only. The rise of stream level at the well field lagged behind the rise of ground-water level by about a day. The earlier rise of the ground-water level probably reflects some recharge from precipitation within the area of influence of the well field and recharge from the stream as its rise progressed downstream toward the well field.

The hydraulic connection between the river and the ground-water body assures the Reading 100-acre well field a supply of water equal at least to the streamflow that under natural conditions would pass the well field. During the recharge season the flow of the stream is substantially larger than the quantity of water currently pumped from the well field. However, during the rest of the year if the summer is dry the stream can furnish only part of the water pumped and the balance must be derived from storage. For example, miscellaneous discharge measurements of the Ipswich River (table 10) above the well field in summer and early autumn of 1956 and 1957, when the stream was entirely diverted, indicate that water from the stream was only a fraction of the quantity being pumped.

The relation of the above situation to ground-water levels and the yield of the well field is illustrated by figure 14, which contrasts the annual (water year) withdrawal of ground water with the annual high and low water levels at an observation well in the well field. The withdrawal for the 7 colder months, October through April, representing most of the nongrowing season and including the normal recharge period, is plotted upward from the zero base line; the withdrawal for the 5 warmer months, May through September, conforming roughly with the growing season, when recharge ordinarily is small, is plotted downward. The annual withdrawal from 1935 through 1947 was nearly uniform, and for this period no significant long-term trend of either the high or low water level can be discerned. From 1948 through 1957 the annual withdrawal generally was increased—the withdrawal during the 7 colder months being increased roughly in the same proportion as the withdrawal during the 5 warmer months. Despite the general increase in the withdrawal from year to year for the 7 colder months, the yearly peak water level remained about the same, showing that recharge was enough to balance discharge and replace the summer draft. In contrast, the progressive increase in withdrawal from year to year for the 5 warmer months was accompanied by a downward trend of the annual low water level, showing that each succeeding summer a larger quantity of water was taken from storage.

When a well draws water principally from storage in a thin water-table aquifer, such as that supplying the 100-acre well field, the drawdown may be a critical factor. Uniform increases of the pumping rate are accompanied by progressively larger increments of drawdown, and

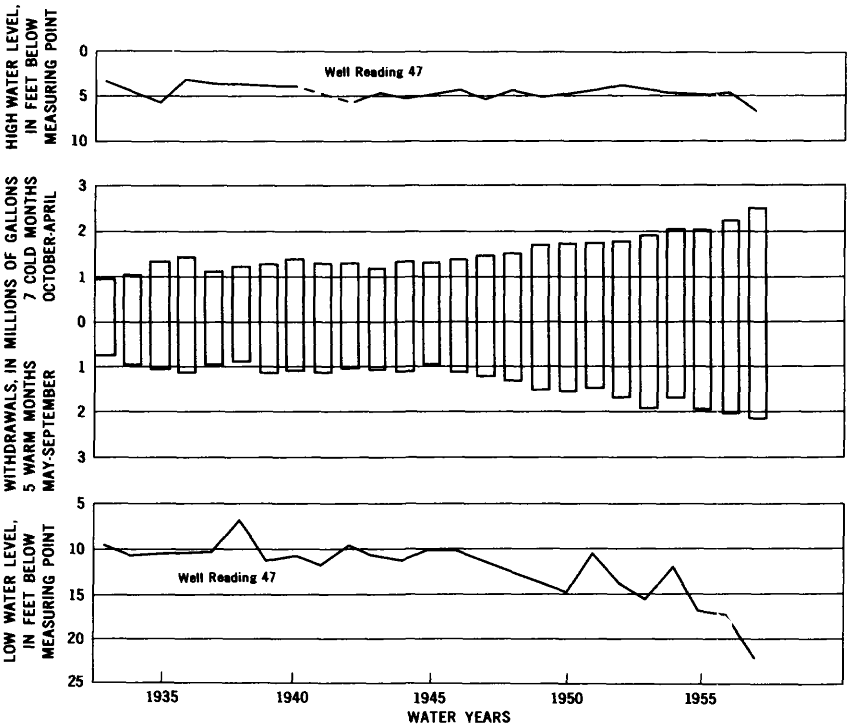

FIGURE 14.—Graph showing yearly high and low water levels and yearly pumpage at Reading 100-acre well field, 1933–57 (water years).

the specific capacity of the well decreases accordingly. In effect, the performance of the well follows the law of diminishing return, and a stage is reached where the increase in yield is too small to justify a further lowering of the pumping level. This is illustrated graphically by figure 15, which presents a theoretical comparison of the yield and drawdown of a well in an "ideal" water-table aquifer—one that is homogeneous, isotropic, and of infinite areal extent. For example, if the saturated thickness of this aquifer were 60 feet, three-fourths of the maximum possible yield of the well would be obtained at a drawdown of 30 feet, and 90 percent of the maximum yield would be obtained at a drawdown of 40 feet.

During the summer of 1957, the drawdowns at observation wells in the 100-acre well field were nearly 20 feet, or almost half the saturated thickness of the aquifer at most of the wells. Because this aquifer differs greatly from the "ideal", the field relation between yield and drawdown may differ greatly from the theoretical relations shown in figure 15. Nevertheless, the drawdowns suggest that the well field was approaching a stage of development in which each

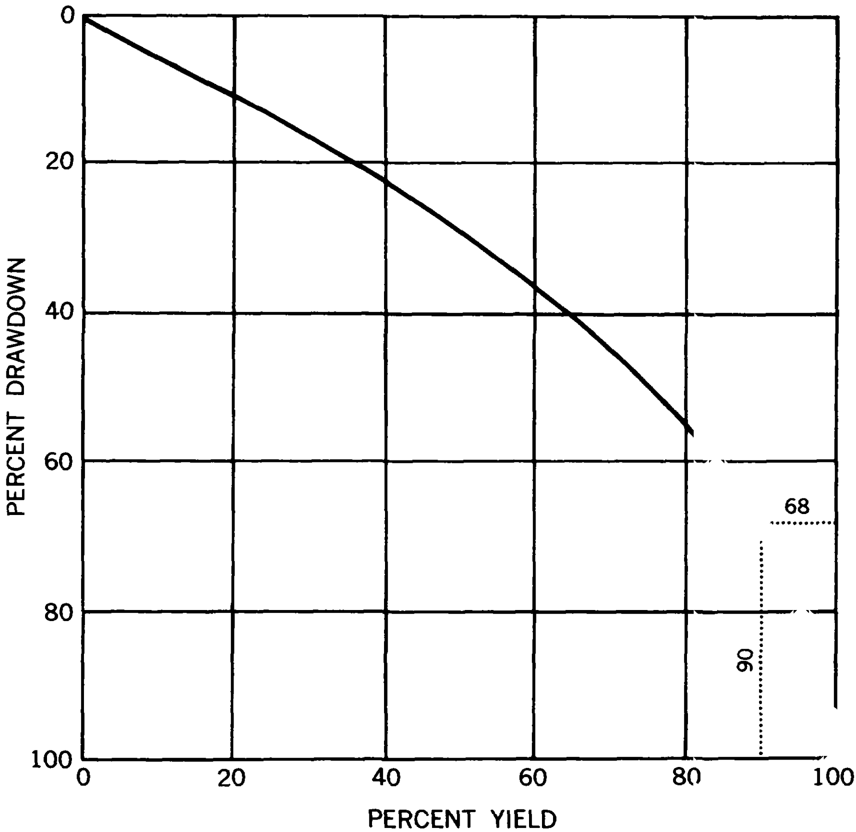

FIGURE 15.—Theoretical relation between the drawdown and the yield of a pumped well drawing water from an ideal water-table aquifer.

added increment of drawdown would produce a substantially smaller increase in the rate of yield.

It is expected that the drainage measures proposed by the Department of Public Works, if successful, will have three principal effects on the conditions at the well field: (1) The lowering of the stream level near the well field will tend to lower the whole cone of depression; (2) the improved connection between the stream and the ground-water reservoir will tend to reduce the hydraulic gradient needed for the wells to induce recharge; (3) the longer duration of low-flow conditions and the smaller low flows will reduce the contribution of the stream to the wells during the summer and early autumn.

The net effect with respect to the performance of the well field doubtless will differ from time to time. During the recharge season and whenever the stream carries water past the well field during the rest of the year the first two effects noted above will tend to counteract each other. Indeed, it is possible that the net effect then may be such as to increase the capacity of the well field to yield water. In contrast, during the summer and early autumn the smaller contribution of the stream coupled with the smaller leeway in drawdown—the result of the initial lowering of the cone of depression—will tend to decrease the capacity of the well field to yield water. In particular, the drainage measures will aggravate the situation at the well field during a severe dry summer such as 1957 when, under existing conditions, the Ipswich is entirely diverted and drawdowns are large. In the new situation the drawdowns in the well field will be larger for any given yield than in the present situation. Conversely, in the new situation the yield of the well field will be smaller for any given set of drawdowns than in the present situation.

CONTROLLED DRAINAGE

In parts of the country where subirrigation is practiced, some irrigation systems are designed to permit rapid discharge of water during high-water stages but limit drainage and control the position of the water table during dry summer months. (Renfro, 1955; Roe, 1943, p. 49.) This may be accomplished by means such as check structures equipped with flash boards. Similar measures might be employed to control drainage in the Wilmington-Reading area. The feasibility of installing and successfully managing a control system should be carefully studied.

SUMMARY OF PRINCIPAL CONCLUSIONS

1. The Wilmington-Reading area has an abundance of water and a substantial annual surplus relative to current withdrawals. However, as most of the surplus drains from the area during the late autumn, winter, and spring seasons, the usable supply is basically limited by the rate at which the use of water can be sustained from storage during the rest of the year, when little recharge takes place and streamflow often is nearly all utilized. This critical period occasionally has lasted more than 4 months.
2. The principal ground-water reservoir in the Wilmington-Reading area is formed by stratified glacial drift that partly fills a preglacial valley system. The ground-water reservoir, the lowland swamps, and the principal streams of the area are interdependent components of a single major hydrologic system.
3. Except for undesirable concentrations of iron in water in some places the chemical quality of ground water in the Wilmington-Reading area is generally suitable for most uses.

4. Recharge to the ground-water reservoir and the storage capacity of the reservoir are sufficient to sustain an annual withdrawal of ground water from the Wilmington-Reading area at several times the 1957 rate, which was about 2½ mgd.
5. The basic limiting factor with respect to maximum development of the ground-water resources is the distribution of thick permeable materials capable of yielding moderate or large quantities of water to wells. This factor determines the extent to which wells can be dispersed—hence, the degree to which the storage capacity of the ground-water reservoir can be utilized. The existing information suggests that the chances of finding thick permeable materials in widespread ice-contact deposits of the Martins Brook-Skug River drainage basin are good and that conditions there are favorable for an increase in the quantity of water currently withdrawn—perhaps to the limit set by the annual recharge. The chances of finding substantial bodies of thick permeable materials elsewhere in the Wilmington-Reading area, excepting the part of the area now being developed by Reading, probably are small. The area has not been fully explored; therefore, this conclusion should be regarded as tentative. Further exploration probably is warranted in the deepest parts of the preglacial valleys, where the stratified drift is thickest.
6. Water and land developments in the Wilmington-Reading area will affect existing and potential water supplies. In particular, those parts of the ground-water reservoir where withdrawals of water depend upon or are likely to depend upon induced recharge are sensitive to developments that affect changes in the streamflow.
7. Measures proposed by the Massachusetts Department of Public Works to drain swampland in Wilmington, Reading, and North Reading will, if successful, prolong and intensify drought conditions with respect to water supply. In the area to be drained, the seasonal decline of the water table will begin earlier, will last longer, and will be larger under the new conditions than under existing conditions. Low-flow conditions in the streams of the area will prevail earlier in the season and will last longer; also, low flows will be smaller.
8. The magnitude and direction of the net effect of drainage upon ground-water supplies will differ from place to place and from time to time depending upon each given situation and set of conditions. Probably the most obvious effect will be a lowering of static water levels in wells; this will be greatest in wells im-

mediately adjacent to improved channels but may be almost insignificant in wells some distance away. Less obvious but no less important will be the detrimental effect of changes in low streamflow conditions on the yields of wells that induce infiltration from streams and the beneficial effect of an improved hydraulic connection between streams and the ground-water body on the yields of some of these wells.

9. A probable consequence of the drainage program will be a decrease in the yield of the town of Reading 100-acre well field during droughts.

SELECTED REFERENCES

Baker, J. A., 1960, Wetland and water supply: U.S. Geol. Survey Circ. 431, 3 p.

Baker, J. A., and Sammel, E. A., 1961, Massachusetts basic-data report no. 1, ground-water series, Wilmington-Reading area: U.S. Geol. Survey open-file report, 50 p., 2 figs.

Brashears, M. L., Jr., 1941, Cooperative ground-water investigations in Massachusetts: New England Water Works Assoc. Jour., v. 56, no. 2, p. 152–156.

——— 1944, Ground-water studies in northeastern Massachusetts: New England Water Works Assoc. Jour., v. 58, no. 4, p. 307–316.

Brown, T. C., 1932, Late Wisconsin ice movements in Massachusetts: Am. Jour. Sci., Ser. 5, v. 137, p. 462–468.

California State Water Pollution Control Board, 1952, Water quality criteria: Sacramento, Calif., Pub. 3, 512 p.

Castle, R. O., 1958, Surficial geology of the Lawrence Quadrangle, Massachusetts-New Hampshire: U.S. Geol. Survey Geol. Quad. Map GQ–107.

——— 1959, Surficial geology of the Wilmington Quadrangle, Massachusetts: U.S. Geol. Survey Geol. Quad. Map GQ–122.

Chute, N. E., 1960, Glacial geology of the Mystic Lakes-Fresh Pond area, Massachusetts: U.S. Geol. Survey Bull. 1061–F, p. 187–216.

Clapp, C. H., 1921, Geology of the igneous rocks of Essex County, Massachusetts: U.S. Geol. Survey Bull. 704, 132 p., 13 pls., 4 figs.

Collins, W. D., 1925, Temperature of water available for industrial use in the United States: U.S. Geol. Survey Water-Supply Paper 520–F, p. 97–104, 4 pls.

Commonwealth of Massachusetts, 1955, Special report of the Department of Public Works relative to the drainage of swamp lands in the town of Wilmington and for such other improvements in the Ipswich River as may be necessary therefor: House doc. no. 2391.

Crosby, I. B., 1937, Ground-water conditions of parts of Middlesex, Worcester, and Norfolk Counties in the buried valleys of the preglacial Merrimack, Sudbury, and Charles Rivers: Ann. Report of the Dept. of Public Health, Commonwealth of Mass., Public doc. no. 34, year ending Nov. 30, 1937, p. 219–224.

——— 1939, Ground water in the preglacial buried valleys of Massachusetts: Jour. New England Water Works Assoc., v. 53, no. 3, p. 372–383

——— 1945, Glacial erosion and the buried Wyoming valley of Pennsylvania: Geol. Soc. America Bull., v. 56, no. 4, p. 389–400.

Crosby, W. O., 1899, Geological History of the Nashua Valley during the Tertiary and Quaternary periods: Tech. Quart., v. 12, p. 228–324.

Currier, L. W., 1941a, Disappearance of the last ice sheet in Massachusetts by stagnation zone retreat (abstract): Geol. Soc. America Bull., v. 52, no. 12, pt. 2, p. 1895.

——— 1941b, Tills of eastern Massachusetts (abstract): Geol. Soc. America Bull., v. 52, no. 12, pt. 2, p. 1895–1896.

——— 1947, Granitization and its significance as a regional metamorphic process in New England: Washington Acad. Sci. Jour., v. 37, no. 3, p. 75–86.

Currier, L. W., and Jahns, R. H., 1952, Geology of the "Chelmsford Granite" area—Field Trip no. 3, *in* Geol. Soc. America, Guidebook for field trips in New England: p. 103–117.

Cushman, R. V., Allen, W. B., and Pree, H. L., Jr., 1953, Geologic factors affecting the yield of rock wells in southern New England: Jour. New England Water Works Assoc., v. 67, no. 2., p. 77–95.

Dachnowski, A. P., 1926, Factors and problems in the selection of peat lands for different uses: U.S. Dept. of Agriculture, Dept. Bull. 1419, 23 p.

Dachnowski-Stokes, A. P., 1935, Peat land as a conserver of rainfall and water supplies: Ecology, v. 16, p. 173–177.

Ellis, E. E., 1909, A study of the occurence of water in crystalline rocks, *in* Gregory, H. E., Underground water resources of Connecticut: U.S. Geol. Survey Water-Supply Paper 232, p. 54–103.

Emerson, B. K., 1917, Geology of Massachusetts and Rhode Island: U.S. Geol. Survey Bull. 597, 289 p.

Fenneman, N. M., 1938, Physiography of the Eastern United States: New York, McGraw-Hill, 714 p.

Ferris, J. G., 1950, A quantitative method for determining ground-water characteristics for drainage design: Agr. Eng., v. 31, no. 6, p. 285–89.

Flint, R. F., 1953, Probable Wisconsin substages and late Wisconsin events in northeastern United States and southeastern Canada: Geol. Soc. America Bull., v. 64, no. 8, p. 897–919.

Harold, L. L., 1934, Relation of streamflow to ground-water levels: Am. Geophys. Union Trans., v. 15, no. 2, p. 414–416.

Hem, J. D., 1959, Study and interpretation of the chemical characteristics of natural water: U.S. Geol. Survey Water-Supply Paper 1473, 269 p., 2 pl.

Jahns, R. H., 1941, Stratigraphy of the Lowell-Fitchburg area, Massachusetts (abstract): Geol. Soc. America Bull., v. 52, no. 12, pt. 2, p. 1910–1911.

——— 1942, Origin of the Ayer granodiorite in the Lowell area, Massachusetts: Am. Geophys. Union Trans., v. 23, no. 2, p. 341–342.

——— 1943, Sheet structure in granites; its origin and use as a measure of glacial erosion in New England: Jour. Geol., v. 51, no. 2, p. 71–98.

King, F. H., 1892, Observation and experiments on the fluctuations in the level and rate of movement of ground water on the Wisconsin Agricultural Experiment Station Farm at Whitewater, Wisconsin: U.S. Dept. Agr. Weather Bureau Bull., no. 5, p. 1–74.

Knox, C. E., and Soule, R. M., 1949, Hydrology of Massachusetts: U.S. Geol. Survey Water-Supply Paper 1105, 240 p.

LaForge, Laurence, 1932, Geology of the Boston area, Massachusetts: U.S. Geol. Survey Bull. 839, 105 p.

Langbein, W. B., and Iseri, K. T., 1960. General introduction and hydrologic definitions, pt. 1 *of* Manual of hydrology: General surface-water techniques; U.S. Geol. Survey Water-Supply Paper 1541–A, 29 p.

718–172 O—64——6

Latimer, W. J., and Lanphear, M. O., 1929, Soil survey of Middlesex County, Massachusetts: U.S. Dept. Agriculture Soil Survey Rept. 26, ser. 1924, 58 p., 1 pl.

Lee, C. H., 1934, The interpretation of water levels in wells and test holes: Am. Geophys. Union Trans., v. 15, no. 2, p. 540–554, 13 figs.

Lee, F. W., Farnham, F. C. Raspet, A., and Currier, L. W., 1940, The seismic method for determining depths of bedrock as applied to the Lowell quadrangle, Massachusetts: Mass. Dept. Public Works—U.S. Geol. Survey, Coop. Geol. Proj., Spec. Paper 3, 46 p.

MacConnell, W. P., 1957, Cover mapping Massachusetts from aerial photographs, repr.: Soc. American Foresters Proc., Syracuse, N.Y., p. 159–162.

Manson, P. W., and Miller, D. G., 1954, Groundwater fluctuations in certain open and forested bogs of northern Minnesota: Minnesota Univ. Agr. Exp. Sta. Tech. Bull. 217, 29 p.

Massachusetts Cooperative Wildlife Research Unit, 1959, Classification of land cover types by towns in Middlesex County: Massachusetts Univ. Coop. Ext. Service, 59 p.

Meinzer, O. E., 1923, The occurrence of ground water in the United States: U.S. Geol. Survey Water-Supply Paper 489, 321 p.

——— 1932, Outline of methods for estimating ground-water supplies: U.S. Geol. Survey Water-Supply Paper 638–C, p. 99–144.

Meinzer, O. E., and Stearns, N. D., 1929, A study of ground water in the Pomperaug Basin, Conn.: U.S. Geol. Survey Water-Supply Paper 597, p. 73–146, 9 pls.

Mills, F. S., 1903, The delta-plain at Andover, Mass.: Am. Geol., v. 32, p. 162–170.

New England-New York Inter-Agency Committee, 1955, The resources of the New England-New York region, Massachusetts Coastal Area: pt. 2, chap. 16, sec. 4, p. IV–1 to IV–34.

Price, W. E., Jr., 1956, Geology and ground-water resources of the Prestonsburg quadrangle, Kentucky: U.S. Geol. Survey Water-Supply Paper 1359, 140 p.

Renfro, G. M., Jr., 1955, Applying water under the surface of the ground, *in* Year Book of Agriculture, 1955: Washington, U.S. Govt. Printing Office, p. 273–278.

Roe, H. B., 1943, The soil moisture and cropping problem on peat and muck lands in the northern United States: Minnesota Univ. Agr. Exp. Sta., Sci. Paper no. 2032, 72 p., pub. by U.S. Dept. Agr., Soil Conservation Service.

Sears, J. H., 1905, The physical geography, geology, mineralogy, and paleontology of Essex County, Mass.; Salem, Mass., Essex Inst., 418 p., 200 figs., 1 map.

Stearns, N. D., 1927, Laboratory tests on physical properties of water-bearing materials: U.S. Geol. Survey Water-Supply Paper 596–F, p. 121–176, pls. 11–13.

Stephens, J. C., 1955, Drainage of peat and muck lands, *in* Year Book of Agriculture, 1955: Washington, U.S. Govt. Printing Office, p. 539–557.

Theis, C. V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage: Am. Geophys. Union Trans., v. 16, p. 519–524, 3 figs.

Theis, C. V., and others, 1954, Estimating transmissibility from specific capacity: U.S. Geol. Survey open-file report, 11 p.

U.S. Dept. of Agriculture, 1957, Hydrology: U.S. Dept. Agriculture, Soil Conservation Service, Eng. Handb., 343 p.

U.S. Geological Survey, 1940–60, Water levels and artesian pressure in observation wells in the United States, pt. 1, Northeastern States: U.S. Geol. Survey Water-Supply Papers 886, 906, 936, 944, 986, 1016, 1023, 1071, 1096, 1126, 1156, 1165, 1191, 1221, 1265, 1321, 1404, 1537.

U.S. Public Health Service, 1946, Public Health Reports, repr. 2697: Washington, U.S. Govt. Printing Office, 14 p.

U.S. Weather Bureau, 1926–55, Climatological data: Washington, U.S. Govt. Printing Office.

INDEX

The U.S. Geological Survey Library has cataloged this publication as follows:

Baker, John Augustus 1925–

Geology and ground-water conditions in the Wilmington-Reading area, Massachusetts, by John A. Baker, Henry G. Healy, and O. M. Hackett. Washington, U.S. Govt. Print. Off., 1964.

v, 80 p. maps (1 col.) diagrs., tables. 24 cm. (U.S. Geological Survey. Water-supply paper 1694)

Part of illustrative matter fold. in pocket.

Prepared in cooperation with the Commonwealth of Massachusetts, Dept. of Public Works.

Bibliography: p. 74–77.

(Continued on next card)

Baker, John Augustus 1925– Geology and ground-water conditions in the Wilmington-Reading area, Massachusetts. 1964. (Card 2)

1. Geology—Massachusetts—Wilmington-Reading region. 2. Water-supply—Massachusetts—Wilmington-Reading region. 3. Water, Underground—Massachusetts—Wilmington-Reading region. I. Healy, Henry G 1917– joint author. II. Hackett, Orwoll Milton, 1920– joint author. III. Massachusetts. Dept. of Public Works. (Series)

U.S. GOVERNMENT PRINTING OFFICE. 1964 O—718-172