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The hydrogeology of Agawam, Longmeadow, East Longemeadow, and Hampden, Massachusetts

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THE HYDROGEOLOGY OF AGAWAM, LONGMEADOW, EAST LONGMEADOW, AND HAMPDEN, MASSACHUSETTS

A Thesis Presented

By

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Geology

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AND HAMPDEN, MASSACHUSETTS

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ABSTRACT

The hydrogeology of Agawam, Longmeadow, East Longmeadow, and western Hampden, Massachusetts, is examined to evaluate the actual and potential utilization of water resources in the region around Springfield, Massachusetts. The bedrock geology consists of Paleozoic metamorphic and igneous rocks and Triassic sedimentary and volcanic rocks. The surficial geology consists of a variety of glacial and proglacial deposits, and alluvial, eolian, and swamp deposits of Quaternary age. All units except the glaciolacustrine deposits yield water to wells, but the most productive aquifers are the sand and gravel deposits (especially the outwash and the buried sand and gravel) and the Triassic bedrock. These aquifers are capable of yields of 100-1000 gallons per minute. Water levels were plotted, and a regional potentiometric surface map was developed for the bedrock aquifer, thus defining areas of recharge and discharge, and general directions of ground-water flow. Fifty-six complete chemical analyses of water samples from the various water-bearing units were made. and numerous records of partial chemical analyses were collected. The chemical quality of the ground water is discussed in general and with respect to each water-bearing unit. The chemical quality varies somewhat between and within the several aquifers, but is generally good and within the U. S. Public Health Service drinking water standards. The most widespread problem is excessive iron and/or manganese. Another problem is high hardness and sulfate apparently due to the presence of gypsum in some areas of the Triassic bedrock. Some samples indicate possible pollution from sewage or road salt. Quantity

and quality requirements, and the potential of the ground-water resources of the area to satisfy these requirements are discussed. It is recommended that the buried sand and gravel and the outwash deposits be investigated in more detail for further future development as municipal supplies, or for optimum development of individual supplies. Nearly 4 million gallons per day of water is estimated to be available from the outwash of Hampden and East Longmeadow. At current rates of usage and population growth, sufficient ground-water supplies exist to satisfy the needs of the study area well into the 21st century. Artificial recharge of excess surface runoff or of treated waste waters is not considered feasible at this time, but could be feasible and desirable in conjunction with large-scale development of certain aquifers. A regional organization for the planning and development of all water resources of the Springfield region is recommended. Also recommended is the construction of a municipal sewerage system in Hampden, and the consideration of the importance of ground water to the area in the planning and conduct of waste disposal activities, and in the use and storage of hazardous substances.

INTRODUCTION

Purpose

This thesis is part of a larger study being conducted by Dr. Ward S. Motts of the University of Massachusetts on the optimum utilization and management of water in formations hydrologically connected to that stretch of the Connecticut River flowing through the metropolitan area of Springfield, Massachusetts. The purpose of the portion of the study that comprises this thesis is to examine the general hydrogeology of the area to the south of Springfield. In particular, it is intended to determine the aquifers in the area, their extent, their yield, the quality of the water in them, and the possibilities of artificial recharge to them.

Location

The area included in this study (figure 1) is located southeast, south, and southwest of Springfield, Massachusetts. It includes, from west to east, the towns of Agawam, Longmeadow, East Longmeadow, and the western part of Hampden, all in Hampden County, Massachusetts. The area lies in portions of the West Springfield, Springfield South, and Hampden, topographic quadrangles, which are bounded by 42° 00' 00" and 42° 07' 30" north latitude, and by 72° 22' 30" and 72° 45' 00" west longitude. The southern boundary of the area is marked by the Massachusetts-Connecticut state line; the western and northern boundaries are marked by the boundaries of the four towns listed above; the eastern boundary is an arbitrary north-south line drawn through west-central Hampden. The area thus defined has a maximum north-south dimension of 4.9 miles, a maximum east-west dimension of 15.1 miles, and an area of about 54 square miles.

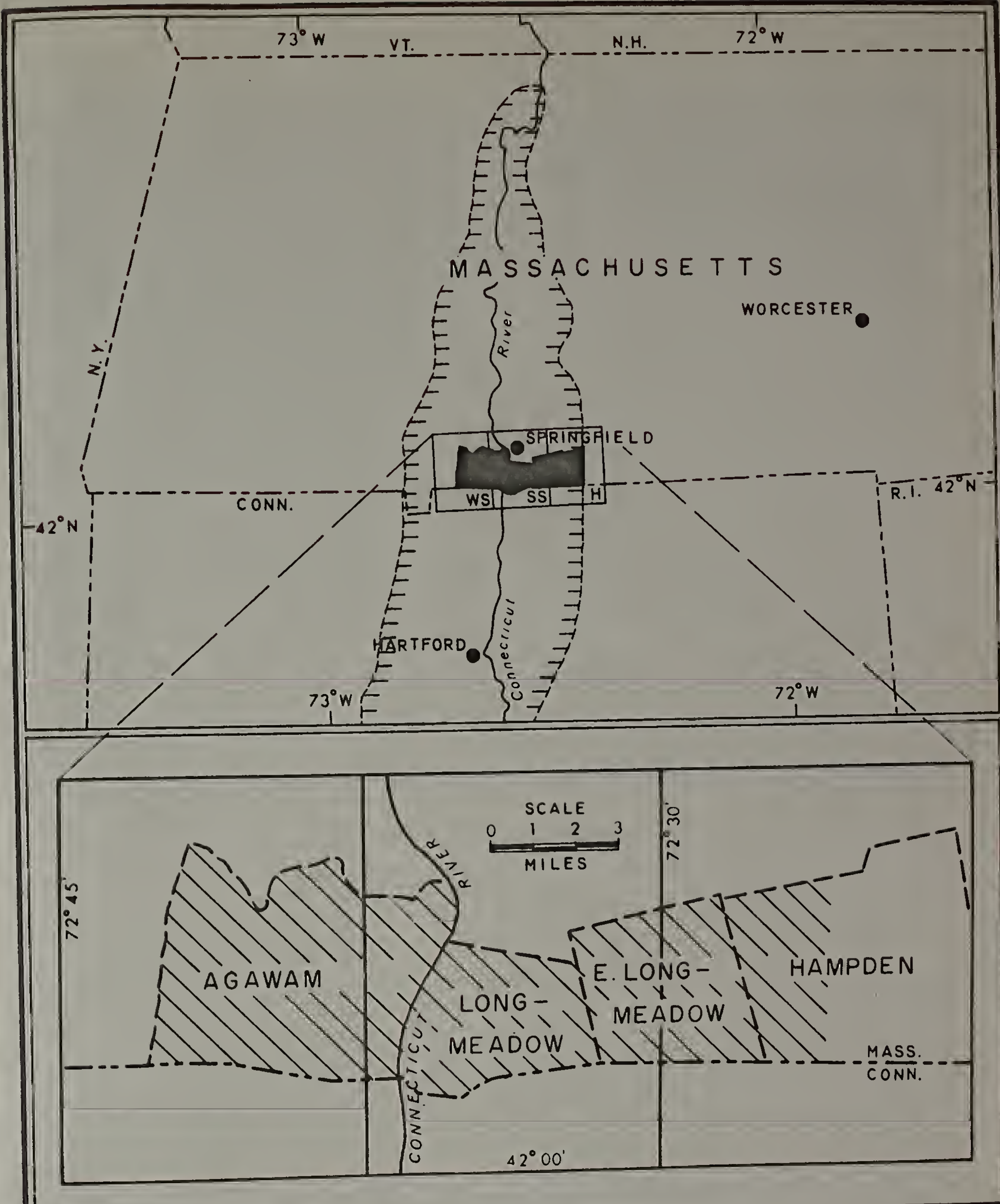

Figure 1. Location Map.
The shaded and diagonally lined areas indicate the area of this study. The hachured area (⊢) shows the approximate boundary of the Triassic Lowland.

7½-minute quadrangle designations: WS = West Springfield; H = Hampden; SS = Springfield South

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Methods of Study

Field work was done during parts of 1968 and 1969. A search of the literature was conducted throughout the course of the study to gather all published information pertinent to this thesis.

Well data were obtained primarily from the records of local water well drillers. Additional well and test boring data were obtained from the records of the Massachusetts Department of Public Health, the Massachusetts Water Resources Commission, the United States Geological Survey, and two engineering consulting firms that have done work in the area. Approximately 500 wells and test borings were scheduled. About 21 of these wells could not be accurately located, and only 485 wells and test borings were ultimately used. Monthly measurements of water levels in two observation wells--one in Triassic bedrock and the other in unconsolidated Pleistocene deposits--close to the study area were provided by the Boston office of the Water Resources Division of the U. S. Geological Survey. Only the bedrock record was considered representative enough to include in this report.

During the summer of 1968 and the summer and fall of 1969, 54 wells and 2 springs were sampled for later chemical analysis at the Water Laboratory of the Massachusetts Department of Public Health at Amherst, Massachusetts. In order to gain some historical perspective on water quality, the files of the Massachusetts Department of Public Health in Boston, Massachusetts, were examined for analyses of water from wells and springs in the area of study. The results of all chemical analyses were tabulated and analyzed by several different methods, only a few of which proved useful enough to be included in this report.

Mapping by the writer was done on a reconnaissance basis because the bulk of the geology of the area has been mapped and published by previous workers. Logs of the wells and test borings mentioned above provided substantial subsurface data, and, with rare exceptions, supported the published maps. On August 20, 1969, Mr. John Kick, graduate student at the University of Massachusetts, Department of Geology and Geography, ran two gravity profiles in northwestern Agawam in order to study the bedrock surface topography in that area. Gravity measurements can be calculated to reflect the gross topography of the bedrock surface, and have been used in this manner with some success in other parts of the Triassic Lowland (Foose and Cunningham, 1968).

The locations of all wells, springs, test borings, seismic data points, and gravity data points are plotted on Plate 1. The various types of data were compiled and tabulated, and geologic maps and cross-sections and hydrologic maps were constructed (plates 1-4).

Previous Geologic and Hydrologic Investigations

Various aspects of the geology of Massachusetts have been studied and reported since the early part of the last century. The major portion of geologic endeavor during the 19th century was in the nature of reports of mineral occurrences. The major exception was Edward Hitchcock's Report on the geology, mineralogy, botany, and zoology of Massachusetts, which was published piecemeal in 1832 and 1833, and complete in a second edition in 1835.

During the last decade of the 19th century a thorough study of the geology of the Connecticut Valley was made by Benjamin K. Emerson. He reported on the geology of the Triassic basin of Massachusetts (1891),

the occurrences of all minerals reported in the counties of Franklin, Hampshire, and Hampden, Massachusetts (1895), the geology of the Holyoke quadrangle, Massachusetts-Connecticut (entirely within the Triassic basin) (1898a), and the geology of the counties of Franklin, Hampshire, and Hampden, Massachusetts (1898b). In 1917 he reported on the geology of the state of Massachusetts. The last two works cited remain to this day the basic comprehensive works on the geology of the Connecticut Valley of Massachusetts and the state of Massachusetts respectively.

Since the work of Emerson few studies significant to this thesis were published until Richard H. Jahns published his work on the terraces and flood plains of the Connecticut River in 1947. In more recent years the U. S. Geological Survey, in cooperation with the state of Massachusetts, has been engaged in a program of mapping the bedrock and surficial geology of the state on a 7½-minute quadrangle basis. The bedrock geology (Colton and Hartshorn, 1966) and the surficial geology (Colton and Hartshorn,1971) of the West Springfield quadrangle, and the geology (bedrock and surficial combined) of the Springfield South quadrangle (Hartshorn and Koteff, 1967) have been published. The surficial geology of the Hampden quadrangle has been mapped by Roger B. Colton (1971a), and has been placed on open file with the U. S. Geological Survey along with a map of bedrock outcrops in the Hampden quadrangle (Colton, 1971b).

Other geologic works of significance to this thesis include a study of the cementation of Triassic arkoses by Heald (1956); soil investigations along the route of interstate highway 91 in Longmeadow in 1958 by Haley and Aldrich, Consulting Soil Engineers of Cambridge, Massachusetts; and a summary of the geology relating to glacial Lake Hitchcock

(Hartshorn and Colton. 1967).

Prior to the 1960's, little hydrologic information was published except for some well-data summaries by the U. S. Geological Survey in Water Supply Papers (Crosby and La Forge, 1904; Pynchon, 1905), a discussion of the Triassic rocks of the Connecticut Valley as a source of water supply (Fuller, 1905), and a brief discussion of the occurrence of ground water in Massachusetts and Rhode Island (Crosby, 1905). The most comprehensive and detailed hydrogeologic study that includes the area of this thesis is a report on the geologic factors affecting the yield of rock wells in southern New England (Cushman, Allen, and Pree, 1953).

In more recent years the U. S. Geological Survey has published some generalized hydrologic reports that include the area of this thesis. These include a basic data report that is mainly a listing of well data (Petersen and Maevsky, 1962); a report written for the layman on water problems in the Springfield-Holyoke area (Kammerer and Baldwin, 1962); a state-by-state summary of the role of ground water in the nation (McGuinness, 1963); and a very general ground-water favorability map of the Connecticut River Basin (Cederstrom and Hodges, 1967).

Three locally sponsored ground-water investigations have been made in the area of this thesis. The consulting engineering firm of Tighe and Bond, Holyoke. Massachusetts, investigated the possibilities of ground-water development for the towns of Agawam (1964) and Longmeadow (1966). The ground-water geology consulting firm of Geraghty and Miller, Port Washington, New York. investigated the ground-water resources of the Springfield region for the city of Springfield (1966).

Well Numbering System

The wells and test borings used in this study were assigned numbers consisting of two groups of digits separated by a hyphen. The left group is a consecutive number arbitrarily assigned to the well or test boring for identification. The right group is a four-digit code group. The first digit denotes the town in which the well or test boring is located--1 is Agawam, 2 is Longmeadow, 3 is East Longmeadow, and 4 is Hampden. The second digit denotes ownership--1 is municipal, 2 is private individual, 3 is industrial, and 4 is other. The third digit denotes whether or not there is a driller's log of the well or test boring--0 is no, 1 is yes. The fourth digit denotes the type of material in which the well or test boring was completed--1 is unconsolidated, 2 is bedrock, 3 is refusal, and 4 is unknown. For example, the number 38-2212 is well or test boring number 38, which is located in Longmeadow, is privately owned, has a log, and is bottomed in bedrock.

GEOGRAPHY

Topography

The area of study lies almost entirely within the Connecticut Valley Lowland (Thornbury, 1965, p. 167). The highest point in the area is in Hampden in the Central Upland (Thornbury, 1965, p. 168), and is 740 feet above sea level. The lowest point is on the Connecticut River, and is about 40 feet above sea level. The total relief is 700 feet, but local relief is generally less than 100 feet.

The most prominent features of the area form the eastern and western boundaries of the study area. On the east the western scarp of the

Central Upland rises abruptly 480 feet above the valley floor. On the west Provin Mountain rises equally abruptly 390 feet above the valley floor. Also quite prominent are the drumlins and drumlinoid hills in central East Longmeadow, with a maximum relief of about 210 feet, and western Agawam, with a maximum relief of about 110 feet. These features are the most direct expressions of the bedrock topography although the drumlins are not all rock cored.

The generally flat Connecticut Valley Lowland floor is the result of the filling of low areas in the bedrock surface by sediments deposited during the Wisconsin glaciation, particularly as the ice sheet retreated northward. These Pleistocene deposits subsequently have been incised, as much as 120 feet, and terraced by the streams that drain the area. In Longmeadow and Agawam many sand dunes, up to 55 feet in height, stand above the otherwise flat surface. The result is that the flat valley floor is by no means a featureless plain.

Drainage

The thesis area is a very small part of the drainage basin of the Connecticut River, which flows across the area from north to south between Agawam and Longmeadow with an average discharge of 16,020 cfs (cubic feet per second) (Paulsen, 1952) at Thompsonville, Connecticut, about 2 miles south of the area. The second largest stream in the area is the Westfield River, which flows from west to east along the northern border of Agawam. It is the only major tributary that joins the Connecticut River in the area of this thesis. The average discharge of the Westfield River, which derives the major portion of its flow from the Berkshire Highlands to the west, is 923 cfs (Paulsen, 1952) in Westfield, about one-quarter of

a mile west of the area. The only other important tributary to the Connecticut River in the area is the Scantic River, which rises in the Central Upland and flows from northeast to southwest across southern Hampden. The only gauging station on the Scantic River is located several miles south of the thesis area in Broad Brook, Connecticut, where the average discharge is 135 cfs (Paulsen, 1952).

All other streams in the area are tributary to one of these three major streams. The northern edge of Agawam is drained by several small streams that flow northward into the Westfield River. Eastern Agawam is drained by Threemile Brook and its easterly flowing tributaries. Threemile Brook flows southeast and south to join the Connecticut River about one-half mile north of the Massachusetts-Connecticut border. Western Agawam is drained by Still Brook and Philo Brook, both of which flow southward into Connecticut. Longmeadow and northwestern East Longmeadow are drained westward directly to the Connecticut River by Pecousic Brook, Cooley Brook, Wheel Meadow Brook, Longmeadow Brook, and Raspberry Brook. Southwestern East Longmeadow is drained to the south into Connecticut. Most of eastern East Longmeadow and most of Hampden are also drained southward into Connecticut via the Scantic River and its tributaries, particularly Watchaug Brook. Northern Hampden and the northeast corner of East Longmeadow are drained west and north out of the area via the South Branch Mill River. All drainage in the area is perennial and is sustained by ground-water discharge.

Floods in the Connecticut River Basin have occurred at all times of the year, but are most frequent in the spring (Cushman, 1964). The most severe floods have occurred in the spring and in the late summer to

early fall. Severe spring floods are the result of heavy rains combined with rapid snow-melt. This was the case with the most severe flood recorded on the Connecticut River, which occurred in March 1936 and reached a depth of about 22 feet over the flood plain in Longmeadow. Severe floods in late summer and early fall have been the result of the abnormally heavy rains brought by hurricanes that have travelled inland instead of following the coast. In September 1938, a hurricane following a period of high rainfall caused a flood, second only to the 1936 flood, that reached a depth of about 19 feet above the Longmeadow flood plain. The flood that occurred in August 1955 was also due to a hurricane, and was the most severe flood recorded on the Westfield River (Higgins, 1967) although it was only the fifth most severe flood on the Connecticut River in Longmeadow. Further information on flooding in the Connecticut River Basin can be found in Jahns (1947), Bogart (1960), Kammerer and Baldwin (1962), and Higgins (1967).

Climate

The area of study lies within the humid temperate climatic region of the northeast United States. The climate is characterized by warm summers and cool winters with a mean growing season of 177 days. Normal temperatures range from 28.5°F in January to 74°F in July while the minimum and maximum recorded temperatures are -18°F in January and February. and 102°F in September, respectively. Precipitation is rather evenly distributed throughout the year, with a normal total of 46.62 inches per year. Normal precipitation ranges from 2.69 inches in February to 4.39 inches in August. Data on precipitation and temperature for the weather station at Springfield, Massachusetts, are summarized in table 1.

Culture

According to the figures of the U. S. Census of 1960, population in the area of this thesis has grown approximately 70 percent between 1950 and 1960. Projections indicate further increases of from 23 percent to 31 percent between 1960 and 1970, and from 24 percent to 30 percent between 1970 and 1980. Population growth in Agawam, Longmeadow, East Longmeadow, and Hampden since 1910 and projected to 1980 is shown in table 2. It should be noted that while the figures shown for Hampden are for the entire town, a very large part of the population increase apparently has occurred in the 7 square miles included in this thesis.

Land use in the thesis area is primarily residential. Agawam has a small amount of light industry and a decreasing proportion of agriculture, which consists of tobacco and vegetable crops and some poultry. The land used for agriculture is gradually giving way to housing. Longmeadow is entirely residential with very little unused land remaining. East Longmeadow has a moderate and growing amount of light industry, but is also a growing residential area. The portion of Hampden included in this thesis has been given over almost entirely to residential purposes, although a large part of the area is swamp.

GEOLOGY

Generalized Geologic Column

The rocks of the area can be placed into three groups according to age and character--the lower and middle Paleozoic "crystalline" rocks, the Triassic sedimentary rocks, and the Quaternary unconsolidated sediments (figure 2). The Paleozioc rocks consist primarily of schists,

TABLE 1.— SUMMARY OF METEOROLOGICAL DATA AT SPRINGFIELD, MASSACHUSETTS[1]

[From U.S. Weather Bureau (1969). Length of record is 31 years (1939-1969) unless otherwise indicated. Mean date of last killing frost, April 21; mean date of first killing frost, October 15; mean length of growing season, 177 days]

	January	February	March	April	May	June	July	August	Sept.	Oct.	Nov.	Dec.	Total
Precipitation:													
Normal[2] .... inches	3.64	2.69	3.76	4.00	3.88	4.17	3.99	4.39	4.13	3.16	3.80	3.87	46.62
Mean .... do	2.99	2.76	3.60	3.80	3.68	3.73	3.69	3.92	3.47	2.96	4.03	3.69	42.32
Maximum in 24-hr period .. do...	2.77	1.69	2.18	4.06	2.80	2.18	2.94	11.47	3.85	3.72	2.64	3.61	11.47
Mean number of days with 0.01 in. or more of precipitation	6	6	7	7	8	7	6	6	5	5	6	7	76
Temperature:													
Normal[2] ...... °F	28.5	29.7	38.0	49.8	61.0	69.3	74.0	72.2	64.8	55.0	43.5	31.4	51.4
Mean .... do	27.2	29.2	37.6	49.5	60.1	68.8	73.6	71.7	64.4	54.8	41.7	30.6	50.8
Record Maximum .... do	67	66	87	90	94	98	99	101	102	83	83	65	102
Record Minimum .... do	-18	-18	-11	10	30	33	44	39	27	22	12	-15	-18

[1] The Springfield station is in a protected urban area and is probably not typical of most rural locations in the general area.

[2] Normal values are based on the period 1931-1960.

Table 2. Population Growth

	Agawam 24.5 sq. mi.	Longmeadow 9.5 sq. mi.	East Longmeadow 13.0 sq. mi.	Hampden 19.4 sq. mi.
1910				
Population	3,501	1,084	1,553	645
Density	143	114	119	33
1920				
Population	5,023	2,618	2,352	624
Change	1,522	1,534	799	-21
% Change	43.5	141.5	51.4	-3.3
Density	205	276	181	32
1930				
Population	7,095	4,437	3,327	684
Change	2,072	1,819	975	60
% Change	41.3	69.5	41.5	9.6
Density	290	467	256	35
1940				
Population	7,842	5,790	3,403	1,023
Change	747	1,353	76	339
% Change	10.5	30.5	2.3	49.6
Density	320	609	262	53
1950				
Population	10,166	6,508	4,881	1,322
Change	2,324	718	1,478	299
% Change	29.6	12.4	43.4	29.2
Density	415	685	375	68
1960				
Population	15,718	10,565	10,294	2,345
Change	5,552	4,057	5,413	1,023
% Change	54.6	62.3	110.9	77.4
Density	642	1,112	792	121
1970				
Population (projected)				
High	20,400	13,000	14,300	3,100
Low	19,200	12,300	13,500	2,900
% Change				
High	29.8	23.0	38.9	32.2
Low	22.2	16.4	31.1	23.7
Density				
High	833	1,368	1,100	160
Low	784	1,295	1,038	149
1980				
Population (projected)				
High	26,100	16,400	19,600	4,000
Low	23,500	14,700	17,700	3,600
% Change				
High	27.9	26.2	37.1	29.0
Low	22.4	19.5	31.1	24.1
Density				
High	1,065	1,726	1,508	206
Low	959	1,547	1,362	186

amphibolites, granulites, and gneisses, with granitic intrusions and basaltic dikes. These rocks form the bedrock of the Central Upland, and crop out in the area of this thesis only along the eastern border (plates 1 and 3). These Paleozoic metamorphic and igneous rocks are also inferred to be the basement complex in which the Connecticut Valley Triassic basin was formed and undoubtedly underlie the entire thesis area.

The Triassic rocks underlie the Connecticut Valley Lowland. They are divided into five formations (Colton and Hartshorn, 1966; Hartshorn and Koteff, 1967) (figure 2). The oldest formation is the New Haven Arkose, which consists of at least 5000 feet of coarse-grained arkose with arkosic siltstone and arkosic conglomerate. Overlying the New Haven Arkose is the Holyoke Basalt, which is a 250-400-foot thick basaltic lava flow. Overlying the Holyoke Basalt is the East Berlin Formation, which consists of 700-1200 feet of arkosic siltstone and shale. The East Berlin Formation is overlain by two basaltic lava flows known as the Hampden Basalt. The lower flow is 50 feet thick and the upper flow is 70 feet thick. The youngest formation in the Triassic sequence is the Portland Arkose, which includes the Longmeadow Sandstone and the Chicopee Shale of Emerson (1898b, and 1917). This formation consists of 6000-8000 feet or more of arkosic shale, sandstone, and conglomerate. The fine-grained facies includes some green and black shale, black limestone, and some halite, gypsum, and pyrite. The Triassic arkoses are cemented mainly by primary hematite and clay, with secondary albite and quartz that were probably precipitated from hydrothermal waters associated with the igneous activity that produced the Holyoke and Hampden basalts and later dikes (Heald, 1956).

The New Haven Arkose crops out west of the thesis area, but nowhere within the area. Being the basal Triassic unit, it presumably extends under most of the area, but its exact eastern limit is unknown. The Holyoke Basalt forms the prominent north-south trending ridge known as Provin Mountain, whose crest marks the western boundary of the study area. The East Berlin Formation and the Hampden Basalt lie consecutively to the east of the Holyoke Basalt with little topographic expression. All three of these units crop out within a north-south belt less than one mile wide approximately parallel to the crest of Provin Mountain. The remainder of the Triassic Lowland is underlain by the Portland Arkose, which crops out along the Westfield River in Agawam and along a north-south belt in the central part of East Longmeadow. In addition there is a small outcrop in the bank of the Connecticut River at the northeast corner of Longmeadow, and there are two small outcrops in Agawam--one in Threemile Brook just north of Elm Street, and the other near the mouth of Worthington Brook at the intersection of South Street and Main Street.

The Quaternary sediments consist of a variety of Pleistocene glacial deposits, and of Holocene alluvial, swamp, and eolian deposits. The Pleistocene deposits consist of various combinations of clay, silt, sand, and gravel that occur as till, varved clay and other glaciolacustrine deposits, deltas, various glaciofluvial deposits such as outwash and ice-contact stratified drift, and stream terraces. The alluvium consists mainly of sand and silt, the swamp deposits are largely organic muck, and the eolian deposits consist of silt and sand. Although the individual deposits are limited in areal extent, the Quaternary deposits as a whole form a generally continuous layer of variable thickness (0-250 feet) over

Figure 2. Geologic Column.

Symbol	System	Geologic Character	Hydrologic Character
Qds	Quaternary	Dune Sand. Fine to medium wind-blown sand.	Poor Aquifer. Highly permeable, but generally unsaturated.
Qs	Quaternary	Swamp. Silt with much clay, muck, and organic matter, and some sand.	Poor Aquifer. Little transmissibility, and highly organic.
Qal	Quaternary	Alluvium. Silt and sand with gravel, clay, and some organic matter.	Fair Aquifer. Low to moderate transmissibility. Areal extent variable.
Qst	Quaternary	Stream Terrace. Sand, silt, and clay, with some gravel.	Fair Aquifer. Low to moderate transmissibility. Generally thin.
Qo	Quaternary	Outwash. Sand, gravel, and boulders, local silt, rare clay.	Excellent Aquifer. Very high transmissibility, and large areal extent.
Qd	Quaternary	Delta. Interstratified sand, gravel, silt, and clay.	Good Aquifer. Moderate transmissibility, and large areal extent.
Ql	Quaternary	Lake. Clay and silt to fine sand, in large part varved.	Aquaclude. Confines water in underlying units.
Qb	Quaternary	Buried Sand and Gravel. Sand and gravel, generally covered by lake clay.	Excellent Aquifer. High transmissibility. Water is generally confined.
Qk	Quaternary	Kame. Sand and gravel with lesser amounts of silt and some clay.	Good Aquifer. High permeability, but variable saturated thickness.
Qt	Quaternary	Till. Compact mixture of materials ranging from clay to boulders.	Fair Aquifer. Low transmissibility due to low permeability.
TRp	Triassic	Portland Arkose. Arkosic shale, sandstone, and conglomerate.	Excellent Aquifer. Largest areal extent of all water-bearing units. High transmissibility due to large saturated thickness. Porosity and permeability due almost entirely to joints, faults, and bedding planes.
TRha	Triassic	Hampden Basalt. Dark gray basalt in two thin flows.	
TReb	Triassic	East Berlin Formation. Arkosic siltstone and shale.	
TRho	Triassic	Holyoke Basalt. Single thick flow of dark gray basalt.	
TRnh	Triassic	New Haven Arkose. Arkosic siltstone, sandstone, and conglomerate.	
Pc	Paleozoic	Crystalline Rocks. Igneous and metamorphic--schist, gneiss, granite, etc.	

the entire thesis area (plates 2 and 3).

Historical and Structural Geology

The oldest rocks that occur in the area of this thesis are the early and middle Paleozoic rocks that underlie the Central Upland, and presumably the Triassic Lowland. These rocks consist of Ordovician, Silurian, and Devonian sedimentary and volcanic eugeosynclinal deposits. From the end of the Devonian sedimentation until the end of the Triassic faulting these rocks were involved in a long series of tectonic events. From oldest to youngest, the major tectonic episodes are as follows: 1) Formation of regional nappe structures and local recumbent folding. 2) Gneiss dome formation and intense isoclinal folding, which was the culmination of regional metamorphism. 3) Local late-metamorphic folding associated with retrograde metamorphism. 4) Post-metamorphic brittle faulting, Triassic in age and including the Triassic Border Fault, accompanied by hydrothermal alteration, brecciation, and intrusion of diabase dikes (Robinson, 1967). As a result of the Paleozoic tectonism the rocks have been folded at least three times, have been metamorphosed to schists, amphibolites, quartzites, granulites, and gneisses, and have been intruded by masses of granitic rock.

During the Triassic period, during the early stages of the opening of the present Atlantic Ocean, rifts formed in the highly folded and metamorphosed Paleozoic rocks (Bird and Dewey, 1970). These rifts were wedge-shaped graben resulting from large-scale normal faulting on one side. Topographically they formed long trough-like basins. As down-faulting created the depressions, torrential streams, flowing from the surrounding highlands, brought in sediment to fill them. In addition to

the fluvial sedimentation, periods of igneous activity produced widespread and thick flows and sills of basaltic lava and some ash. Many of the streams were ponded for variable periods of time, particularly by the lava flows, and lake and swamp deposits were also formed.

There is some controversy as to the climate that prevailed during the Triassic period. In 1892 I. C. Russell suggested that the climate was a warm humid one, and W. M. Davis later agreed with this view (Krynine, 1950). In 1917 B. K. Emerson, who had originally agreed with Russell and Davis, came to the conclusion that the climate must have been drier and proposed a semi-arid climate with cycles of varying humidity, and increasing aridity with time. Krynine (1950) presented a good argument that the climate was a tropical humid savannah type with wet and dry seasons. This view has gained considerable acceptance among other recent workers. One of the factors that led Emerson to suggest an arid climate is the occurrence of evaporite minerals, such as halite, gypsum, and glauberite (Emerson, 1895; Wherry, 1916), in the Triassic sediments. However, I believe that their occurrence, as well as the Triassic sequence as a whole, is better explained by the climatic scheme of Krynine.

The structure of the Triassic rocks is basically a homocline striking approximately north and dipping approximately east. The structure terminates abruptly on the east side against a normal fault of 17,000 to 35,000 feet displacement (Krynine, 1941; Robinson, 1967). Well logs and outcrops suggest that the border fault is a fault zone, perhaps 600 feet or more in width, with numerous fault planes in the Triassic rocks. Considerable brecciation is indicated in the Triassic rocks. The fault zone is open in some places and very tightly cemented with vein quartz in other

places. The average angle of dip of the bedding increases from east to west, or from younger to older rocks, being about 15 degrees in East Longmeadow in the Portland Arkose, about 18 degrees in North Agawam in the Portland Arkose, and about 22 degrees in western Agawam in the East Berlin Formation. This change in dip reflects in part the continued growth of the basin by downfaulting along the border fault during deposition. The overall eastward dip reflects continued downfaulting after deposition ceased. Variations in the strike and dip are related to post-depositional (probably late Triassic age) warping and normal faulting. The warping, which is most obvious in the outcrop pattern of the ridge-forming basalts, consists of broad half-canoe-shaped synclines separated by narrow anticlines. The warping has been ascribed by various writers to differential compaction, irregularities in the border fault surface, and two different episodes and types of folding.

The final structural episode of normal faulting, believed to be late Triassic in age, involved the Paleozoic basement rocks as well as the Triassic sediments. These faults cut all other structures and are both strike faults and cross faults with respect to the general homoclinal and warp structures. The strike faults strike essentially north, and the cross faults strike both northeast and northwest. The northeast-striking cross faults are dominant. Many of these faults served as conduits for the diabase dikes in both the Paleozoic and Triassic rocks. Some late Triassic faults have been inferred in western Agawam by Colton and Hartshorn (1966) (plates 1 and 3). Few of these faults have been recognized in the remainder of the study area, due mainly to the scarcity of outcrop, although some undoubtedly exist as they have been mapped in

other parts of the Connecticut Valley basin (Emerson, 1898b, pp. 376 and 449-451, and pls. IX, XXIX, and XXXIV; Emerson, 1917; Krynine, 1950).

There is no evidence of Jurassic, Cretaceous, or Tertiary deposition, so the area may well have been subjected to erosion since the end of the Triassic period. Part of the preglacial topography and the main lines of drainage can be seen in the contours on the bedrock surface shown in plate 1. Whether or not the main channel that runs north and south through the central portion of the thesis area is the preglacial channel of the Connecticut River cannot be argued on the basis of the data in this thesis. However, some major drainage apparently did occupy this portion of the lowland. There is also some indication of an important preglacial channel approximately underlying the present Westfield River along the northern border of Agawam. Unfortunately this channel is ill-defined due to a scarcity of subsurface date in northern Agawam, and the contours shown in plate 1 are extremely interpretive. In an attempt to determine whether this postulated preglacial Westfield River might have taken some course other than through the present gap in the Hampden Basalt, gravity profiles were run south from that gap for about 1.5 miles along Westfield Street, then west about 0.8 miles along North Street Extension and east about 0.5 miles along North Street and Wilbert Terrace. A specific gravity of 2.67 was assumed for the unconsolidated Quaternary deposits overlying the bedrock. The profiles (figure 3) suggest no other gap in the Hampden Basalt south of the one presently occupied by the Westfield River. These results have been used to guide the contouring of the bedrock surface in the northwestern corner of Agawam. The problem of preglacial drainage is a major problem in itself

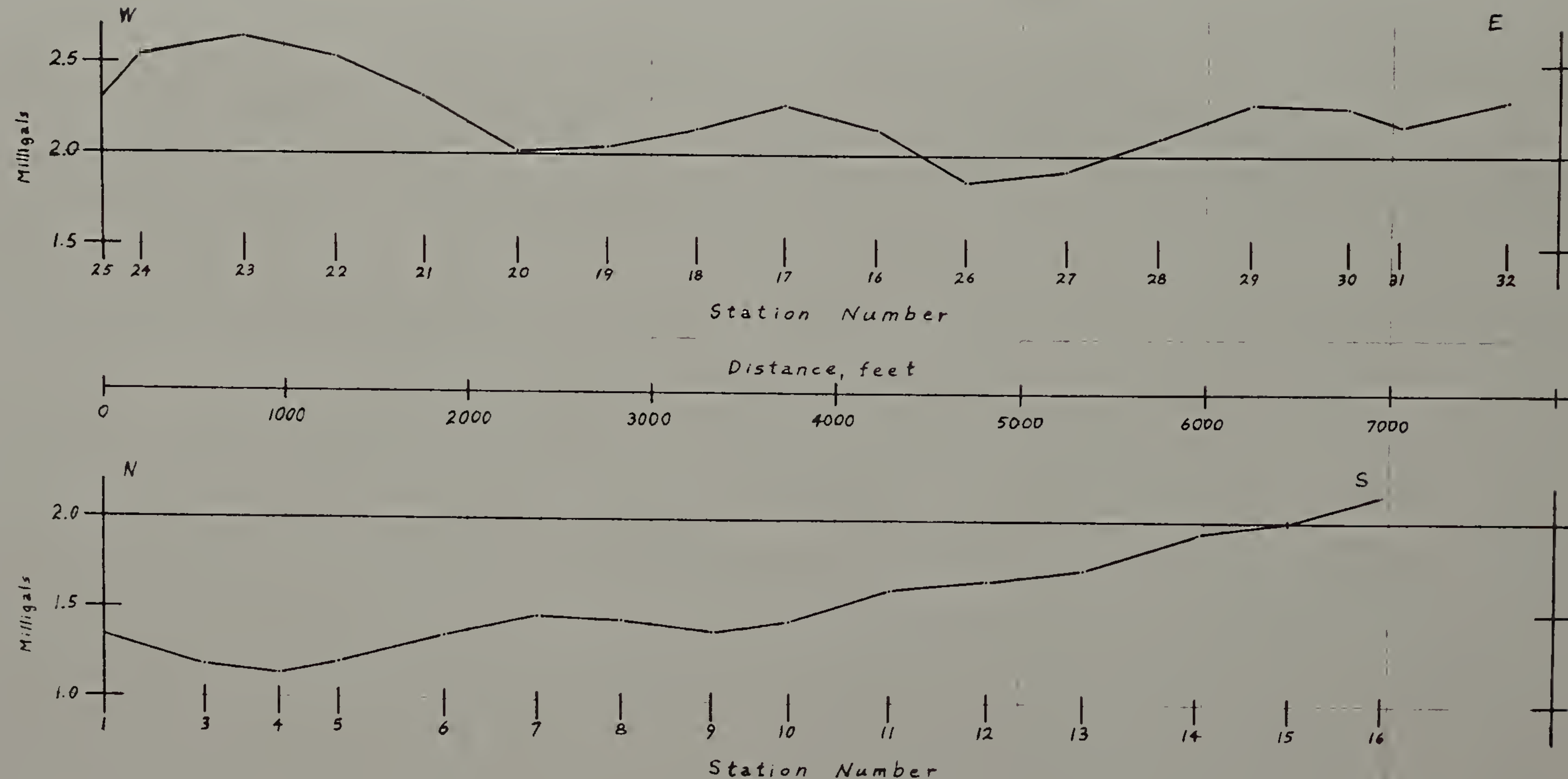


Figure 3. Gravity profiles, Agawam, Massachusetts.

and has been obscured, possibly beyond recognition, by the events of the Pleistocene Epoch. It is beyond the scope of this thesis to pursue this problem further.

The late Tertiary topography was modified at least during the last continental glaciation of the Pleistocene Epoch about 20,000 years ago (Hartshorn and Koteff, 1967, p. 1). Erosional features are seen in a general streamlining of the bedrock topography, glacial polish and striae on the bedrock surface, and overdeepening of the preglacial drainage channels, which is indicated by the 100-150-foot-deep closed depression in the major channel between Agawam and Longmeadow (plate 1). The greater part of the modification resulted from the deposition of various sediments during the retreat of the ice sheet. The history of glacial retreat in the Connecticut Valley is very complex and not yet understood in detail. Parts of this history may be found in Hartshorn and Koteff (1967), Hartshorn and Colton (1967), Colton (1960), Cushman (1964), and numerous others. For purposes of this thesis it is sufficient to say that as the ice retreated through the thesis area it was fronted by a large lake, the main stage of which is known as glacial Lake Hitchcock. This lake occupied virtually all of Agawam and Longmeadow, except for ground above a present elevation of 200-220 feet. In East Longmeadow and Hampden, particularly in the lower elevations, the retreating glacier was fronted by tracts of outwash. The major Pleistocene deposits include: a layer of till (probably lodgement till) of variable thickness covering most of the area; ice-contact stratified drift and outwash deposits primarily of fluvial origin; lacustrine deposits, including varved clays, and deltas of glacial Lake Hitchcock; and stream-terrace deposits formed during the reestablish-

ment of the Connecticut River after glacial Lake Hitchcock drained about 10,700 years ago (Hartshorn and Koteff, 1967, p. 3).

Further modification of the landscape during the Holocene Epoch includes: incision of the Pleistocene deposits by the developing drainage system; deposition by the wind of a layer of fine sand and silt, known as the eolian mantle, over much of the land surface; deposition by the wind of sand dunes on the stream terraces and, to a lesser extent, on the deltas; the deposition of alluvium on the flood plains of the rivers and streams; and the accumulation of sediment rich in organic matter in the swamps and marshes.

Economic Geology

The rocks of the area provide a small contribution to the economy of the study area. In the past they comprised the major portion of the economy of East Longmeadow. The sandstone of the Triassic Portland Arkose crops out most extensively in East Longmeadow and has been quarried there for building stone during the past 150 years. At least ten such quarries have been operated in East Longmeadow during the 19th and 20th centuries to produce brownstone, which occurs in three shades--bright red, dark red, and brown. An interesting description of production at the end of the 19th century, during the time that brownstone enjoyed wide popularity, is provided by Emerson (1898b). He lists six quarries active in East Longmeadow in 1884. Presently the largest, and probably the best known, is the Worcester Quarry (also known as the Norcross Quarry). After a period of inactivity in the mid-20th century, the Worcester and Redstone (formerly the Maynard) Quarries were reopened and are presently operated by the McCormick-Longmeadow Stone Company, Inc.

Trap rock is quarried from the Holyoke Basalt, primarily for crushed stone. There are no active quarries in the study area, but one small abandoned quarry is located on the Agawam-Southwick town line on Provin Mountain.

Finally, many of the Quaternary deposits provide the construction industry with sand, gravel, and fill.

HYDROGEOLOGY

General

The Hydrogeology of the thesis area is described only in qualitative terms because of scarcity of data throughout a large part of the area, and limitations of the data throughout the remaining part. Of course one can observe the various geologic units only at outcrops or in quarries generally above the water table, and one must then assume that a projection of these observations to some depth and into the zone of saturation is valid. Subsurface observations must be made indirectly by means of water wells and test holes that have been drilled for various purposes. Unfortunately, most of the available subsurface data do not include complete and accurate hydrologic observations and tests. This is particularly true of the domestic water wells that provide the bulk of the subsurface data for this investigation. The only hydrologic observations made in these wells are the static water level in the aquifer and a rough measure of the yield. The yield typically is measured by pumping the well at a rate considerably greater than that required for domestic consumption for about one hour (unless the well goes dry sooner) and observing the resultant drawdown in the well. This procedure may be

sufficient for the well driller and his client, but it does not provide the proper information to evaluate quantitatively the hydrologic characteristics of an aquifer, nor its long term capacity to supply water to a well.

The data that I have been able to obtain from the local well drillers are of use in making some general semiquantitative comparisons of the several water-bearing units. To this end the following quantities were tabulated: 1) total depth of wells; 2) depth of wells into water-bearing unit; 3) percentage of wells, within specified limits of depth, in the several water-bearing units; 4) percentage of wells, within specified limits of depth into bedrock, in the several bedrock units; 5) yield of wells; 6) percentage of wells, within specified limits of yield, in the several water-bearing units; 7) average yield of wells, within specified limits of depth, in the several water-bearing units; 8) yield per thickness of water-bearing unit penetrated; 9) yield per saturated thickness of water-bearing unit penetrated; 10) average yield of wells, within specified limits of depth into bedrock, in the several bedrock units; 11) bottom elevation; 12) average yield of wells, within specified limits of bottom elevation, in the several water-bearing units; and 13) percentage of wells, within specified limits of bottom elevation, in the several water-bearing units. Only the first eight of these tabulations are included in the discussion to follow (tables 3-10). The latter five tabulations were found to add little to the discussion of the water-bearing properties of the various geological units.

For purposes of the tabulations the water-bearing units have been divided into several geological categories. The bedrock is divided into

the Triassic bedrock, the Triassic Border Fault Zone bedrock, and the Paleozoic bedrock. Since only one well was tabulated that was drilled into the Triassic igneous rocks, it has been included with the Triassic sedimentary rocks. The Triassic bedrock has also been subdivided into the four towns of the thesis area because these political divisions fall conveniently close to subdividing the Triassic bedrock according to certain gross geologic properties that have some bearing on the ensuing discussion of the water-bearing properties of the Triassic bedrock. The wells included in the Triassic Border Fault Zone bedrock are those in which there is some doubt as to what unit or units were encountered. They may be in either Triassic or Paleozoic bedrock, or in both. The Border Fault Zone unit was further subdivided into the Triassic and Paleozoic sides, in which the wells are thought to be at least primarily in Triassic or Paleozoic bedrock respectively. The Quaternary deposits have been included in the tables as a single unit because there is so little information available on wells producing water from these deposits. They have been included in the tables also for purposes of comparison between the consolidated and unconsolidated units. However, the water-bearing properties of the individual Quaternary deposits will be discussed separately.

Depth to water in the various water-bearing units is discussed in the section on potentiometric surfaces.

Sediments and sedimentary rocks normally have intergranular porosity, with water or other fluids occurring in the pore spaces. In general it can be said that the finer the sediment, the greater the porosity (Todd, 1959, p. 16). Intergranular porosity is normally insignificant

in igneous and metamorphic rocks. According to Cushman, et al. (1953, p. 80) the solid rocks of southern New England in general have less than 1 percent porosity. However, the sandstones of the Triassic bedrock are reported to have porosities of about 7 percent (Cushman, et al., 1953, p. 80; Cushman, 1964, p. 32). Openings in consolidated rocks also result from separation along joints, faults, and bedding planes. These openings are referred to as fracture, or secondary, porosity.

Permeability refers to the ease with which water will move through the pore spaces of a material. In the case of materials with intergranular porosity, the permeability depends upon the size and degree of interconnection of the pore spaces. Coarse-grained materials have larger pore spaces than fine-grained materials, and, in general, coarser materials are more permeable than finer materials. In the case of materials with fracture porosity, the permeability depends upon the frequency, interconnection, and openness of joints, faults, and bedding planes.

Bedrock

General

In the Triassic and Paleozoic bedrock, ground water occurs and moves primarily along joints, faults, and bedding planes. Lithification of sediments usually means compaction and cementation, both of which tend to reduce porosity and permeability. The intergranular movement of water through even the porous sandstone beds is probably insignificant for reasons based on the following observations. First, the average and median reported yields to wells in the Triassic bedrock (table 7) are lower in Hampden and East Longmeadow, where sandstones are more frequently encountered in wells, than in Longmeadow and Agawam, where siltstones

and shales are prevalent. Second, observations in two sandstone quarries presently in operation in East Longmeadow indicate that most, if not all, of the water entering these quarries moves along joints and bedding planes rather than through the intergranular pore space of the sandstone beds. Third, the yield per thickness of bedrock penetrated (table 10) is higher in Hampden than in the other three towns, and is lowest in East Longmeadow. If the high value in Hampden is due to water moving through the intergranular pore space of the sandstone beds this quantity should be equally high in East Longmeadow. The higher yield per thickness of bedrock penetrated in Hampden may be due to more abundant fractures in the bedrock near the Triassic Border Fault, although this quantity is as low in the Border Fault Zone itself as in East Longmeadow, Longmeadow, and Agawam. It is probable that this situation results from the filling of many of the fractures in the immediate vicinity of the fault with vein quartz, such as that which crops out in the Border Fault Zone along Valley View Drive in the Echo Hills housing development. The lack of intergranular permeability in the sandstones is probably due to cementation, which Heald (1956, p. 1143) estimates eliminated more than half of the porosity that remained after compaction.

The yield to bedrock wells, whether Triassic or Paleozoic, depends upon the permeability of the bedrock, which is governed by the frequency and size of the joints, faults, and bedding planes encountered. Because of the limited outcrop it is difficult to determine the fracture patterns and attitudes sufficiently to predict the success of a well drilled into the bedrock. However, an examination of the records of existing wells will give an indication of what to expect from future wells. Such records

will be used in the following discussion of the water-bearing properties of the various bedrock units. Both the Triassic and Paleozoic bedrock units are water bearing and are, therefore, in a strict sense, aquifers (Todd, 1959, p. 15). However, yield to wells in these units is limited and variable, and they may not be considered aquifers where high yields are required.

Paleozoic Bedrock

The depth to which a well must be drilled in the Paleozoic bedrock depends primarily upon the depth to water (See section on potentiometric surfaces), which is generally much greater in the hills than in the valleys. Once the saturated zone has been reached, the total depth of the well depends upon the number of fractures penetrated and upon the desired yield. The total depth of 25 wells drilled into the Paleozoic bedrock for domestic supplies ranged from 80 to 457 feet, with median and average depths of 172 and 220 feet respectively (table 3). Only 9, or 36 percent, of these wells were drilled more than 200 feet into the bedrock (table 6) and none went more than 383 feet into bedrock (table 4).

The yields of 25 domestic wells ranged from 2 to 15 gpm (gallons per minute), with median and average yields of 5 and 7 gpm respectively (table 7). In addition 13, or 52 percent, of the wells yielded between 1 and 5 gpm (table 8), and all wells were reported to yield at least 1 gpm. However, yields from 0 to 1 gpm have been reported in other parts of southern New England (Cushman, et al., 1953), and more particularly in adjacent north-central Connecticut (Cushman, 1964).

In relating yield and depth it appears from these 25 wells that there is little chance of increasing the yield of a well by drilling to

depths of more than 200 feet (table 9). Cushman (1964), using 123 wells in adjacent north-central Connecticut, suggests that the yield of a well will not increase significantly after a depth of 250 feet has been attained. Another method of relating yield and depth is to calculate the yield per foot of aquifer penetrated. Among 25 wells this value ranged from less than 0.01 to 0.26 gpm/ft (gallons per minute per foot), with average and median values of 0.07 and 0.04 gpm/ft respectively (table 10). Thus, if it is desired to obtain a yield of 10 gpm, a driller could expect to drill to a depth of 143 feet into bedrock on the average, but would be more likely to have to drill to a depth of about 250 feet into bedrock. In summary, it is reasonable to expect a yield of no more than 10 gpm from a well in the Paleozoic bedrock, and it is likely that the yield obtained will be closer to 5 gpm. In most cases it will be fruitless to drill more than 250 feet into the Paleozoic bedrock.

Triassic Bedrock

The depth to which a well in the Triassic bedrock must be drilled depends in large part upon the depth to bedrock. This is true because water levels in much of the Triassic bedrock are at or above the bedrock surface so that water is obtained as soon as an open fracture or bedding plane is penetrated. It is also true because the frequency of joints decreases and the tightness of joints and bedding planes increases with depth, although not in a predictable manner. The total depths of 365 wells drilled into the Triassic bedrock ranged from 46 to 674 feet, with median and average depths of 112 and 134 feet respectively (table 3). Only 46, or 13 percent, of the 365 wells were drilled to a depth of more than 200 feet (table 5), and only 58, or 16 percent, were drilled more

than 100 feet into the bedrock (table 6). In addition, both the total depth and the depth into bedrock were greatest in Longmeadow, where the depth to bedrock is greatest, and least in Hampden, where the bedrock is relatively shallow and the fractures are presumably more abundant.

The reported yields to 359 domestic wells ranged from 4 to more than 300 gpm, with median and average yields of 18 and 28 gpm respectively (table 7). No wells were reported to yield less than 1 gpm, although such wells have been reported in other parts of the Triassic Lowland by Cushman, et al. (1953, p. 88), and by Cushman (1964, p. 33), and in the study area itself by Crosby and LaForge (1904, p. 114). Yields of greater than 10 gpm were reported in 257, or 71.5 percent, of the 359 wells, but only 29, or 8 percent, of the wells were reported to yield more than 50 gpm (table 8).

In relating depth and yield it appears from 362 domestic wells that it is productive in terms of yield to drill a Triassic bedrock well to a depth of about 500 feet (table 9). This figure is in agreement with the findings of Cushman, et al. (1953, p. 95) for southern New England, and of Cushman (1964, p. 35) for north-central Connecticut. It is interesting to note that the highest reported yield of more than 300 gpm was obtained from a well 500 feet deep. This supports the suggestion of Cushman, et al. (1953, p. 82) and of Cushman (1964, p. 33), that many of the wells might have produced greater yields if they had been drilled deeper and had been developed more completely. The yield per foot of bedrock penetrated for 356 domestic wells ranged from 0.01 to 12.50 gpm/ft, with average and median values of 1.04 and 0.33 gpm/ft respectively (table 10). This means that wells drilled 200 feet into the Triassic

bedrock should obtain a yield of about 200 gpm on the average, but would be more likely to obtain a yield of about 66 gpm. In summary, a well in the Triassic bedrock might reasonably be drilled to a depth of 500 feet. The yield that might be expected is harder to predict, but a yield of about 30 gpm would seem to be quite reasonable. However, there are indications that considerably higher yields ought to be expected. This is apparently the case in the Hartford, Connecticut, area where a number of industrial wells yield over 100 gpm and up to 578 gpm (Cushman, 1964, p. 33).

Triassic Border Fault Zone Bedrock

The water-bearing properties of the Triassic Border Fault Zone bedrock are intermediate between the Paleozoic and Triassic bedrock. The total depth of 56 domestic wells ranged from 82 to 466 feet, with median and average depths of 170 and 194 feet respectively (table 3). Only 19, or 34 percent, were more than 200 feet in depth (table 5), and only 14, or 25 percent, were more than 200 feet into the bedrock (table 6).

The reported yields to 56 domestic wells in the fault zone ranged from 1 to 60 gpm, with median and average yields of 8 and 13 gpm respectively (table 7). Only 8, or 14.5 percent, of the wells yielded more than 20 gpm (table 8), and these were all on the Triassic side of the fault. Only 16, or 28.5 percent, of the wells yielded 5 gpm or less (table 8), and these were evenly divided between the two sides of the fault. The yield of wells on the Triassic side of the fault was less than the yield to Triassic bedrock wells, but greater than the yield to wells in the Paleozoic bedrock. The yield to wells on the Paleozoic side of the fault was about equal to the yield to wells in the Paleozoic bedrock.

Table 3. Total Depth of Wells

Unit	Number of Wells	Range	Mean ft	Median ft	Average ft
Quaternary Deposits	31	18-164	91	76	76
Triassic Bedrock	365	46-674	360	112	134
Agawam	15	112-500	306	188	214
Longmeadow	23	170-674	422	304	325
East Longmeadow	37	77-510	294	146	191
Hampden	290	46-485	266	97	108
Border Fault Zone Bedrock	56	82-466	274	170	194
Triassic Side	37	82-466	274	166	196
Paleozoic Side	19	96-342	219	172	190
Paleozoic Bedrock	25	80-457	269	172	220

Table 4. Depth into Water-bearing Unit

Unit	Number of Wells	Range	Mean ft	Median ft	Average ft
Quaternary Deposits	21	10-93	52	28	32
Triassic Bedrock	361	4-608	306	52	67
Agawam	12	52-245	149	100	118
Longmeadow	23	49-608	329	95	158
East Longmeadow	36	41-432	237	94	132
Hampden	290	4-446	225	36	50
Border Fault Zone Bedrock	56	22-406	214	112	142
Triassic Side	37	22-406	214	109	133
Paleozoic Side	19	67-312	190	152	160
Paleozoic Bedrock	25	31-383	212	145	187

Table 5. Percentage of Wells, Within Specified Limits of Depth (in feet), in the Several Water-bearing Units.

Unit	Number of Wells	0-101	101-200	201-300	301-400	401-500	Over 500
Quaternary Deposits	31	64.5	35.5	----	----	----	----
Triassic Bedrock	365	43.0	44.0	7.0	3.0	2.0	1.0
Agawam	15	----	60.0	27.0	6.5	6.5	----
Longmeadow	23	----	4.5	43.5	35.0	8.5	8.5
East Longmeadow	37	19.0	51.0	16.0	3.0	5.5	5.5
Hampden	290	52.0	45.5	2.0	----	0.5	----
Border Fault Zone Bedrock	56	9.0	57.0	19.5	11.0	3.5	----
Triassic Side	37	11.0	56.5	13.5	13.5	5.5	----
Paleozoic Side	19	5.0	58.0	32.0	5.0	----	----
Paleozoic Bedrock	25	12.0	48.0	8.0	24.0	8.0	----

Table 6. Percentage of Wells, Within Specified Limits of Depth (in feet) into Bedrock, in the Several Rock Units.

Unit	Number of Wells	0-101	101-200	201-300	301-400	401-500	Over 500
Triassic Bedrock	361	84.0	12.0	1.5	1.5	0.5	0.5
Agawam	12	50.0	42.0	8.0	----	----	----
Longmeadow	23	52.0	22.0	9.0	9.0	4.0	4.0
East Longmeadow	36	61.0	22.0	5.5	8.5	1.0	----
Hampden	290	90.5	9.0	---	----	0.5	----
Border Fault Zone Bedrock	56	39.0	36.0	18.0	5.0	2.0	----
Triassic Side	37	48.5	32.5	11.0	5.5	2.5	----
Paleozoic Side	19	21.0	42.0	32.0	5.0	----	----
Paleozoic Bedrock	25	24.0	40.0	8.0	28.0	----	----

Table 7. Yield of Wells

Unit	Number of Wells	Range	Mean gpm	Median gpm	Average gpm
Quaternary Deposits	12	10-675	343	50	198
Triassic Bedrock	359	4-300	152	18	28
Agawam	15	8-300	154	20	43
Longmeadow	23	10-90	50	27	33
East Longmeadow	32	5-115	60	13	25
Hampden	289	4-150	77	18	27
Border Fault Zone Bedrock	56	1-60	30	8	13
Triassic Side	37	1-60	30	9	15
Paleozoic Side	19	2-20	11	6	7
Paleozoic Bedrock	25	2-15	9	5	7

Table 8. Percentage of Wells, Within Specified Limits of Yield, in the Several Water-bearing Units.

Unit	Number of Wells	1-5 gpm	6-10 gpm	11-20 gpm	21-50 gpm	51-100 gpm	100 gpm
Quaternary Deposits	12	---	8.5	25.0	25.0	8.5	33.0
Triassic Bedrock	359	3.5	25.0	33.5	30.0	6.5	1.5
Agawam	15	---	13.0	47.0	27.0	6.5	6.5
Longmeadow	23	---	8.5	26.0	48.0	17.5	----
East Longmeadow	32	3.0	31.5	34.5	19.0	6.0	6.0
Hampden	289	4.0	26.5	33.0	30.0	5.5	1.0
Border Fault Zone Bedrock	56	28.5	34.0	23.0	12.5	2.0	----
Triassic Side	37	21.5	35.0	21.5	19.0	3.0	----
Paleozoic Side	19	42.0	31.5	26.5	----	---	----
Paleozoic Bedrock	25	52.0	24.0	24.0	----	---	----

Table 9. Average Yield, in gpm, of Wells, Within Specified Limits of Depth (in feet), in the several Water-bearing Units.

Unit	Number of Wells	0-101	101-200	201-300	301-400	401-500	Over 500
Quaternary Deposits	12	44	505	---	---	---	---
Triassic Bedrock	362	36	15	22	51	92	57
Agawam	15	---	20	26	60	300	---
Longmeadow	23	---	25	27	42	43	21
East Longmeadow	34	9	13	20	112	59	93
Hampden	290	37	15	15	---	50	---
Border Fault Zone Bedrock	56	18	14	7	15	4	---
Triassic Side	37	20	17	10	15	4	---
Paleozoic Side	19	10	9	4	11	---	---
Paleozoic Bedrock	25	10	8	4	6	3	---

Table 10. Yield per Thickness of Water-bearing Unit Penetrated

Unit	Number of Wells	Range	Mean gpm/ft	Median gpm/ft	Average gpm/ft
Quaternary Deposits	12	0.22-38.71	19.47	2.92	8.36
Triassic Bedrock	356	0.01-12.50	6.25	0.33	1.04
Agawam	12	0.05-0.47	0.26	0.17	0.22
Longmeadow	23	0.02-1.64	0.83	0.32	0.36
East Longmeadow	32	0.06-0.44	0.25	0.14	0.17
Hampden	289	0.01-12.50	6.25	0.43	1.23
Border Fault Zone Bedrock	56	0.001-2.27	1.14	0.08	0.17
Triassic Side	37	0.001-2.27	1.14	0.14	0.23
Paleozoic	19	0.007-0.16	0.08	0.04	0.06
Paleozoic Bedrock	25	0.005-0.26	0.13	0.04	0.07

In relating depth and yield it appears that about 400 feet is the maximum advisable depth that a well should be drilled in the Triassic Border Fault Zone bedrock (table 9). The yield per foot of bedrock penetrated ranged from 0.001 to 2.27 gpm/ft. with median and average values of 0.08 and 0.17 gpm/ft respectively (table 10). On the Triassic side of the fault this value was somewhat lower than, but in line with, the higher values in the Triassic bedrock. On the Paleozoic side of the fault, these values are about equal to the lower values in the Paleozoic bedrock.

In summary, a well drilled into the Triassic Border Fault Zone bedrock should obtain its maximum yield within a depth of 400 feet. Such a well might be expected to yield about 15 gpm on the Triassic side, and about 10 gpm on the Paleozoic side.

Quaternary Deposits

General

The Quaternary deposits consist of several types of unconsolidated sediments, all of which have intergranular porosity but essentially no fracture porosity. The permeability of a sediment decreases as the particle size decreases, and sediments consisting of material finer than sand normally have permeabilities that are too low for the sediment to yield useful amounts of water to a well. In general, then, silt and clay deposits can be considered as aquicludes or aquitards. That is, they may contain water in appreciable amounts, but the movement of water through them is insignificant for purposes of water supply. Clay deposits, although not absolutely impermeable, may have sufficiently low permeability to confine water under considerable pressure. Deposits

consisting of gravel, sand, or a mixture of sand and gravel with limited amounts of silt and clay usually have sufficient permeability to supply useful amounts of water to a well and may generally be regarded as aquifers.

The depth of wells in the Quaternary deposits depends, with some exceptions, upon the thickness of the deposit to be tapped. The depths of 31 wells and test borings ranged from 18 to 164 feet, with median and average depths each of 76 feet (table 3). Only 11, or 35.5 percent, of these wells and test borings were greater than 100 feet in depth (table 5). However, it should be noted that 18 of the 31 wells were test borings drilled to refusal. Of these 8 were drilled beyond any unconsolidated water-bearing unit, and the other 10 encountered a buried sand and gravel unit. The depth into the water-bearing unit in 21 wells and test borings ranged from 10 to 93 feet, with median and average depths of 28 and 32 feet respectively (table 4).

The yields to 12 wells ranged from 10 to 675 gpm, with median and average yields of 50 and 198 gpm respectively (table 7). No wells were reported to yield less than 10 gpm, but only 4, or 33 percent, of the wells were reported to yield more than 100 gpm (table 8). The deepest wells produced the highest yields (table 9), but this is undoubtedly in part a result of testing procedures as most of the deeper wells were tested for purposes of municipal supply whereas most of the shallower wells were for domestic purposes. The yield per foot of water-bearing unit penetrated in 12 wells ranged from 0.22 to 38.71 gpm/ft, with median and average values of 2.92 and 8.36 gpm/ft respectively (table 10).

The Quaternary deposits will be discussed below in terms of their aquifer potential by individual map unit (plate 2).

Excellent Aquifer Potential

These units are considered to have excellent potential because of high transmissability combined with large areal extent and the ability to yield water in excess of 100 gpm. They are capable of supplying municipal and industrial requirements.

Outwash deposits. The outwash deposits are highly permeable and consist mainly of sand, gravel, and boulders, with minor amounts of silt and clay. These deposits are quite extensive areally and are as much as 100 feet in thickness, with an average thickness of approximately 50 feet. The outwash deposits have an average saturated thickness of about 30 feet. Yields of 30 and 24 gpm are reported from two domestic wells that draw water from the outwash. However, the reported yield from one industrial well is 140 gpm, and larger yields could be expected from wells in these deposits. Cushman (1964, p. 53-54) reports yields ranging from 100 to 400 gpm to wells in similar deposits in north-central Connecticut. These deposits are generally recharged by the bedrock aquifer as well as by direct infiltration. They have the potential to be an important aquifer.

Buried sand and gravel. One or more deposits of highly permeable sand and gravel have been located beneath the clays of glacial Lake Hitchcock in Longmeadow and Agawam. These deposits occur in or associated with the deeper channels in the bedrock surface and may prove to be quite extensive. These sands and gravels have been tested by the firms of Tighe and Bond, Inc. and Geraghty and Miller in connection with possible municipal supplies for Agawam, Longmeadow, and Springfield, and have by far

the largest reported yields of any water-bearing unit in the area of this study. Yields reported by Tighe and Bond (1964; 1966) range from 50 to 675 gpm, and yields of 1,000-2,000 gpm can be expected (Geraghty and Miller, 1966). Two wells in Longmeadow drilled into this unit are being placed into service to supply water to the town of Longmeadow. These buried sand and gravel deposits have the potential to be a major, if not the most important, source of water in the study area. However, these deposits may be difficult to locate unless they are indeed associated with the preglacial drainage channels in the Triassic bedrock. These sands and gravels are not known to have any surface connection or outcrop and are probably recharged from, and therefore hydraulically a part of, the Triassic bedrock aquifer. Supporting evidence for this assumption is that these deposits are artesian, and water rises in wells tapping them in accordance with the regional potentiometric surface of the Triassic bedrock, which is also artesian in the area in which these deposits have been located. Also, the sands and gravels commonly are in direct contact with the underlying bedrock, or are separted from the bedrock by less than 4 feet of till. Possible recharge problems could limit their potential.

Good Aquifer Potential

These units are considered to have good aquifer potential because of moderate to high transmissability, moderate to large areal extent, and the ability to yield 100 gpm or more. They are capable of supplying commercial and some industrial requirements.

Kame deposits. The kame deposits consist in large measure of sand and gravel with lesser amounts of silt and occasional clay and are

generally of moderate to high permeability. The kame deposits are primarily ice-contact stratified drift, but other small sand and gravel deposits of obscure origin are included. These deposits are of quite variable sedimentary character with correspondingly variable water-bearing characteristics. They may be quite extensive areally, and they may be as much as 60 to 100 feet in thickness. Kame deposits occur in variable topographic situations. They are frequently well up on hillsides where they are well drained with little saturated thickness. However, they also occur in lower places where they may have considerable saturated thickness. No wells examined in this study draw water from kame deposits, but such wells in adjacent north-central Connecticut are reported to yield more than 450 gpm (Cushman, 1964, p. 47). They are recharged mainly by direct infiltration, but in part by the bedrock aquifer as well. The kame deposits have the potential to be a locally important aquifer.

Delta deposits. The delta deposits consist of the topset and foreset beds of the Westfield River and Harts Pond Gap glacial deltas. They are a complex mixture of interstratified gravel, sand, silt, and clay of moderate overall permeability. The delta deposits are quite variable in character vertically and horizontally, are seldom more than about 20 feet in thickness, and generally occur above the level of local drainage, which limits, and may eliminate, their saturated thickness. One well was driven 18 feet into the Westfield River delta and is reported by the owner to yield 20 gpm. Similar deposits in adjacent north-central Connecticut are reported to yield as much as 100 gpm to industrial wells (Cushman, 1964, p. 58). They are recharged by direct infiltration. Their potential generally is limited by small saturated thickness.

Fair Aquifer Potential

These units are considered to have fair aquifer potential because of low to moderate transmissability, variable areal extent, and the ability to yield up to 20 gpm. They are generally capable of supplying only domestic or small commercial requirements.

Alluvium. The alluvium consists of low to moderate permeability flood plain deposits composed of silt and sand with gravel, clay, and some organic matter. These deposits are of variable composition, permeability, and size. The alluvium may be as much as 77 feet in thickness, but is more often 20 to 30 feet thick along the major rivers, and less than 20 feet thick along the smaller streams. Their saturated thickness is usually nearly equal to their total thickness. One driven domestic well has a reported yield of 10 gpm. These deposits are recharged by direct infiltration of precipitation and flood waters. The alluvium in general is of minor importance as a water-bearing unit. The potential is best along the Connecticut River, the Westfield River, and possibly the Scantic River, where the yield may be enchanced by induced infiltration of the river water.

Stream-terrace deposits. The stream-terrace deposits consist of sand, silt, and clay, with some gravel, and have moderate permeability. They are cut by a number of small streams and are in large part above the level of local drainage. The saturated thickness of these deposits is generally small. These deposits may be as much as 60 feet thick, but are more commonly only 20 feet or less. The reported yield from one dug well is 20 gpm. Recharge is by direct infiltration. The stream terrace deposits are of limited importance as a water-bearing unit.

Till. The most widespread of the deposits is the till. This is a low-permeability deposit consisting of a compact mixture of materials ranging in size from clay to boulders. It is commonly known as hardpan. Although no wells that produce water from the till were examined in this study, there are undoubtedly old dug wells in the area that tap this deposit. Such wells in adjacent north-central Connecticut reportedly yield from 1 to 2 gpm (Cushman, 1964, p. 43), which is sufficient for individual domestic supply. However, with such low yields, due to generally low permeability, the till is a relatively unimportant water-bearing unit.

Poor Aquifer Potential

These units are considered to have poor aquifer potential because of very low transmissability or limited areal extent. They yield little or no water, and are not capable of supplying even domestic requirements.

Dune sand. The dunes consist of highly permeable wind-deposited fine to medium sand and are as much as 55 feet in height. These deposits generally lie above the water table and are unsaturated. They are therefore unimportant as a source of water supply. However, the dunes, due to their high permeability, do facilitate the infiltration and transmission of precipitation to the underlying deposits.

Swamp deposits. The swamp deposits consist of silt with considerable amounts of clay, muck, and organic matter, and some sand. They are thin, discontinuous, and limited in areal extent. This, combined with low to moderate permeability, makes them unimportant as a water-bearing unit.

Lake deposits. The lake deposits are low-permeability deposits

of clay and silt to fine sand, in large part varved, that formed on the bottom of glacial Lake Hitchcock. The glaciolacustrine deposits are unimportant as a water-bearing unit and should not be considered as a source of water supply. The practically impermeable clays are most important as an aquaclude confining the water in part of the Triassic bedrock and in the buried sand and gravel deposits.

A thin layer of windblown sand and silt covers large portions of the surface of the area. This layer may somewhat reduce the rate of infiltration of precipitation to coarser underlying deposits, but it is otherwise unimportant and is not shown on plate 2.

POTENTIOMETRIC SURFACES

Bedrock Potentiometric Surface

Most of the wells scheduled during this study included measurement of the static water level in the well at the time of completion. All but a few of these wells were drilled into bedrock. Measurements were made at various times of the year and over a period of 16 years from about 1954 through 1969. The potentiometric surface was contoured at an interval large enough to eliminate or subdue the effects of both short and long-term fluctuations of the water levels and therefore should indicate the general character of the regional potentiometric surface in the bedrock (plate 4).

Fluctuations of the water level in the Triassic bedrock over the 10-year period from 1960 through 1969 are shown in figure 4, which is based on the monthly water-level measurements at U. S. Geological Survey observation well SG-20 located just outside of the study area, approxi-

mately 2,200 feet north of the northwest corner of East Longmeadow. Figure 4 shows a maximum fluctuation of less than 8 feet over the 10 year period. This observation well is in the confined portion of the Triassic bedrock. Water levels in the water-table portion of the bedrock might be expected to fluctuate over a greater interval, but there are no data. If it can be assumed that the data from observation well SG-20 are representative of the Triassic bedrock, then the potentiometric surface contour interval of 50 feet used in plate 4 is more than sufficient to eliminate most of the effect of water-level fluctuations. Even if this assumption is not valid it is doubtful that the water levels in any part of the bedrock fluctuate as much as 30 feet. I think then that plate 4 is a sufficient representation of the regional potentiometric surface in the bedrock to indicate areas of recharge and discharge and to show general directions of ground-water movement through the bedrock.

It is apparent from the data in plate 4 that the Paleozoic and Triassic bedrock are parts of a single hydraulic system, which I shall henceforth refer to as the bedrock aquifer, because the potential contours show no effect of the change in lithology from metamorphic and igneous rocks to sedimentary rocks, nor of the major fault between. The bedrock aquifer is in part a confined, or artesian, aquifer. The confined portion includes almost all of Longmeadow and the greater part of Agawam (plate 4). Water is confined in the bedrock by the overlying glaciolacustrine clay deposits. Water-table conditions are present in the remaining portions of the bedrock aquifer. In parts of this unconfined area water levels in the bedrock wells rise above the bedrock surface into overlying unconsolidated deposits. This is because of the

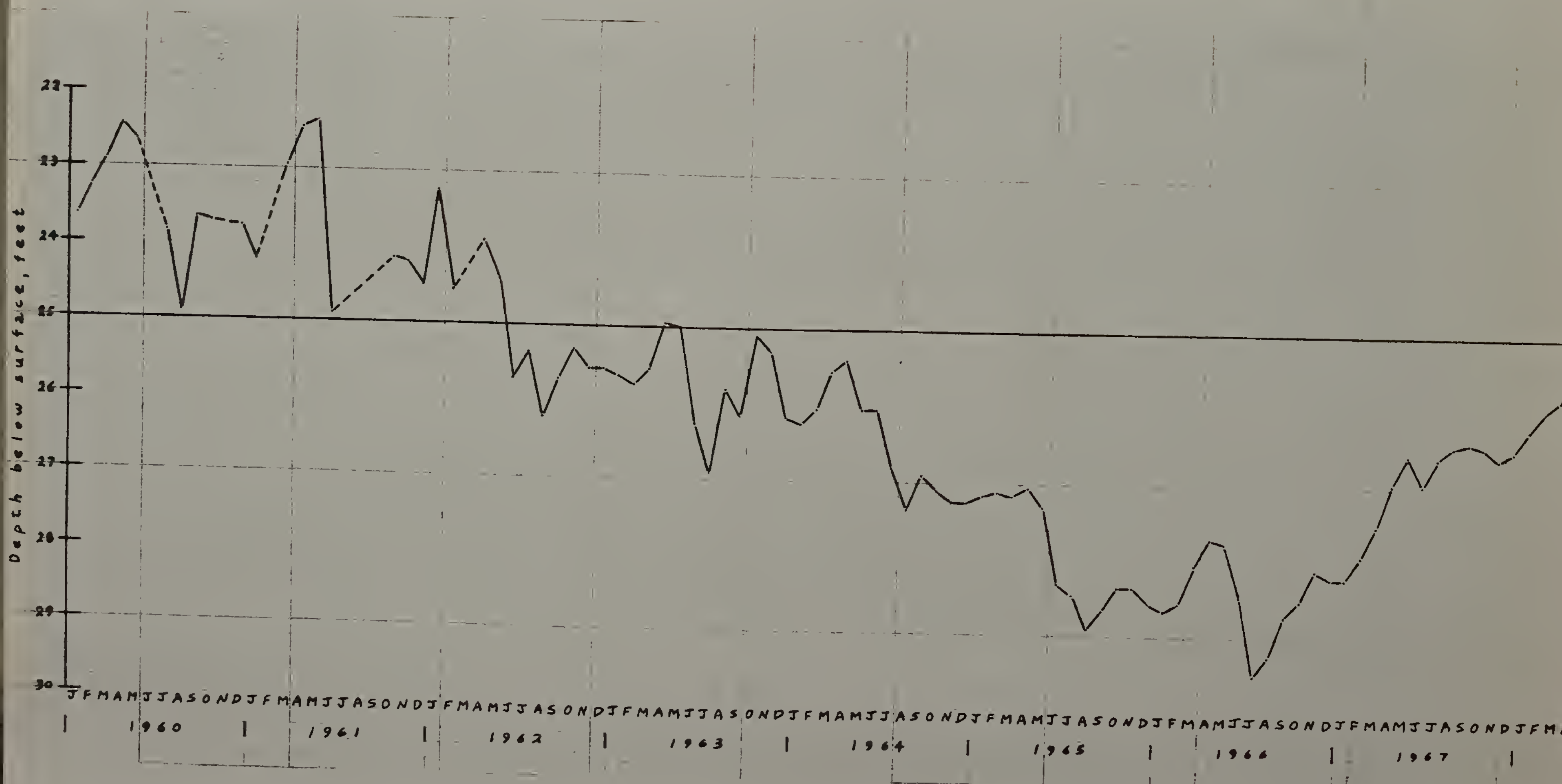


Figure 4. Water levels in Triassic bedrock at U. S. Geological Survey observation well SG-20, Springfield, Massachusetts, 1960-1969.

bedrock surface topography. In these instances the valleys in the bedrock are lower than the water table, and since there is no confining layer between the bedrock and the overlying unconsolidated deposits, the bedrock potentiometric surface in these areas lies in, and is the same as the water table in, the overlying deposits. In other parts of the unconfined area the bedrock surface is even with or above the water table, and the potentiometric surface lies within the bedrock.

Recharge areas include the Central Upland along the eastern border of the thesis area, the hills of central East Longmeadow, and Provin Mountain along the western border of the area. Recharge may also occur through the drumlins of western Agawam. Discharge occurs in the low, flat, swampy portion of Hampden and eastern East Longmeadow. Some discharge may also occur in the vicinity of the Connecticut River.

Study of the water levels indicated that the swampy area of outwash and some kame deposits in western Hampden and eastern East Longmeadow are areas of discharge for the bedrock aquifer. This is evidenced by the fact that the water in bedrock wells in this area rises to the elevation of the water in the swamps and lakes that occur throughout the area. Further support is added by the logs of these wells, which show that much of the outwash sand and gravel lies directly on the bedrock. Where this is not the case the outwash is separated from the bedrock by only a thin layer of till, which may slow, but does not prevent, the movement of water from the bedrock to the sand and gravel. In addition, the swamps, and the streams that drain them, are perennial features that would undoubtedly disappear, at least during dry weather, were it not for the discharge of water from the bedrock aquifer. Finally, a long-

time resident of East Longmeadow, Mr. B. J. Melbourne of Allen Street, reports that pumping from one of the bedrock wells (143-3202) causes nearby dug wells, 40 to 50 feet deep in the outwash sand and gravel, to go dry during dry weather. When pumping in the bedrock well is stopped, recovery occurs in the dug wells. Dug wells within at least 200-300 yards of the bedrock well are affected.

Additional discharge from the bedrock aquifer occurs along the Triassic Border Fault in scattered springs, which in the past served as an important source of water supply to the farms along the eastern side of the Triassic Lowland. Only one of these springs was actually observed by this writer, but others were reported by the residents of Hampden to have been in use along Wilbraham Road. In addition, flowing wells were drilled near the one observed spring in the Echo Hills housing development.

The general direction of movement of ground water in the bedrock aquifer is westward from the upland on the east and eastward from Provin Mountain on the west toward the Connecticut River. Although much of the water from the upland discharges through the outwash in Hampden, it seems likely that part of this water moves through deeper fractures to the area below the Connecticut River. Most of the water from the East Longmeadow hills probably moves west toward the Connecticut River, but a part of this water also moves east to discharge in the outwash of eastern East Longmeadow. There are also some flowing wells on the eastern side of the East Longmeadow hills near the southern border of East Longmeadow.

Plate 4 does not give information about specific points of discharge, but it does aid in predicting where some points of discharge may

occur. The Connecticut River flows through the area of lowest potential in the bedrock aquifer, but it flows across a thick deposit of clay that confines the water in the bedrock. Thus, the Connecticut River cannot be a general area of discharge for the bedrock aquifer. However, the bedrock and some drumlins penetrate the confining clay in a few places. Where these penetrations coincide with a potentiometric surface elevation that is higher than the top of the clay, discharge will occur. Among these places of penetration the most likely point of discharge is in southeast Agawam where the bedrock crops out in Worthington Brook.

Potentiometric Surfaces of the Quaternary Deposits

Due to scanty data, only a few general remarks can be made about water levels in the various Quaternary deposits. First, water-table conditions are present in most of these deposits. The exceptions are till, where it occurs beneath clay of glacial Lake Hitchcock, and the buried sand and gravel deposits. Artesian conditions are present in these clay-covered deposits. The potentiometric surface under water-table conditions is a subdued reflection of the topography, and it slopes toward the local drainage.

As already suggested, many of these deposits are hydraulically connected to the bedrock aquifer. This is generally true of the buried sand and gravel and outwash deposits, and it is true for parts of the till, kame, swamp, and alluvial deposits. The deposits that overlie the clays of glacial Lake Hitchcock, particularly the stream-terrace and delta deposits, and parts of the swamp and alluvial deposits, contain perched bodies of ground water.

Recharge to the deposits under water-table conditions is through

essentially direct infiltration of part of the precipitation that falls on the surface of the deposits. Where the deposits are hydraulically connected with the bedrock aquifer they may receive large amounts of recharge from the bedrock.

Movement of water through the unconsolidated deposits, except those under artesian conditions, is toward the local drainage, where the ground water is discharged. The buried sand and gravel deposits are not known to discharge naturally, at least not within the area of this study.

WATER QUALITY

General

Determination of water quality is important for making decisions regarding water use and water treatment. Water quality may also give some insight into the geology and hydrogeology of an area. The primary interest of this study is in the chemical character of the water. Although a detailed study of ground-water pollution is beyond the scope of this thesis, a few general comments will be made concerning this aspect of water quality.

In order to determine the quality of the ground water in the various water-bearing units, 56 water samples were submitted to the Massachusetts Department of Public Health Water Laboratory in Amherst, Massachusetts, for chemical analysis. An effort was made to distribute the samples from wells in the bedrock aquifer as evenly as possible over the area of study. The success of this effort was limited by the distribution of the wells from which samples could be obtained. Sampling of the Quaternary deposits was more difficult due to the small number of wells

drawing water from these deposits. The 56 samples include 46 from the bedrock aquifer and 10 from the Quaternary deposits. Within the bedrock aquifer, 39 samples were from wells in the Triassic Portland Arkose, 1 sample was from a well in the Triassic Holyoke Basalt, 3 samples were from wells in the Triassic Border Fault Zone, and 3 samples were from wells in the Paleozoic bedrock. Within the Quaternary deposits 3 samples were from wells in stream-terrace deposits, 3 samples were from wells in outwash deposits, 2 samples were from a spring and a test boring in till, 1 sample was from a well in delta deposits, and 1 sample was from a well in buried sand and gravel deposits.

In addition to the sampling program for more or less complete chemical analyses, 66 partial analyses from 32 additional wells and test borings were obtained from the files of the Massachusetts Department of Public Health, the Water Commissioner of the Town of Longmeadow, and the Springfield Water Works. A number of these wells were sampled and analyzed more than once, providing some data on quality through time. Of the 32 additional wells and test borings, 11 were in the Triassic Portland Arkose of the bedrock aquifer, and 21 were in the Quaternary deposits--2 in alluvium, 1 in till, 1 in stream-terrace deposits, 8 in outwash deposits, and 9 in buried sand and gravel deposits.

The 56 complete analyses include determinations of specific conductance, total dissolved solids, pH, total hardness, alkalinity, calcium, magnesium, sodium (50 samples only), total iron, manganese, sulfate, chloride, nitrate, and silica. In addition, one sample, in which pollution was strongly suspected, was analyzed for nitrite and ammonia. In most of the samples there was no noticeable suspended material at the

time of collection. However, in a few cases, considerable suspended matter, apparently iron oxide or hydroxide, was present and total iron is reported for both filtered and nonfiltered samples. The partial analyses may include any of the determinations in the complete analyses except calcium, magnesium, and sodium, and they usually do not include specific conductance, total dissolved solids, or sulfate.

All determinations are reported in mg/l (milligrams per liter) of the constituent analyzed (table 11) except that total hardness and alklinity are expressed in mg/l of an equivalent amount of calcium carbonate, pH is reported in pH units, specific conductance is reported in micromhos per centimeter at 25 degrees Centigrade, and temperature is reported in degrees Fahrenheit. Calcium, magnesium, sodium, sulfate, chloride, nitrate, bicarbonate, and carbonate are also reported in epm (equivalents per million).

Concentrations of bicarbonate and carbonate have been estimated from the alkalinity determination using the nomographs provided in Standard Methods (American Public Health Association et al., 1965, p. 78-81), and the equations given in Sawyer (1960, p. 224). It is assumed here, in accordance with common practice, that the alkalinity is due to carbonate, bicarbonate, or hydroxide ions, and that the effects of other ions are negligible. According to Sawyer (1960, p. 220-221), water with a pH of 8.3 or less has only bicarbonate alkalinity, and water with a pH between 8.3 and 11 has bicarbonate and carbonate alkalinity. In addition water with hydroxide alkalinity will usually have a pH well above 10, and water with no bicarbonate alkalinity has a pH of 9.5 or higher. Since the pH of all samples in this study is 8.8 or less, and usually less than

8.3, all samples are presumed to have bicarbonate alkalinity. Only in the few samples that have a pH greater than 8.3 does some carbonate alkalinity occur in addition to the bicarbonate. In no sample is there hydroxide alkalinity.

The analyses made by the Massachusetts Department of Public Health laboratories, and presumably also those made at other laboratories, were carried out in accordance with the procedures listed in Standard Methods. When the cation and anion concentrations are converted from mg/l to epm, the totals of cations and anions should be approximately equal. In all but one of the 50 samples in which all major ions were determined, the total of cations is excessively higher than the total of anions. The ratio of cations to anions ranges from 0.8 to 7.4 and averages 2.8. I suspect that the difference can be attributed to the concentrations of calcium and magnesium because it is very difficult to separate these two ions in wet chemical analyses. According to Hem (1959, p. 84):

> The presence of large amounts of magnesium in water may tend to interfere with the calcium determination and lead to unreliable results for determinations of both elements unless special procedures are used.

Thus, because the procedures recommended in Standard Methods do not include these special procedures, the calcium and magnesium determinations are likely to be erroneously high.

As a check on the hypothesis that the error lay mainly in the calcium and magnesium determinations, I calculated the total hardness for each of the 50 samples, using the reported values of calcium and magnesium, according to the equation

$$TH = 2.497\ Ca + 4.115\ Mg$$

where TH is total hardness measured in mg/l of calcium carbonate, and Ca and Mg are the calcium and magnesium determinations, respectively, measured in mg/l (Todd, 1959, p. 183). In all of the samples the calculated total hardness values turned out to be considerably greater than the reported total hardness values, which were determined by titration. Assuming first that the reported values of total hardness are accurate, and second that the reported values of calcium and magnesium are in the correct proportion, I next calculated new values of calcium and magnesium by multiplying the reported values by the ratio of reported total hardness to calculated total hardness. After converting these new values to epm it was found that the total cations were now approximately equal to the total anions. The ratio of cations to anions now ranged from 0.6 to 3.1 and averaged 1.1. These results support the hypothesis that the error is primarily in the calcium and magnesium determinations. However, the fact that cation to anion ratios of as much as 3.1 remain suggests that one or both of the assumptions upon which the calculations were based is not valid. Indeed,the assumption of correct proportion is so likely to be invalid that the calculated values of magnesium cannot be considered any more accurate than the reported values, although the calculated values are of a more reasonable magnitude.

There are many techniques used in the organization and study of water-analysis data, many of which are described in Hem (1959, p. 149). Many of these techniques were tried in the course of this study. Considerable time was spent in the calculation of numerous ratios of various constituents and combinations of constituents; in the construction of numerous graphic displays including trilinear plots, frequency diagrams,

Table 11. Chemical Analyses.

Well Number	Date of Analysis	Temperature	Specific Conductance	Total Dissolved Solids	pH	Total Hardness, mg/l as $CaCO_3$	Ca^{++}		Mg^{++}		Na^{+}		Total Iron	Mn^{++}	Alkalinity mg/l as $CaCO_3$	e. HCO_3^-	e. $CO_3^=$	$HCO_3^- + CO_3^=$	$SO_4^=$		Cl^-		Nitrogen			SiO_2
																							NO_3^-	NO_2^-	NH_3	
		°F		mg/l			mg/l	epm	mg/l	epm	mg/l	epm	mg/l	mg/l		mg/l	mg/l	epm	mg/l	epm	mg/l	epm	mg/l	mg/l	mg/l	mg/l
Triassic		Holyoke Basalt																								
104-1212	8/5/69 a	—	230	111	6.5	56	38	1.90	11	0.91	4	0.17	0.13	0.10	36	44	0	0.72	14	0.29	5	0.14	0.92	—	—	12
Triassic		Portland Arkose																								
17-2212	8/13/68 a	65	2,200	1,418	8.7	800	348	17.37	62	5.10	—	—	f0.07/1.00	f0.20	88	107	2	1.82	608	12.65	23	0.65	0.51	—	—	12
19-2212	8/7/69 a	70	460	182	8.0	98	78	3.89	14	1.15	12	0.52	0.16	0.12	72	88	0	1.44	40	0.83	4	0.11	0.50	—	—	20
22-2212	7/19/66 b	—	—	—	8.0	68	—	—	—	—	—	—	0.30	—	—	—	—	—	—	—	—	—	—	—	—	—
23-3312	9/2/69 a	60	450	206	7.8	130	100	4.99	36	2.96	7	0.30	0.08	0.10	90	110	0	1.80	26	0.54	15	0.42	2.70	—	—	5
30-3212	8/12/69 a	62	340	156	8.0	88	64	3.19	16	1.32	7	0.30	0.38	0.06	60	73	0	1.20	5	0.10	11	0.31	3.75	—	—	12
33-3212	8/12/69 a	57	650	300	6.7	156	108	5.39	32	2.63	20	0.87	0.20	1.92	108	132	0	2.16	32	0.67	15	0.42	0.50	—	—	14
36-2212	8/22/68 a	68	350	145	8.0	72	54	2.69	7	0.58	—	—	0.07	0.08	78	95	0	1.56	35	0.73	2	0.06	0.02	—	—	9
39-3212	8/22/68 a	71	440	190	8.7	108	56	2.79	9	0.74	—	—	0.21	0.11	40	49	1	0.83	38	0.79	13	0.37	6.00	—	—	10
40-2212	8/13/68 a	67	1,100	865	8.0	416	160	7.98	48	3.95	—	—	0.77	0.15	46	56	0	0.92	456	9.48	20	0.56	0.16	—	—	10
42-2212	8/13/68 a	72	170	87	7.0	54	17	0.85	9	0.74	—	—	0.07	0.08	48	59	0	0.97	9	0.19	2	0.06	0.23	—	—	16
44-3212	8/22/68 a	68	450	170	8.4	114	48	2.40	23	1.89	—	—	0.08	0.10	58	71	1	1.19	16	0.33	26	0.73	5.80	—	—	11
47-4204	9/27/67 a	—	—	—	8.7	52	—	—	—	—	—	—	0.06	0.01	32	39	1	0.67	—	—	4	0.11	1.58	0.000	0.012	—
49-1304	9/24/69 a	58	460	178	7.8	116	70	3.49	37	3.05	16	0.70	0.07	0.05	112	137	0	2.25	27	0.56	8	0.23	0.04	—	—	12
50-1304	9/24/69 a	56	480	184	7.7	120	72	3.59	53	4.36	17	0.74	0.17	0.08	130	159	0	2.61	16	0.33	2	0.06	0.04	—	—	13
53-3212	9/12/58 a	—	—	—	7.5	140	—	—	—	—	—	—	0.06	—	88	107	0	1.75	—	—	2	0.06	0.15	0.000	—	—
56-2212	10/6/69 a	55	4,000	2,830	7.4	1,500	1,300	64.87	320	26.34	77	3.35	0.12	0.48	42	51	0	0.84	1,590	33.07	22	0.62	0.05	—	—	10
57-2212	6/6/66 c	—	—	—	7.9	84	—	—	—	—	—	—	0.16	0.00	71	87	0	1.43	—	—	2	0.06	0.09	0.000	0.00	—
	10/6/69 a	63	260	136	7.9	88	62	3.09	28	2.30	7	0.30	0.34	0.07	78	95	0	1.56	12	0.25	2	0.06	0.10	—	—	12
59-2212	10/1/69 a	67	2,400	1,260	7.8	780	660	32.93	200	16.46	31	1.35	0.55	0.14	56	68	0	1.12	650	13.52	13	0.37	0.04	—	—	10
61-4212	8/19/69 a	65	350	150	7.9	88	62	3.09	42	3.46	5	0.22	0.08	0.17	50	61	0	1.00	33	0.69	7	0.20	1.50	—	—	12
65-4212	8/26/69 a	63	350	134	8.1	88	60	2.99	6	0.49	5	0.22	0.06	0.00	78	95	0	1.56	20	0.42	3	0.08	0.94	—	—	20
74-4212	8/22/69 a	61	320	138	7.0	84	50	2.50	50	4.11	8	0.35	0.08	0.05	66	81	0	1.33	13	0.27	11	0.31	1.09	—	—	14

Table 11. Chemical Analyses (continued).

Well Number	Date of Analysis	Temperature °F	Specific Conductance	Total Dissolved Solids mg/l	pH	Total Hardness, mg/l as $CaCO_3$	Ca^{++} mg/l	Ca^{++} epm	Mg^{++} mg/l	Mg^{++} epm	Na^{+} mg/l	Na^{+} epm	Total Iron mg/l	Mn^{++} mg/l	Alkalinity mg/l as $CaCO_3$	e. HCO_3^- mg/l	e. $CO_3^=$ mg/l	$HCO_3^- + CO_3^=$ epm	$SO_4^=$ mg/l	$SO_4^=$ epm	Cl^- mg/l	Cl^- epm	Nitrogen NO_3^- mg/l	Nitrogen NO_2^- mg/l	Nitrogen NH_3 mg/l	SiO_2 mg/l
77-4212	8/19/69[a]	60	510	207	7.5	124	48	2.40	64	5.27	11	0.48	0.06	0.10	78	95	0	1.56	30	0.62	21	0.59	3.00	—	—	16
79-3212	8/12/69[a]	55	330	138	8.0	68	38	1.90	33	2.72	14	0.61	0.26	0.06	82	100	0	1.64	15	0.31	3	0.08	0.10	—	—	12
80-4212	8/26/69[a]	69	750	350	8.2	206	126	6.29	57	4.69	10	0.44	0.08	0.08	86	105	0	1.72	14	0.29	3	0.08	0.05	—	—	12
82-1212	8/5/69[a]	—	610	250	7.8	156	90	4.49	34	2.80	14	0.61	0.25	0.06	110	134	0	2.20	105	2.18	2	0.06	0.05	—	—	14
93-3212	8/14/69[a]	59	185	84	8.0	42	28	1.40	16	1.32	5	0.22	0.38	0.09	48	59	0	0.97	4	0.08	2	0.06	0.05	—	—	13
102-4204	2/19/69[a]	—	—	—	7.3	84	—	—	—	—	—	—	0.03	0.05	58	71	0	1.19	—	—	9	0.25	3.90	0.000	0.016	—
103-3212	8/12/68[a]	—	—	—	8.0	70	—	—	—	—	—	—	0.25	0.09	66	81	0	1.33	—	—	3	0.08	1.12	0.000	0.014	—
105-3312	10/15/69[a]	56	580	284	7.8	178	108	5.39	57	4.69	10	0.44	0.08	0.10	72	88	0	1.44	82	1.71	3	0.08	0.20	—	—	10
108-1212	8/7/69[a]	68	520	186	7.8	120	62	3.09	63	5.18	11	0.48	0.20	0.13	100	122	0	2.00	36	0.75	5	0.14	0.75	—	—	16
109-1212	9/12/69[a]	62	410	166	8.8	50	30	1.50	13	1.07	41	1.78	0.23	0.13	58	67	2	1.16	25	0.52	6	0.17	0.45	—	—	6
110-1212	8/5/69[a]	—	400	152	8.0	64	46	2.30	10	0.82	30	1.31	0.14	0.09	102	124	0	2.03	25	0.52	2	0.06	0.10	—	—	10
111-4112	12/5/68[a]	—	—	—	7.6	80	—	—	—	—	—	—	0.05	0.06	70	85	0	1.39	—	—	4	0.11	0.80	0.000	0.036	—
112-3212	8/26/69[a]	60	250	110	7.4	62	44	2.20	5	0.41	5	0.22	0.06	0.08	52	63	0	1.03	9	0.19	6	0.17	0.75	—	—	1
115-2212	10/1/69[a]	63	600	258	7.8	140	124	6.19	5	0.41	20	0.87	0.07	0.06	60	73	0	1.20	113	2.35	7	0.20	0.02	—	—	8
118-4212	8/22/69[a]	57	150	78	7.2	38	28	1.40	6	0.49	6	0.26	0.08	0.05	42	51	0	0.84	7	0.15	3	0.08	0.03	—	—	14
122-4212	9/10/69[a]	62	290	126	8.0	88	66	3.29	36	2.96	7	0.30	0.14	0.09	58	71	0	1.19	12	0.25	8	0.23	1.00	—	—	5
123-3212	10/20/69[a]	58	260	104	7.8	74	44	2.20	18	1.48	26	1.13	0.05	0.08	62	76	0	1.25	12	0.25	5	0.14	1.12	—	—	12
131-3212	8/14/69[a]	64	250	92	8.0	56	30	1.50	18	1.48	8	0.35	0.18	0.14	58	71	0	1.19	5	0.10	3	0.08	0.75	—	—	12
134-1202	10/6/69[a]	54	470	208	7.8	140	56	2.79	70	5.76	14	0.61	0.07	0.11	134	163	0	2.20	17	0.35	5	0.14	0.05	—	—	12
135-3212	10/20/69[a]	67	450	196	6.7	108	82	4.09	36	2.96	12	0.52	0.17	0.11	64	78	0	1.28	26	0.54	26	0.73	1.80	—	—	14
137-4312	3/22/60[a]	—	—	—	6.6	40	—	—	—	—	—	—	0.15	—	32	39	0	0.64	—	—	4	0.11	0.25	0.010	0.002	—
	10/29/64[a]	—	—	—	6.4	36	—	—	—	—	—	—	0.04	0.05	24	29	0	0.48	—	—	4	0.11	0.25	0.000	0.058	—
	2/21/66[a]	—	—	—	6.6	34	—	—	—	—	—	—	0.08	0.03	26	32	0	0.52	—	—	4	0.11	0.15	0.000	0.014	—
	2/19/69[a]	—	—	—	6.4	36	—	—	—	—	—	—	0.03	0.03	24	29	0	0.48	—	—	5	0.14	0.17	0.000	0.010	—
143-3202	2/14/67[a]	—	—	—	6.8	78	—	—	—	—	—	—	0.36	0.00	40	49	0	0.80	—	—	9	0.25	1.50	0.000	0.032	—

Table 11. Chemical Analyses (continued).

Well Number	Date of Analysis	Temperature	Specific Conductance	Total Dissolved Solids	pH	Total Hardness, mg/l as $CaCO_3$	Ca^{++}		Mg^{++}		Na^{+}		Total Iron	Mn^{++}	Alkalinity mg/l as $CaCO_3$	e. HCO_3^-	e. $CO_3^=$	$HCO_3^- + CO_3^=$	$SO_4^=$		Cl^-		Nitrogen			SiO_2
		°F		mg/l			mg/l	epm	mg/l	epm	mg/l	epm	mg/l	mg/l		mg/l	mg/l	epm	mg/l	epm	mg/l	epm	NO_3^- mg/l	NO_2^- mg/l	NH_3 mg/l	mg/l
158-4204	11/26/63[2]	—	—	—	7.8	74	—	—	—	—	—	—	0.02	0.02	56	68	0	1.12	—	—	5	0.14	1.25	0.000	0.016	—
161-4212	9/10/69[2]	70	350	156	8.0	108	68	3.39	34	2.80	6	0.26	0.07	0.07	86	105	0	1.72	12	0.25	20	0.56	0.97	—	—	5
181-4212	9/10/69[2]	63	142	72	6.5	34	24	1.20	6	0.49	4	0.17	0.08	0.08	20	24	0	0.39	14	0.29	7	0.20	0.89	—	—	4
260-4212	10/30/69[2]	59	290	126	7.8	88	54	2.69	17	1.40	3	0.13	0.05	0.06	84	102	0	1.67	8	0.17	6	0.17	1.31	—	—	12
479-3204	3/14/68[2]	—	—	—	6.3	56	—	—	—	—	—	—	0.03	0.03	30	37	0	0.61	—	—	13	0.37	4.60	0.000	0.036	—
480-1204	4/21/60[2]	—	—	7,732	8.4	1,320	—	—	—	—	—	—	1.81	—	72	85	1	1.42	468	9.73	315	8.88	—	0.000	0.050	—
S3	11/24/69[2]	50	750	318	7.8	212	146	7.29	20	1.65	18	0.78	0.03	0.11	158	193	0	3.17	21	0.44	43	1.21	1.64	—	—	10
Triassic Border Fault Zone																										
125-4212	9/12/69[2]	57	230	101	7.2	80	36	1.80	17	1.40	6	0.26	33.0 ±0.20	±0.17	108	132	0	2.16	9	0.19	2	0.06	0.15	—	—	3
299-4212	10/30/69[2]	55	142	76	6.2	32	20	1.00	12	0.99	4	0.17	0.41	0.09	24	29	0	0.48	8	0.17	10	0.28	0.23	—	—	20
375-4212	10/15/69[2]	57	300	154	7.7	80	66	3.29	17	1.40	11	0.48	0.12	0.14	80	98	0	1.61	15	0.31	2	0.06	0.15	—	—	12
Paleozoic Crystalline																										
70-4212	10/22/69[2]	54	160	106	7.2	32	20	1.00	19	1.56	4	0.17	0.00	0.21	16	20	0	0.33	12	0.25	4	0.11	3.56	—	—	9
120-4212	10/22/69[2]	64	290	160	8.0	76	66	3.29	14	1.15	6	0.26	0.03	0.07	66	81	0	1.33	15	0.31	8	0.23	0.67	—	—	10
280-4212	10/22/69[2]	60	190	112	7.8	44	26	1.30	17	1.40	6	0.26	0.00	0.08	32	39	0	0.67	5	0.10	8	0.23	1.45	—	—	12
Quaternary Outwash																										
81-4211	8/19/69[2]	70	195	86	6.3	42	30	1.50	16	1.32	4	0.17	0.10	0.16	22	27	0	0.44	17	0.35	6	0.17	1.06	—	—	13
103-3211	5/10/68[2]	—	—	—	6.3	96	—	—	—	—	—	—	0.12	0.04	40	49	0	0.80	—	—	30	0.85	0.94	0.000	0.010	—
133-4211	8/22/69[2]	62	117	70	6.1	22	24	1.20	7	0.58	4	0.17	0.10	0.00	12	15	0	0.25	15	0.31	3	0.08	0.12	—	—	—
136-3301	6/24/58[1]	—	—	—	5.8	52	—	—	—	—	—	—	0.10	—	14	17	0	0.28	—	—	8	0.23	0.00	0.000	0.000	—
	11/13/69[2]	57	85	62	6.3	14	12	0.60	2	0.16	7	0.30	31.00 ±0.14	±0.12	6	7	0	0.11	10	0.21	9	0.28	0.17	—	—	4
474-4201	6/6/63[2]	—	—	—	6.2	20	—	—	—	—	—	—	0.17	0.02	14	17	0	0.28	—	—	2	0.06	0.50	0.001	0.016	—
475-4201	1/29/63[2]	—	—	—	6.0	24	—	—	—	—	—	—	0.08	—	16	20	0	0.33	—	—	3	0.08	0.25	0.000	0.014	—
476-4201	11/16/61[2]	—	—	—	5.8	60	—	—	—	—	—	—	0.10	—	30	37	0	0.61	—	—	6	0.17	1.30	0.000	0.014	—
477-4201	6/27/61[2]	—	—	—	6.2	28	—	—	—	—	—	—	0.90	—	22	27	0	0.44	—	—	2	0.06	0.10	0.000	0.010	—

Table 11. Chemical Analyses (continued).

Well Number	Date of Analysis	Temperature	Specific Conductance	Total Dissolved Solids	pH	Total Hardness, mg/l as $CaCO_3$	Ca^{++}		Mg^{++}		Na^{+}		Total Iron	Mn^{++}	Alkalinity mg/l as $CaCO_3$	HCO_3^-	$CO_3^=$	$HCO_3^- + CO_3^=$	$SO_4^=$		Cl^-		Nitrogen			SiO_2
		°F		mg/l			mg/l	epm	mg/l	epm	mg/l	epm	mg/l	mg/l		mg/l	mg/l	epm	mg/l	epm	mg/l	epm	NO_3^- mg/l	NO_2^- mg/l	NH_3 mg/l	mg/l
478-4201	6/10/59[a]	—	—	—	5.6	68	—	—	—	—	—	—	0.40	—	16	20	0	0.33	—	—	22	0.62	8.50	0.090	0.202	—
482-4201	11/16/61[a]	—	—	—	6.1	50	—	—	—	—	—	—	0.20	—	32	39	0	0.64	—	—	6	0.17	1.00	0.002	0.006	—
483-4201	5/22/59[a]	—	—	—	6.5	22	—	—	—	—	—	—	0.06	—	20	24	0	0.39	—	—	4	0.11	0.40	0.000	0.006	—
Quaternary Buried Sand and Gravel																										
9-1113	12/30/63[a]	—	—	—	7.0	96	—	—	—	—	—	—	14.80	0.51	90	110	0	1.80	—	—	7	0.20	0.10	0.000	0.088	—
10-1113	12/30/63[a]	—	—	—	8.0	118	—	—	—	—	—	—	0.15	0.14	70	85	0	1.39	—	—	12	0.34	0.10	0.000	0.012	—
12-1113	12/30/63[a]	—	—	—	8.0	150	—	—	—	—	—	—	0.22	0.21	102	124	0	2.03	—	—	17	0.48	0.10	0.000	0.052	—
	1/2/64[a]	—	—	—	7.9	150	—	—	—	—	—	—	0.04	0.16	100	122	0	2.00	—	—	16	0.45	0.10	0.000	0.038	—
13-1113	1/21/64[a]	—	—	—	8.3	126	—	—	—	—	—	—	0.12	0.14	86	105	0	1.72	—	—	14	0.39	0.05	0.000	0.018	—
	4/1/64[c]	—	—	—	8.0	128	—	—	—	—	—	—	0.06	0.13	86	105	0	1.72	—	—	10	0.28	0.05	0.000	0.074	—
	4/3/64[c]	—	—	—	8.0	128	—	—	—	—	—	—	0.04	0.10	86	105	0	1.72	—	—	10	0.28	0.05	0.000	0.044	—
	4/6/64[c]	—	—	—	8.2	126	—	—	—	—	—	—	0.06	0.11	88	107	0	1.75	—	—	10	0.28	0.05	0.000	0.042	—
	4/7/64[c]	—	—	—	8.1	128	—	—	—	—	—	—	0.06	0.12	88	107	0	1.75	—	—	11	0.31	0.05	0.000	0.046	—
	4/8/64[c]	—	—	—	8.2	130	—	—	—	—	—	—	0.08	0.11	88	107	0	1.75	—	—	10	0.28	0.05	0.000	0.052	—
	4/9/64[c]	—	—	—	8.1	128	—	—	—	—	—	—	0.06	0.10	86	105	0	1.72	—	—	10	0.28	0.10	0.000	0.034	—
	4/10/64[c]	—	—	—	8.2	128	—	—	—	—	—	—	0.04	0.12	90	110	0	1.80	—	—	10	0.28	0.05	0.000	0.034	—
	4/11/64[c]	—	—	—	8.2	130	—	—	—	—	—	—	0.07	0.09	—	—	—	—	—	—	—		—	—	—	—
	4/12/64[c]	—	—	—	8.2	130	—	—	—	—	—	—	0.05	0.12	—	—	—	—	—	—	—		—	—	—	—
	4/13/64[c]	—	—	—	8.2	130	—	—	—	—	—	—	0.04	0.14	90	110	0	1.80	—	—	10	0.28	0.05	0.000	0.054	—
88-2204	8/14/69[a]	56	210	86	8.1	48	40	2.00	5	0.41	4	0.17	0.16	0.16	40	49	0	0.80	16	0.33	2	0.06	0.05	—	—	14
154-2113	4/14/66[a]	—	—	—	8.2	78	—	—	—	—	—	—	0.08	0.10	56	68	0	1.12	—	—	2	0.06	0.05	0.000	0.028	—
	9/28/66[c]	—	—	—	8.2	80	—	—	—	—	—	—	0.04	0.00	48	59	0	0.97	—	—	3	0.08	0.09	0.010	0.018	—
	10/6/66[a]	—	—	—	8.4	86	—	—	—	—	—	—	0.18	0.11	56	67	1	1.13	—	—	3	0.08	0.15	0.000	0.026	—
	10/7/66[a]	—	—	—	8.4	88	—	—	—	—	—	—	0.03	0.07	56	67	1	1.13	—	—	2	0.06	1.00	0.000	0.028	—
	10/9/66[a]	—	—	—	8.2	88	—	—	—	—	—	—	0.10	0.06	54	66	0	1.08	—	—	2	0.06	0.20	0.000	0.010	—

Table 11. Chemical Analyses (continued).

Well Number	Date of Analysis	Temperature	Specific Conductance	Total Dissolved Solids	pH	Total Hardness, mg/l as $CaCO_3$	Ca^{++}		Mg^{++}		Na^{+}		Total Iron	Mn^{++}	Alkalinity mg/l as $CaCO_3$	e. HCO_3^-	e. $CO_3^=$	$HCO_3^- + CO_3^=$	$SO_4^=$		Cl^-		Nitrogen			SiO_2
		°F		mg/l			mg/l	epm	mg/l	epm	mg/l	epm	mg/l	mg/l		mg/l	mg/l	epm	mg/l	epm	mg/l	epm	NO_3^- mg/l	NO_2^- mg/l	NH_3 mg/l	mg/l
154-2113	10/9/66[a]	—	—	—	8.4	82	—	—	—	—	—	—	0.15	0.08	56	67	1	1.13	—	—	2	0.06	0.20	0.000	0.024	—
	10/10/66[a]	—	—	—	8.4	82	—	—	—	—	—	—	0.14	0.06	56	67	1	1.13	—	—	2	0.06	0.20	0.000	0.048	—
	11/17/66[a]	—	—	—	8.2	80	—	—	—	—	—	—	0.03	0.03	56	68	0	1.12	—	—	2	0.06	0.05	0.000	0.016	—
	11/17/66[c]	—	—	—	8.6	78	—	—	—	—	—	—	0.07	0.00	46	54	1	0.92	—	—	1	0.03	0.14	0.016	0.140	—
	11/18/66[a]	—	—	—	8.2	78	—	—	—	—	—	—	0.03	0.02	54	66	0	1.08	—	—	2	0.06	0.05	0.000	0.016	—
	11/22/66[a]	—	—	—	8.2	82	—	—	—	—	—	—	0.03	0.02	54	66	0	1.08	—	—	2	0.06	0.25	0.000	0.024	—
155-2113	4/14/66[a]	—	—	—	8.2	96	—	—	—	—	—	—	0.12	0.12	52	63	0	1.03	—	—	2	0.06	0.25	0.000	0.026	—
	11/7/66[a]	—	—	—	8.0	96	—	—	—	—	—	—	0.03	0.05	52	63	0	1.03	—	—	2	0.06	1.25	0.002	0.012	—
	11/8/66[a]	—	—	—	8.1	86	—	—	—	—	—	—	0.03	0.05	52	63	0	1.03	—	—	2	0.06	1.00	0.001	0.014	—
	11/9/66[a]	—	—	—	8.1	88	—	—	—	—	—	—	0.03	0.05	56	68	0	1.12	—	—	2	0.06	1.25	0.000	0.010	—
	11/17/66[a]	—	—	—	8.2	88	—	—	—	—	—	—	0.03	0.05	54	66	0	1.08	—	—	2	0.06	0.05	0.000	0.028	—
	11/17/66[c]	—	—	—	8.5	80	—	—	—	—	—	—	0.04	0.00	45	52	1	0.88	—	—	1	0.03	0.08	0.079	0.180	—
	11/18/66[a]	—	—	—	8.2	104	—	—	—	—	—	—	0.03	0.03	52	63	0	1.03	—	—	2	0.06	0.05	0.000	0.016	—
	11/22/66[a]	—	—	—	8.2	86	—	—	—	—	—	—	0.03	0.02	54	66	0	1.08	—	—	2	0.06	0.25	0.000	0.022	—
Quaternary Delta																										
129-1211	9/24/69[a]	62	380	158	6.8	88	60	2.99	51	4.20	10	0.44	0.10	0.04	72	88	0	1.44	28	0.58	5	0.14	0.47	—	—	10
Quaternary Alluvium																										
481-2201	4/15/58[a]	—	—	—	5.8	58	—	—	—	—	—	—	0.96	—	38	46	0	0.75	—	—	12	0.34	0.25	0.020	0.036	—
	6/18/58[a]	—	—	—	6.4	78	—	—	—	—	—	—	1.72	—	38	46	0	0.75	—	—	22	0.62	0.40	0.030	0.024	—
Quaternary Stream Terrace																										
28-1201	8/16/66[d]	—	150	—	6.1	51	—	—	—	—	—	—	0.35	0.02	10	12	0	0.20	—	—	19	0.54	0.22	0.000	—	—
54-2214	10/20/69[a]	58	380	208	5.8	84	62	3.09	18	1.48	7	0.30	0.13	0.32	10	12	0	0.20	2	0.04	15	0.42	22.40	—	—	8
55-2201	5/12/67[c]	—	—	—	6.5	102	—	—	—	—	—	—	0.19	0.00	29	35	0	0.57	—	—	8	0.23	0.22	0.15	0.150	—
	10/1/69[a]	60	420	176	7.2	118	64	3.19	18	1.48	5	0.22	0.20	0.08	52	63	0	1.03	43	0.89	10	0.28	2.90	—	—	7
58-2201	10/15/69[a]	55	450	188	6.1	34	16	0.80	6	0.49	26	1.13	2.94 f0.07	0.38 f0.32	14	17	0	0.28	42	0.87	62	1.75	0.05	—	—	5

Table 11. Chemical Analyses (continued).

Well Number	Date of Analysis	Temperature °F	Specific Conductance	Total Dissolved Solids mg/l	pH	Total Hardness, mg/l as $CaCO_3$	Ca^{++} mg/l	Ca^{++} epm	Mg^{++} mg/l	Mg^{++} epm	Na^{+} mg/l	Na^{+} epm	Total Iron mg/l	Mn^{++} mg/l	Alkalinity mg/l as $CaCO_3$	$^{e}HCO_3^-$ mg/l	$^{e}CO_3^=$ mg/l	$HCO_3^- + CO_3^=$ epm	$SO_4^=$ mg/l	$SO_4^=$ epm	Cl^- mg/l	Cl^- epm	Nitrogen NO_3^- mg/l	Nitrogen NO_2^- mg/l	Nitrogen NH_3 mg/l	SiO_2 mg/l
Quaternary Till																										
53-3201	9/12/58 [a]	—	—	—	7.0	140	—	—	—	—	—	—	0.13	—	88	107	0	1.75	—	—	20	0.56	2.00	0.010	—	—
134-1201	10/8/69 [a]	67	800	448	6.6	178	114	5.69	120	988	19	0.83	0.10	0.32	24	29	0	0.48	46	0.96	48	1.35	15.00	0.014	0.500	14
52	8/7/69 [a]	52	220	96	6 5	50	38	1.90	14	1.15	3	0.13	0.15	0.14	34	41	0	0.67	18	0.37	4	0.11	0.80	—	—	12

Notes:

a. Analysis by Massachussetts Department of Public Health.

b. Analysis by Mutter's Industrial Testing Labbratory, Holyoke, Mass.

c. Analysis by Tighe and Bond, Consulting Engineers, Holyoke, Mass.

d. Analysis by Springfield Water Works, Springfield, Mass.

e. HCO_3^- and $CO_3^=$ calculated from alkalinity using nomographs in <u>Standard Methods</u>, 1965, p.78, and equations from Sawyer, 1960, p 224.

f Filtered Sample.

bar graphs, and pattern diagrams (e.g. the Stiff diagram and the kite diagram); in devising a water classification system based on Palmer's geochemical classification; in tabulating the raw and processed data; and in attempting to correlate the increase of one constituent with the increase or decrease of others. Out of these efforts have come table 11, which lists the basic data, figure 5, which presents the samples in terms of the major constituents on trilinear diagrams (after Piper, 1945), and plate 4, which shows the spatial relationships and relative quality of the numerous samples from the bedrock aquifer by means of Stiff diagrams and other symbols. All other attempts at organization and display of the water-analysis data appeared to be of little or no value toward the discussion of water quality in this study.

Interpretation

Examination of plate 4 reveals some interesting facts about the quality of the ground water in the bedrock aquifer. The most readily apparent of these is the wide variation of quality and the apparent random distribution of the variations. It also shows that in general the water is softer and lower in dissolved solids in areas of recharge and becomes harder and higher in dissolved solids toward areas of discharge. This is a predictable pattern since rain water is soft and low in dissolved solids. As the water percolates into and through the bedrock it has a chance to dissolve more and more minerals. In addition, as the water moves away from the recharge area it generally moves deeper where higher pressures allow larger quantities of carbon dioxide to be dissolved, which in turn enables the water to dissolve larger quantities of the major hardness-causing ions, calcium and magnesium (Hem, 1959,

p. 74 and 81). The specific conductance of water, dependent upon and a measure of the dissolved solids, has the same pattern as the dissolved solids.

It is easy to explain this general pattern of hardness, dissolved solids, and specific conductance, but it is not so easy to explain the range of variation within the pattern. One reason may be found in the sampling procedure. All of the wells had to be sampled from a storage tank in which the water had been sitting for varying lengths of time. There is no way of knowing to what extent the release of carbon dioxide and the precipitation of hardness-causing compounds may have occurred. A second reason for exceptions to the pattern may be that, with the homoclinal structure of the Triassic rocks, and with the different wells having been drilled to various depths, even adjacent wells are not likely to intersect all of the same beds or fractures. Thus, the water reaching one well may have more or less opportunity to dissolve minerals than the water reaching an adjacent well.

In the bedrock aquifer, 10, or 18 percent, of the wells sampled have water with a hardness greater than 150 mg/l, and 21, or 37 percent, have water with a hardness of less than 75 mg/l. The hardness ranges from 32 to 1500 mg/l. The four wells--17-2212, 40-2212, 56-2212, and 59-2212--in which the water is exceptionally hard (that is, greater than 300 mg/l) (table 11) are quite high in calcium (50-70 percent of the cations) and extremely high in sulfate (86-98 percent of the anions). Apparently these wells, or the fractures intercepted by these wells, have intersected one or more zones of gypsum, which, as previously mentioned, has been reported in the study area (Emerson, 1895). Other wells,

such as 82-1212, 115-2212, and 480-1204 (table 11) in which the water is unusually high in sulfate, have water that has probably also been in contact with gypsum. There are, however, other possible sources of sulfate, such as pyrite.

In the Quaternary deposits the water is generally softer, with lower dissolved solids and specific conductance than in the bedrock aquifer. The main reason for this is that there is less opportunity for the solution of minerals by the water in these deposits than there is for water in the bedrock aquifer because of the shorter residence time and the shorter distances of travel in the Quaternary deposits. Omitting the wells in the buried sand and gravel deposits, which are apparently recharged through the bedrock aquifer, only 1, or 5 percent, of the wells sampled has water with a hardness of greater than 150 mg/l, and 14, or 67 percent, have a hardness of less than 75 mg/l. The hardness ranges from 14 to 178 mg/l. Among 10 wells and test borings in the buried sand and gravel deposits, 1 well has water with a hardness of less than 75 mg/l, and the other 9 wells and test borings have water with a hardness of 75 to 150 mg/l. The hardness ranges from 48 to 150 mg/l.

Apparently no characteristic of the water in any water-bearing unit can be considered indicative of that unit, but certain characteristics are more or less consistent. The consistencies are most apparent in figure 5, in which the major cations--calcium, magnesium, and sodium--and the major anions--bicarbonate (plus carbonate when present), sulfate, and chloride--have been plotted on trilinear diagrams. Figure 5-a shows the samples from the bedrock aquifer. A definite clustering can be seen in the diamond field, showing, without the interference of arbitrary

Figure 5-a. All bedrock wells.

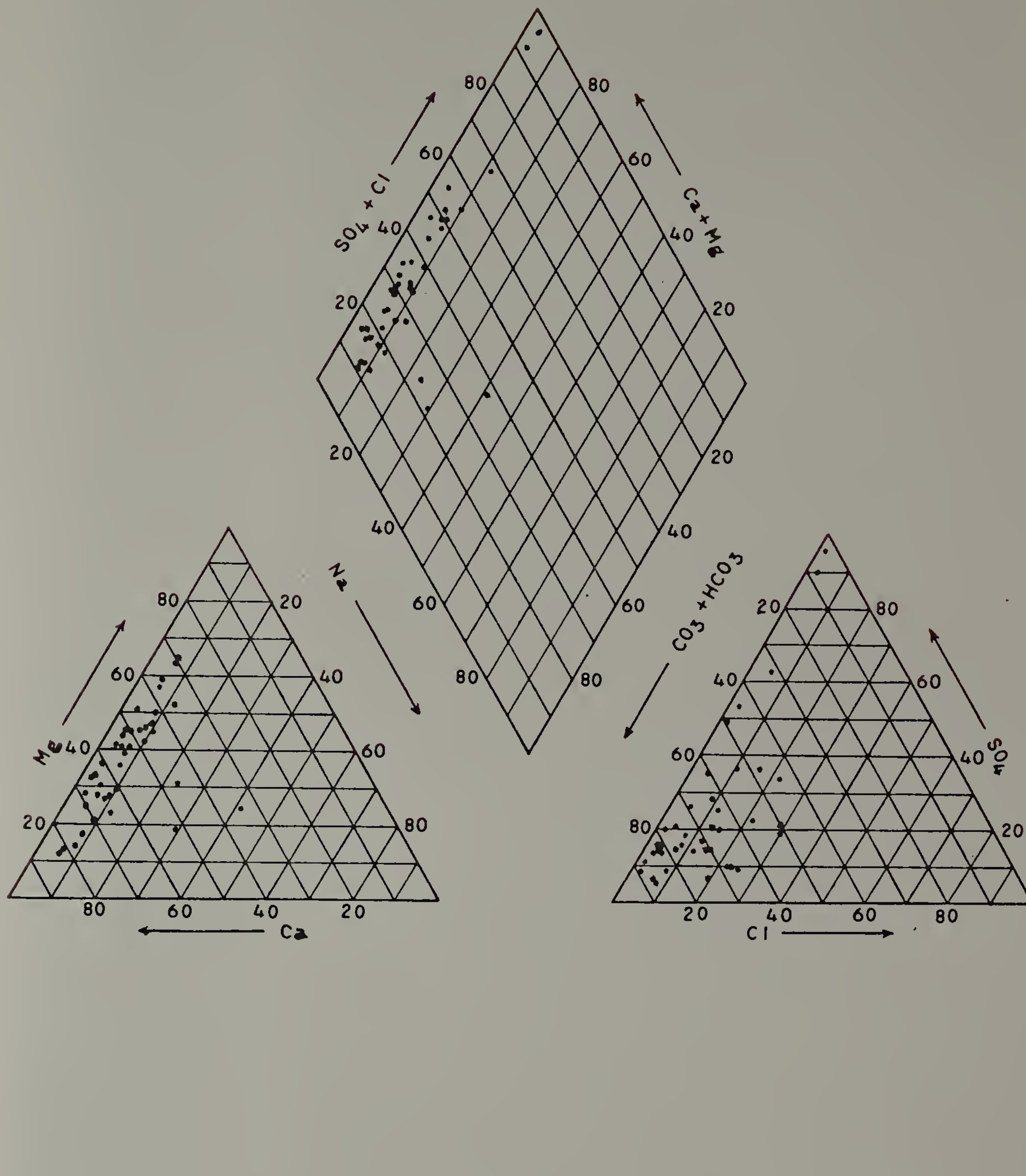
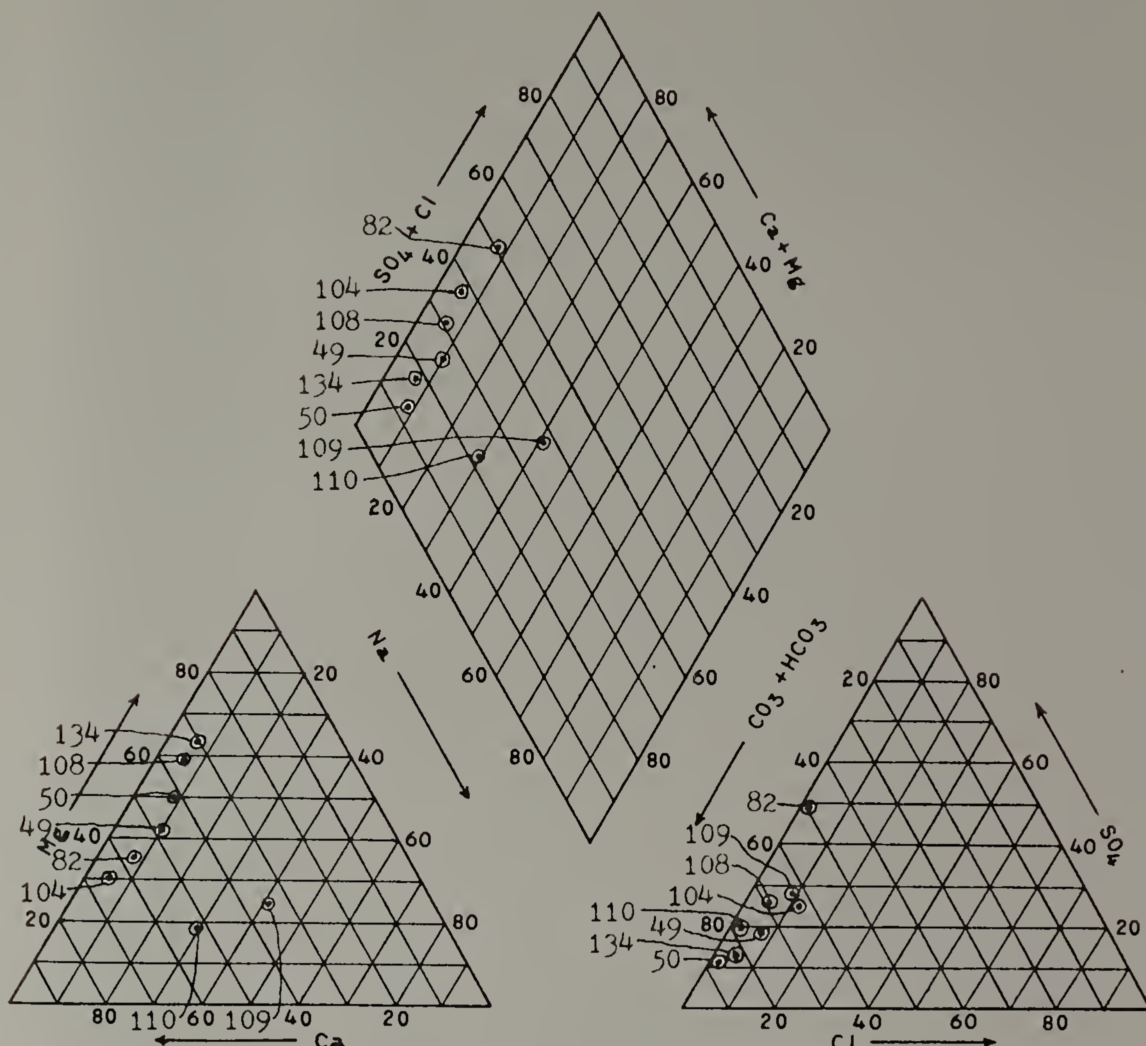
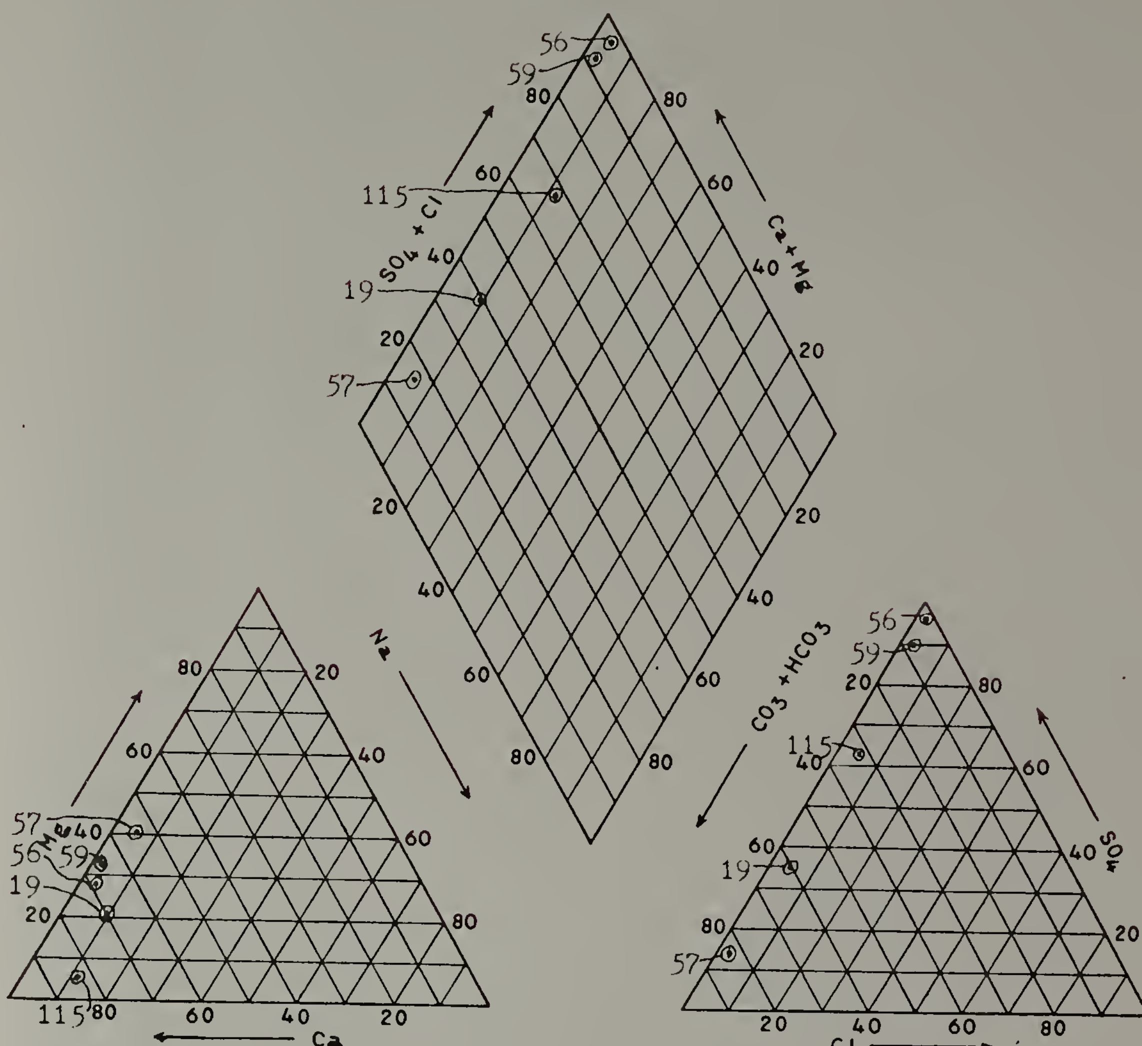


Figure 5-b. Triassic bedrock wells--Agawam.



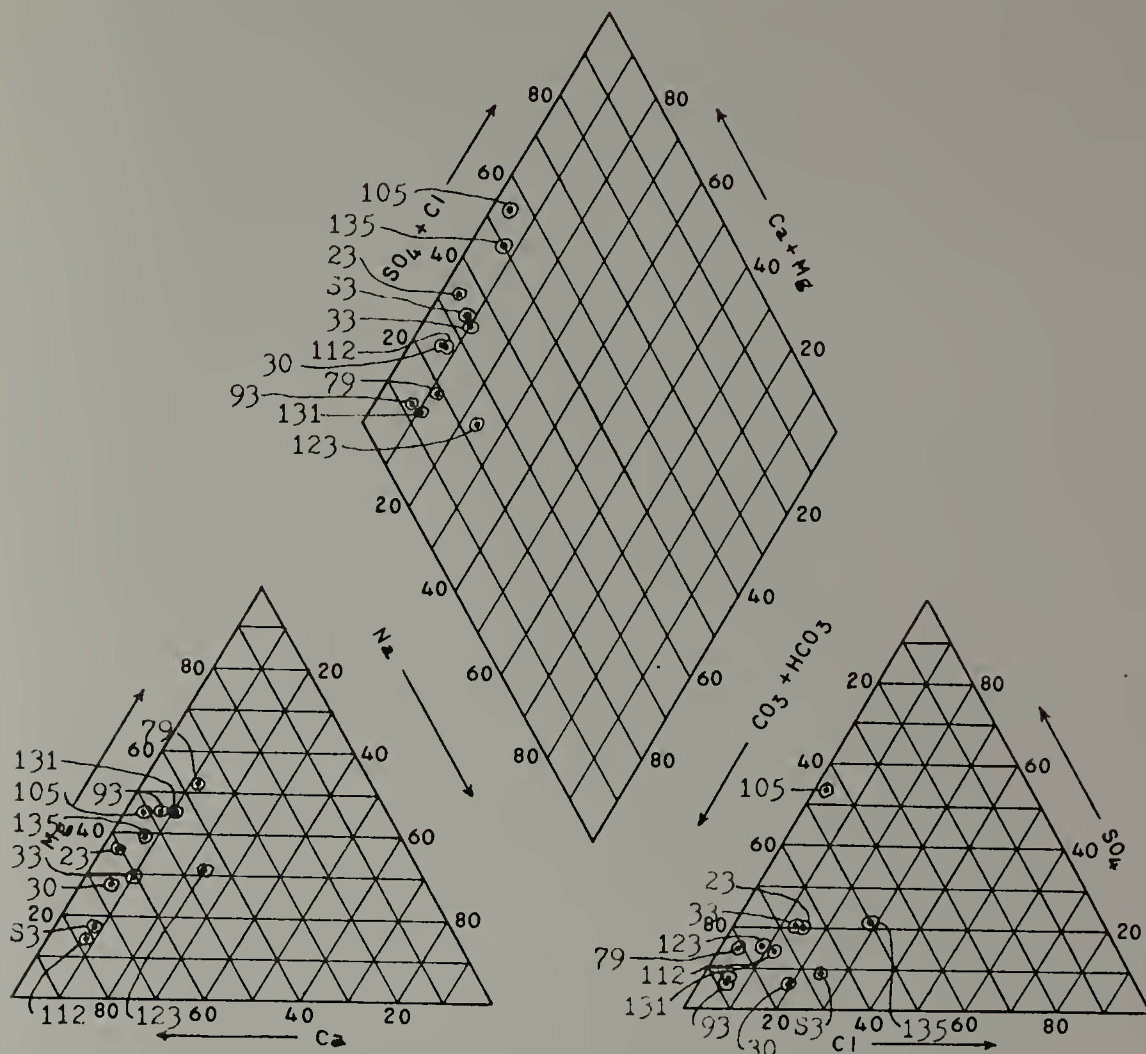
104-1212 -- Holyoke basalt
49-1304 --
50-1304 --
82-1212 --
108-1212 -- Portland Arkose
109-1212 --
110-1212 --
134-1202 --

Figure 5-c. Triassic bedrock wells--Longmeadow.



19-2212 --
56-2212 --
57-2212 -- Portland Arkose
59-2212 --
115-2212 --

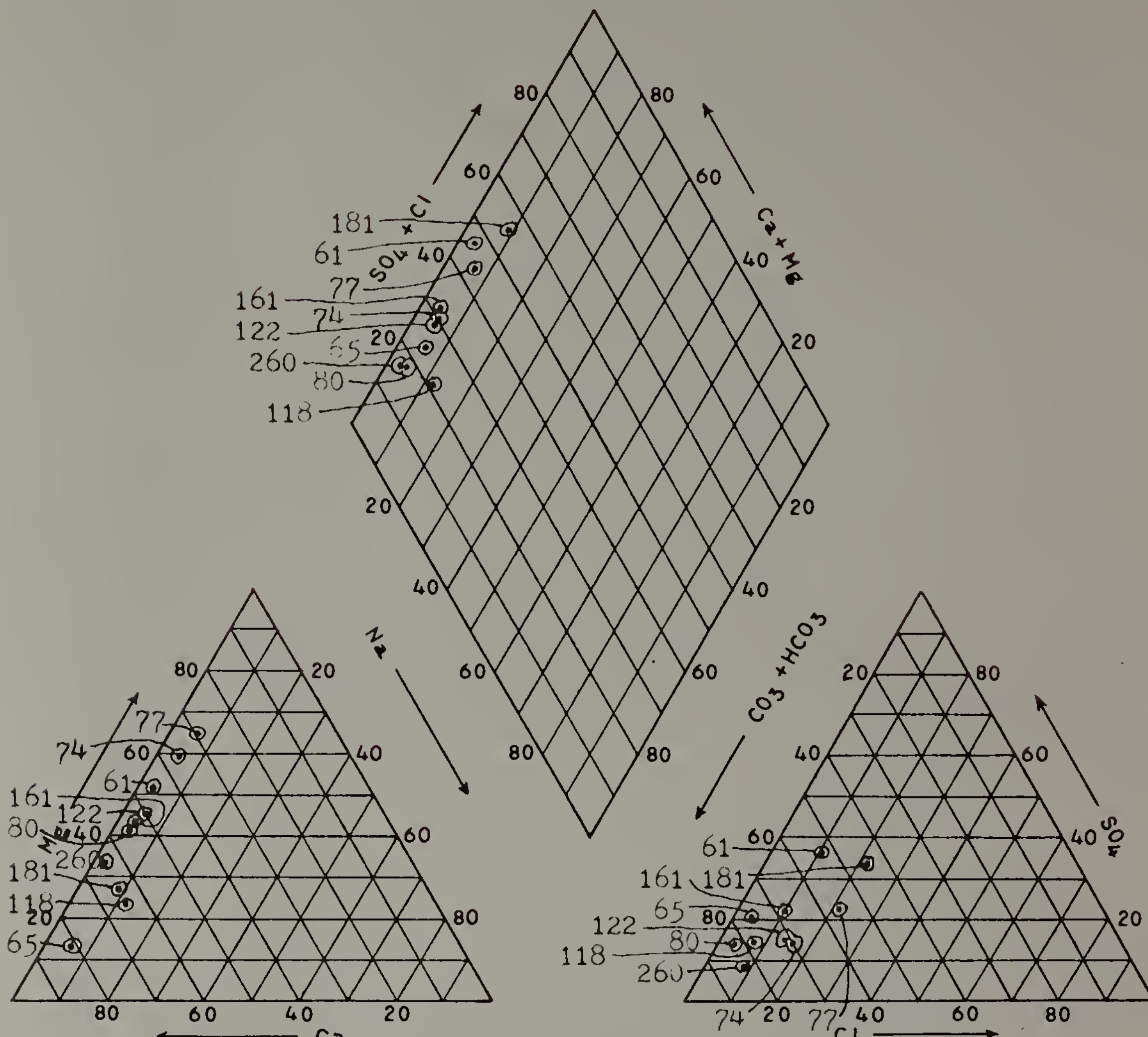
Figure 5-d. Triassic bedrock wells--East Longmeadow.



23-3312 --
30-3212 --
33-3212 --
79-3212 --
93-3212 --
105-3312 --
112-3212 --
123-3212 --
131-3212 --
135-3212 --
S3 --

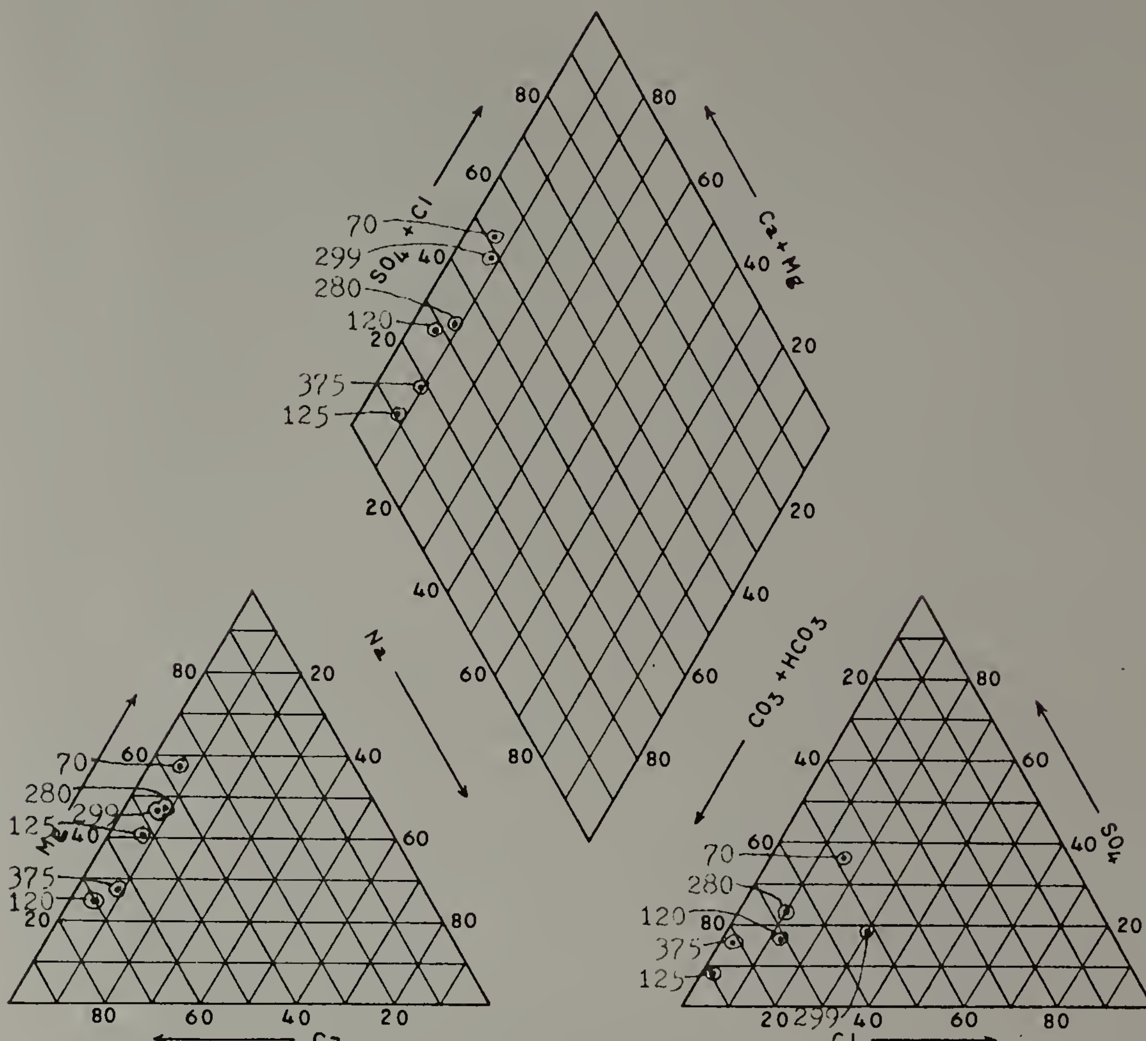
} Portland Arkose

Figure 5-e. Triassic bedrock wells--Hampden.



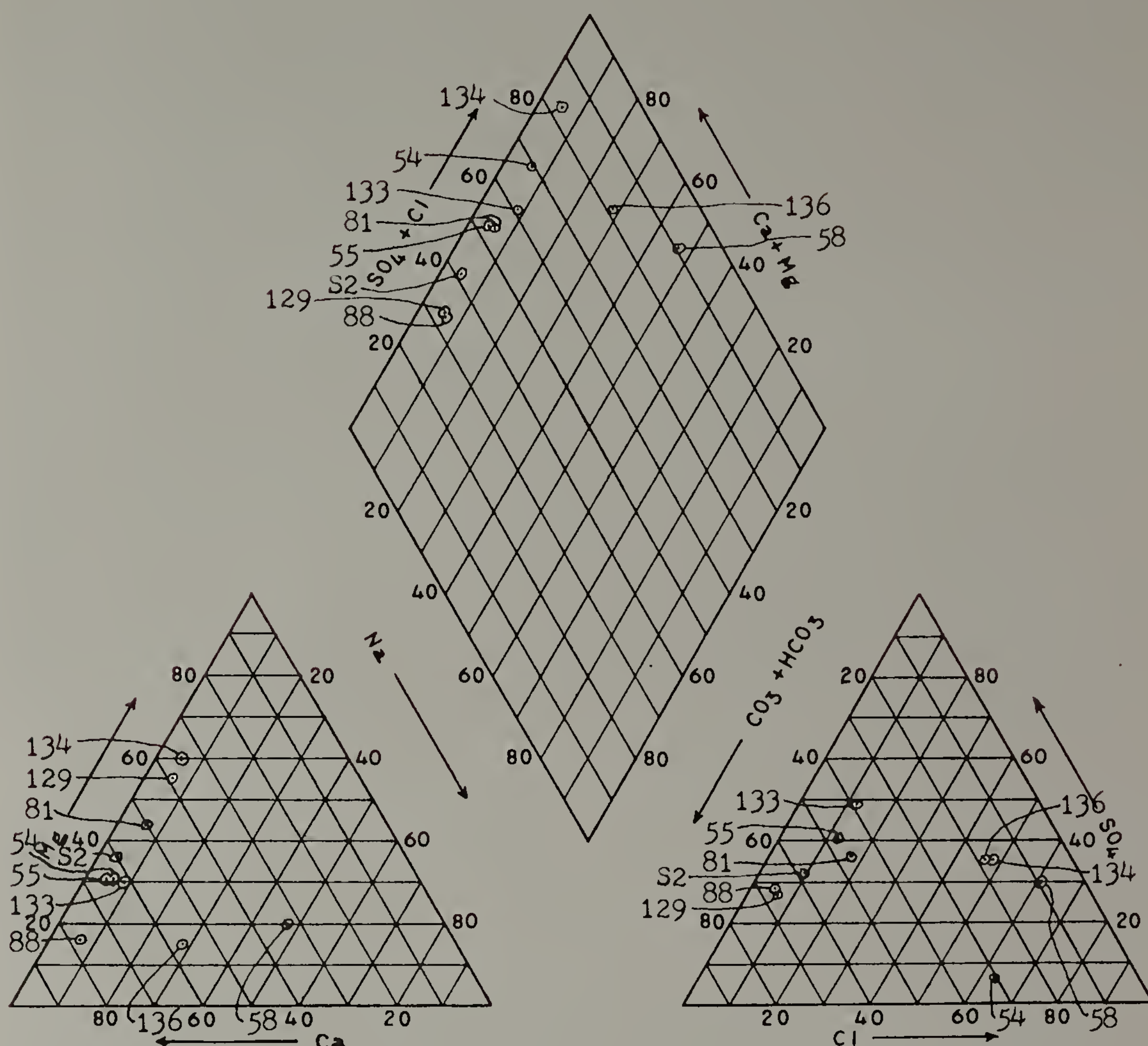
61-4212 --
65-4212 --
74-4212 --
77-4212 --
80-4212 --
118-4212 -- Portland Arkose
122-4212 --
161-4212 --
181-4212 --
260-4212 --

Figure 5-f. Triassic Border Fault Zone bedrock and Paleozoic bedrock wells.



125-4212 -- }
299-4212 -- } Border Fault Zone
375-4212 -- }
70-4212 -- }
120-4212 -- } Paleozoic
280-4212 -- }

Figure 5-g. Wells in Quaternary deposits.



81-4211 -- }
133-4211 -- } Outwash
136-3301 -- }
88-2204 -- Buried sand and gravel
129-1211 -- Delta
54-2214 -- }
55-2201 -- } Stream terrace
58-2201 -- }
134-1201 -- }
S2 -- } Till

limits or categories, the consistency of most of the water in the bedrock aquifer. Unfortunately in discussion a certain amount of categorization, which will be based on whether a component constitutes more than 50 percent of the total cations or anions, cannot be avoided. The cluster is very strongly in the alkaline-earth subarea. That is, calcium plus magnesium exceeds sodium, or alkali. The cluster overlaps the weak-acid and strong-acid subareas. About nine-tenths of the cluster lies in the weak-acid subarea with the other one-tenth lying on the weak-acid side of the strong-acid subarea. That is, in nine-tenths of the clustered samples bicarbonate plus carbonate exceeds sulfate plus chloride, and in the other one-tenth the opposite is true although weak-acid anions remain significant. Six samples fall outside of this cluster. Three of these are definitely dominated by strong-acid anions, but are also dominated by the alkaline-earth cations. The other three aberrant samples are also dominated by the weak-acid anions, and differ from the main cluster in having a higher proportion of alkali cations.

The trilinear diagrams of figure 5-b through 5-f are presented for easier identification of individual samples on the plots and particularly to illustrate the variations among the major ions in the ground water in the different sections of the bedrock aquifer. For example, only in Longmeadow (figure 5-c) is sulfate overwhelmingly dominant in any sample. Elsewhere bicarbonate is usually the dominant anion. Again in Longmeadow, and to a lesser extent in East Longmeadow (figure 5-d), calcium is the dominant cation, whereas in other sections magnesium is also abundant. Only in Agawam (figure 5-b) does sodium constitute more

than 25 percent of the cations in any sample. Chloride is very weak in Agawam and Longmeadow, where the bedrock aquifer is essentially sealed by the overlying clay, suggesting that much of the chloride in other parts of the bedrock aquifer may be derived from pollution by road salt or sewage. It is also notable that the water quality, at least with respect to the dominant ions, is quite the same in the Paleozoic bedrock and the Triassic Border Fault Zone bedrock (figure 5-f) as it is in the Triassic bedrock of Hampden (figure 5-e). This lends further support to my contention that the Paleozoic bedrock and the Triassic bedrock constitute a single hydraulic unit.

Figure 5-g is a trilinear plot of the major ions for the samples from the Quaternary deposits. This plot shows no definite grouping. On the contrary, it shows the diversity of quality among the Quaternary deposits. The samples are too few to say much about the constancy of quality within the individual deposits. It is apparent from figure 5-g that like the bedrock aquifer, ground water in the Quaternary deposits is likely to be dominated by the alkaline-earth cations, but that unlike the bedrock aquifer it is likely to be dominated by the strong-acid ions. Also, chloride is much more abundant in the Quaternary deposits than it is in the bedrock aquifer, suggesting greater susceptibility to pollution by road salt and sewage.

The water from a number of wells has been analyzed more than once over various periods of time (table 11). These analyses show remarkably little change in the quality of water from a given well in the bedrock aquifer (57-2212 and 137-4312) and the buried sand and gravel deposits

(12-1113, 13-1113, 154-2113, and 155-2113) over periods ranging from a few days to 9 years. However, a well in stream-terrace deposits (55-2201) and a well in outwash deposits (136-3301) show considerable change after 3 and 11 years respectively. Well 55-2201 shows marked increases in nitrate and alkalinity with some increase in chloride. This could be due to pollution from sewage. Well 136-3301 shows a marked increase in iron, a small increase in pH, and decreases in hardness and alkalinity. The reason for these changes is puzzling, but may be related to bacterial activity and/or carbon dioxide content.

Iron and manganese can become a problem when they occur in a combined concentration of more than 0.30 mg/l. The problem that they cause is primarily aesthetic as they have no sanitary or health significance. At concentrations of more than 0.30 mg/l iron and manganese may come out of solution in sufficient quantity to stain clothes and plumbing fixtures or to color the water. Table 11 shows that it is not uncommon for iron and manganese to occur in sufficient concentrations as to be troublesome, and such concentrations may occur anywhere in the study area, in any water-bearing unit, and with no apparent pattern. Part of the very large amount of iron in the unfiltered sample from well 125-4212 is due to the fact that the sample could be obtained only from the bottom of the storage tank. Thus, iron that had been precipitating for some time was undoubtedly included in the sample. The water is normally treated, however, to remove the iron before use. On the other hand, well 136-3301 was pumped for 10-15 minutes with no visible decrease in suspended iron (table 11, 1969 sample). This was reported to be very unusual, however, and not normally a problem, as suggested by the 1958 analysis of

water from the same well (table 11). The iron and manganese data presented in this study are not likely to be representative of conditions in the ground because iron may be lost from the water by oxidation and precipitation as soon as the water enters the well, or because iron may even be added to the water from the well casing, storage tank, pump, and pipes of the water system, depending upon a complex set of variables (Hem, 1959).

The occurrence of nitrogen in ground water may be in the form of ammonia (NH_3), ammonium ion (NH_4+), gaseous nitrogen (N_2), nitrite ion (NO_2-), or nitrate ion (NO_3-). The primary significance of nitrogen is sanitary and it is an indicator of possible pollution by sewage. When organic pollution is not an object of study, nitrate is usually the only nitrogen determination that is made, but in a sanitary analysis, such as most of the partial analyses in table 11, ammonia, nitrite, and nitrate nitrogen determinations are usually made. High concentrations of nitrogen accompanied by high concentrations of chloride may indicate organic pollution, but this should be verified by bacterial analysis. Examination of table 11 will reveal a number of analyses in which organic pollution might be suspected. One analysis (134-1201) is of water from a test boring in till in Agawam that was strongly suspected of coming into contact with chicken manure at the We Hope Poultry Farm, also causing problems of air pollution by the production of ammonia from the wet manure. This sample produced the second highest nitrogen and the third highest chloride determinations of all the analyses, being 15.00 mg/l nitrate and 48 mg/l chloride.

In summary, the quality of water from a well in the study area is predictable only within broad limits. The dominant cations are almost sure to be the alkaline earths, with calcium more likely to be dominant than magnesium, especially in the Longmeadow portion of the bedrock aquifer. In the bedrock aquifer the dominant anion is likely to be the weak acid, bicarbonate, except in Longmeadow where the strong acid, sulfate, is equally likely to dominate. In the Quaternary deposits the dominant anion will probably be one or the other of the strong acids, sulfate or chloride. It is likely that the water in the bedrock aquifer will have a hardness between 75 and 150 mg/l, except in the recharge areas where the hardness is more likely to be less than 75 mg/l. Water in the Quaternary deposits is most likely to have less than 75 mg/l of hardness, except in the buried sand and gravel deposits, which are most likely to have water with a hardness of 75 to 150 mg/l. Iron and manganese are a potential problem in any water-bearing unit in any part of the study area. Polution, especially from road salt and sewage, is a potential problem in all of the water-bearing units where water-table conditions prevail, but particularly in Hampden where there is no municipal sewerage system.

WATER USE

Water use may be divided into three categories--domestic, commercial and industrial, and public (Linsley and Franzini, 1964, p. 407-408; Hardenbergh and Rodie, 1960, p. 43-44). Domestic use includes the water that is used in private residences (including apartment houses) for household purposes such as drinking, bathing, laundering, cooking, and sanitation.

It also includes water used for such purposes as lawn and garden watering, air conditioning, and private swimming pools. In the Springfield-Holyoke area of Massachusetts, of which the study area is a part, domestic use averaged 50-60 gpcd (gallons per capita per day) in 1960 (Kammerer and Baldwin, 1962, p. 50), and may be more than 60 gpcd today because of the increase in air conditioning, private swimming pools, garbage disposals, automatic dish washers, etc., during recent years. This figure will vary from dwelling to dwelling depending upon the economic status of the resident (Linsley and Franzini, 1964, p. 408). Also, there is some agriculture carried on in Agawam. Residents of these farms, particularly where tobacco is grown, undoubtedly use more water per capita than do the non-farming residents that comprise the bulk of the population.

Commercial and industrial use includes the water that is used in commercial establishments and in industrial activities for a wide variety of purposes. The amount of water used for these purposes depends upon the type of commercial establishment, such as car wash, laundry, bakery, grocery store, etc., upon the manufacturing process involved in the industry, and upon the size of the business. On the average, commercial and industrial use may range from 10 gpcd in a small residential community to 100 gpcd in an industrial city (Linsley and Franzizi, 1964, p. 408). In 1960, municipal water systems in the Springfield-Holyoke area provided about 80-90 gpcd for industrial and commercial purposes (Kammerer and Baldwin, 1962, p. 50).

Public use includes water used in civic buildings, parks, schools, public swimming pools, churches, hospitals, street cleaning, fire fight-

ing, etc. According to Linsley and Franzini (1964, p. 408) public use amounts to about 10 gpcd, whereas Hardenbergh and Rodie (1960, p. 44) estimate that public use represents from 10 to 25 percent of total water use. Using these estimates and the figures on water use provided in Kammerer and Baldwin (1962, p. 50) and Durfor and Becker (1962, p. 7), public use in the Springfield-Holyoke area in 1960 may have been as low as 10 gpcd, or as high as 45 gpcd.

Hardenbergh and Rodie (1960, p. 48) and Linsley and Franzini (1964, p. 408) state that loss of water from municipal systems due to leakage and waste may range from 3 to 40 gpcd and that losses are commonly estimated at 20 gpcd for planning purposes. This leakage and waste occurs within the distribution system and as a result of all types of uses. Although it is not strictly a water use, it may represent a significant amount of water lost from the system and must be taken into account.

During 1960 the city of Springfield supplied about 181 gpcd to meet the city's requirements. The suburbs of Springfield, which includes the area of this study, required only 68 gpcd (Durfor and Becker, 1962, p. 6-7). The difference between the industrial city and the primarily residential area in 1960 was about 113 gpcd. This difference is probably smaller now, as a number of industries have moved from the city to the suburbs in recent years.

Water-quality requirements vary widely according to use. For domestic and public purposes water-quality considerations are primarily the aesthetic and sanitary requirements for drinking water. The U. S. Public Health Service Drinking Water Standards are presented in table 12.

It will be noted that most of the chemical characteristics, including those that may cause serious health problems, are not usually determined even in sanitary analyses. This is because these elements normally occur in such low concentrations, if at all, that they have been very difficult and expensive to analyse in the past. For other than drinking purposes there is wide latitude in the water-quality requirements for domestic and public uses. However, certain chemical characteristics may cause some problems. For example, hardness may produce problems of boiler scale in hot water heaters and in hot water or steam heating systems. Hardness may also cause problems of excessive soap use in laundering. Problems of iron and manganese staining have been discussed previously.

For commercial and industrial purposes there is an extremely wide variety of water-quality requirements that depend upon the specific use for which the water is intended. Most chemical characteristics of water that are of major concern for commercial and industrial purposes are usually determined in water analyses, and include hardness, iron and manganese, total solids, alkalinity, pH, and hydrogen sulfide. Specific requirements for some commercial and industrial purposes are listed in Hem (1959, p. 253-254), Hardenbergh and Rodie (1960, p. 417), and Todd (1959, p. 186-187).

GROUND-WATER RESOURCES POTENTIAL

There are two basic systems of water supply, private and municipal. In the private system each individual user is concerned only with his own particular needs. If the user is domestic his needs are small and relatively

Table 12. U.S. Public Health Service Drinking Water Standards, 1962.

Characteristic	Limit Not to Be Exceeded	Cause for Rejection
Physical		
Color	15 units	
Taste	Unobjectionable	
Odor	3	
Turbidity	5 units	
Chemical	mg/l	mg/l
ABS	0.5	
Arsenic	0.01	0.05
Barium		1.0
Cadmium		0.01
Chloride	250	
Chromium (hexavalent)		0.05
Copper	1	
Cyanide	0.01	0.2
Fluoride*	0.7-1.2	1.4-2.4
Iron	0.3	
Lead		0.05
Manganese	0.05	
Nitrate	45	
Phenols	0.001	
Selenium		0.01
Silver		0.05
Sulfate	250	
Total Dissolved Solids	500	
Zinc	5	

*The actual recommended concentration of fluoride for a given water supply is a complex determination, but depends primarily upon the annual average maximum daily air temperatures.

easily satisfied, usually on the basis of a single household or small group of households. If the user is commercial or industrial his needs may be quite large and more difficult to supply. Industrial and commercial requirements, however, are usually quite specific and essentially constant. A municipal system, on the other hand, can be quite complicated. It must take into account the needs of domestic, industrial and commercial, and public users with the variety of demands made by each. Previously cited water supply figures for 1960 show that a municipal system in the Springfield area must be able to provide an average of from 70 to 180 gpcd depending upon the size of the population, and upon the number and types of industries and commercial establishments served. In addition to maintaining the everyday needs of its customers, a municipal system must provide a maximum additional flow, determined by population, for fire-fighting purposes as recommended by the National Board of Fire Underwriters (Hardenbergh and Rodie, 1960, p. 45; Linsley and Franzini, 1964, p. 412).

In the Springfield area, private domestic systems generally utilize ground water from springs and wells, but municipal systems and private industrial supplies primarily employ surface water (Kammerer and Baldwin, 1962, p. 51). At the present time the Springfield water system draws its water from the Cobble Mountain and Borden Brook reservoirs on the Little River, and supplies the needs of Agawam, Longmeadow, and East Longmeadow, among other towns (Kammerer and Baldwin, 1962, p. 43; Durfor and Becker, 1962, p. 205). However, because of restricted use during dry weather, particularly in the middle 1960's, many homeowners have had wells drilled for supplementary supplies for purposes of watering lawns and

gardens, washing cars, and other outdoor domestic uses. Hampden has no municipal water system, and water supply is primarily from private ground-water sources on an individual household basis.

In view of the growing population and industrial and commercial activity in the Springfield region, it is only prudent to examine the ground-water resources of the region for possible new sources of water supply. A ground-water investigation was made in 1963-1964 by the firm of Tighe and Bond, consulting engineers, for the town of Agawam with the hope of locating and developing a municipal water-supply system. To my knowledge, although an apparently satisfactory water source was located and a test well (113-1113) installed and test pumped (Tighe and Bond, 1964), no further action has been taken. A similar investigation was also made by Tighe and Bond in 1966 for the town of Longmeadow. A satisfactory source of water was located (Tighe and Bond, 1966), and two test wells (154-2113 and 155-2113) have been placed into service. The firm of Geraghty and Miller, consulting ground-water geologists, conducted a ground-water investigation in 1966 for the city of Springfield with the purpose of locating one or more sources of ground water to supplement the present surface sources of the Springfield water system. They found that deposits of buried sand and gravel in the preglacial bedrock channels had the best potential for development. They recommended that one such deposit in northeast Agawam be investigated further (Geraghty and Miller, 1966). This deposit is the same one located by Tighe and Bond in their earlier study for Agawam. The two Longmeadow wells tap similar deposits in southwestern Longmeadow. The deposits in Agawam and Longmeadow may be parts of one extensive buried sand and

gravel deposit that apparently underlies the Connecticut River in a deep preglacial channel (plates 1 and 3).

Water in these buried sand and gravel deposits occurs under confined conditions, as I have mentioned earlier in this report. Test pumping by Geraghty and Miller indicates that the deposits in Agawam could yield 6-10 mgd (million gallons per day) from individual wells producing 1,000 to 2,000 gpm each. They also determined the coefficients of transmissibility and storage for the deposit to be 125,000 gallons per day per foot and 0.0003 respectively. The specific capacity of the well was 30 gpm per foot of drawdown (Geraghty and Miller, 1966, p. 24-25). Tighe and Bond did not determine the coefficients of transmissibility and storage in their testing, but the specific capacity of the wells in Longmeadow was found to be between 8 and 11 gpm per foot of drawdown. The Geraghty and Miller test in Agawam also indicated vertical leakage, which they believed was downward through the overlying clay, silt, and sand. This might suggest some induced infiltration from the Westfield River, although the findings of Tighe and Bond were that the buried sand and gravel is not hydraulically connected with the river. I would suggest that the vertical leakage might be upward from the bedrock, which I believe recharges the sand and gravel deposits. As to quality, only iron and manganese seem to present any serious problem (table 11). Tighe and Bond rejected one test well (9-1113) in the same, or similar, deposits near Leonard Street in Agawam because of high iron and manganese content (table 11).

In the area of this thesis only the buried sand and gravel deposits in the bedrock channel between Agawam and Longmeadow were considered

by Geraghty and Miller and by Tighe and Bond to yield sufficient quantities of water of appropriate quality for municipal supply. It is my opinion also that the buried sand and gravel deposits have the best potential for the development of municipal supplies, and that they certainly will bear further investigation and probably development. They also have the advantage that the overlying clay adds protection from pollution. It should also be noted that these buried sand and gravel deposits have been found north of Agawam and have been traced south into Connecticut (Geraghty and Miller, 1966, p. 22), and similar deposits appear to be present in other channels in Longmeadow (wells 21-2212 and 88-2204, plate 2).

The tract of outwash in the eastern section of the study area, primarily in Hampden (plate 2), is a water-bearing unit that has high potential as a source of water for municipal supply, but has been overlooked in other ground-water investigations. I have obtained no records of pumping tests of wells in the outwash that were sufficient to compute the coefficients of transmissibility and storage of these deposits. However, some estimates of the water-production potential of the outwash can be made. Davis, Green, Olmsted, and Brown (1959) have made an extensive study of the storage capacity of various water-bearing materials in the San Joaquin Valley of California. They suggest a specific yield of 25 percent for sand, gravel, and mixtures of sand and gravel. Similar studies in the Sacramento Valley of California suggest a specific yield of 20 percent for mixed sand and gravel deposits (Todd, 1959, p. 25; Davis, et al., 1959, p. 209). The coefficient of storage is equivalent to specific yield under unconfined conditions. Granted that the outwash

deposits of Massachusetts are not the same as the thick alluvial deposits of the Central Valley of California, I think that there is sufficient similarity of materials to warrant the use of these figures for purposes of estimation. Estimating the area of outwash within the study area to be about 3,000-4,000 acres, estimating the average saturated thickness to be about 30 feet, and assuming the more conservative specific yield of 20 percent, I calculate that there are from 6 to 8 billion gallons of water in storage in the outwash deposits of western Hampden and eastern East Longmeadow. No tests have shown the true capacity of the outwash to yield water to a well, but wells in outwash in Connecticut, as previously mentioned, yield up to 400 gpm, with specific capacities of as much as 31 gpm per foot of drawdown (Cushman, 1964, p. 54). It seems reasonable to expect that somewhat higher yields than 400 gpm might be obtained from properly located and constructed wells.

Recharge to the outwash is by the direct infiltration of precipitation and by discharge from the underlying bedrock aquifer, which receives its recharge primarily from precipitation in the uplands to the east. No means of estimating the amount of recharge from the bedrock aquifer is available, but a rough estimate of the recharge from precipitation can be made. It has been previously noted that about 46.62 inches of precipitation falls on the study area annually (table 1). The area of the outwash is estimated to be 3,000-4,000 acres. Thus, about 12,000-15,000 acre-feet, or about 4-5 billion gallons, of water falls on the outwash every year. Based on infiltration estimates cited in Cushman (1964, p. 62-63), 30 percent of this rainfall may reach the saturated zone. Therefore, 1.2-1.5 billion gallons of water may annually recharge

the ground-water body by direct infiltration into the outwash. This is equivalent to about 3.5 mgd and may indicate a minimum safe yield from the outwash in Hampden and eastern East Longmeadow. On the basis of the quantity of water available the outwash deposits compare favorably with, but are definitely second to, the buried sand and gravel deposits as a potential source of water for municipal supply. It must be noted here that these outwash deposits extend northward into Wilbraham and southward into Connecticut, and only a part of their potential has been discussed in this analysis. Furthermore, part of the kame deposits on the eastern border of the outwash might properly have been included.

These outwash deposits are less favorable than the buried sand and gravel deposits on the basis of ground-water quality. The overall chemical quality of the water in the outwash is excellent, and the water is less highly mineralized than the water in the buried sand and gravel (table 11). However, a number of domestic wells in the outwash have been abandoned due to organic pollution. This is a problem that must be given careful consideration if the outwash is developed for municipal supply because every building in Hampden has its own waste disposal system of septic tanks, which have been responsible for the pollution in most of the abandoned wells. Where domestic wells in the outwash have been polluted, recourse has usually been made to the bedrock aquifer. This solution may not be feasible in the case of municipal supply because of the much lower yields of bedrock wells and because of the likelihood of drawing polluted water from the outwash into the bedrock with the large volumes of water that would be pumped from a municipal well or well field.

The only other water-bearing unit in the study area that might have a sufficient volume of water available for municipal supply is the outwash deposit in western East Longmeadow (plate 2). This deposit, though similar in character to the outwash of Hampden, is less extensive areally and generally thinner with less saturated thickness. Again no pumping test data are available and only estimates can be made of the water-production potential of the outwash. Estimating the area of the deposit to be about 1,500 acres, estimating the average saturated thickness to be about 20 feet, and again assuming the specific yield to be 20 percent, I calculate that there are about 2 billion gallons of water in storage in this deposit. As in Hampden, no tests have yet shown the true capacity of this outwash to yield water to a well. The only reported yield from a well in this outwash is 140 gpm and is the result of a short-term test only. Larger yields certainly ought to be expected.

Recharge to the East Longmeadow outwash is by the direct infiltration of precipitation, which I estimate to be about 1,500-1,800 acre-feet, or about 150-200 million gallons annually. If the infiltration rate is 30 percent, 45-60 million gallons of water per year is recharged into the outwash. This amounts to 0.3-0.4 mgd and is indicative of the probable safe yield for these deposits. There may be significant recharge from the bedrock aquifer, which is recharged in the hills to the east, but there is no way of estimating what this contribution might be.

From the point of view of water quality, the East Longmeadow outwash deposit is less attractive than either the Hampden outwash or the buried sand and gravel deposits. The overall chemical quality is again excellent, but the East Longmeadow outwash is subject to iron and manganese

problems (table 11, sample 136-3301, 1969), for which it is reported to have been rejected in the past by the town of East Longmeadow as a source of municipal supply. As in Hampden, it is also susceptible to pollution from road salt, sewage, and other wastes.

In order to put the quantities of water involved here into perspective, some statistics will be useful. In 1957 the Springfield water system used an average of 36 mgd, with a maximum use of 62 mgd in any one day (Kammerer and Baldwin, 1962, p. 51). In 1960, the Springfield water system supplied an average of 68 gpcd to Agawam, Longmeadow, and East Longmeadow (Durfor and Becker, 1962, p. 205), which amounted to about 2.5 mgd. Assuming that population growth in these towns reaches the high projections for 1980 (table 2), a total of about 4 mgd will be required by them, if the rate of use does not rise significantly. The town of Hampden, with its lack of industry and preponderance of private ground-water supplies, will draw only about 0.2-0.3 mgd from the ground-water sources by 1980. Thus, it is apparent that there is the potential in the ground-water resources of the study area to supply the needs of the towns in the study area through municipal systems.

No other deposits appear suitable, from the standpoint of volume of water in storage and potential yield to wells, for development as a source of municipal water supply. However, for industrial and commercial uses, the bedrock aquifer, certain kame deposits, and possibly certain delta and alluvial deposits, in addition to the buried sand and gravel and outwash might be suitable from the standpoint of both quantity and quality. This, of course, will depend upon the specific requirements of the industrial or commercial enterprise.

Since the average daily needs of a household of six people could be satisfied from a well yielding less than 0.5 gpm, any of the water-bearing units in the study area may be suitable for domestic supply. Which unit might be preferable will depend upon the local conditions-- geologic, hydrologic, and economic-- at the particular well site, and upon the intended use, or uses, of the water.

Artificial Recharge

Artificial recharge refers to the augmentation of natural infiltration of precipitation or surface water into the ground. Artificial recharge may be accomplished by a variety of methods including water spreading, recharging through wells, shafts, pits, and excavations, and pumping to induce recharge from rivers or other bodies of surface water. Water spreading includes flooding, basin, ditch or furrow, natural channel, and irrigation methods (Todd, 1959, p. 251). Artificial recharge may be employed for two reasons. The first is as a method of storing excess runoff or treated sewage and waste water for later use. Underground storage may be preferable to a surface reservoir because large volumes of water can be stored underground with relatively small loss of valuable land that could be put to other uses, because losses due to evaporation can be greatly reduced or eliminated, and because artificial recharge is cheaper than building dams. The second reason for employing artificial recharge is to increase the production from an aquifer by increasing the rate of recharge or by increasing the amount of water available to a producing well.

In order for artificial recharge to be feasible certain conditions must be satisfied. First, there must be a formation, or other geologic

unit, available that is capable of receiving the water and storing it without significant natural discharge. Second, the unit receiving the recharge must be either thick enough or deep enough to prevent water-logging of the land surface, which might preclude other productive use of the land. Third, there must be sufficient land available to construct the recharge facility. Spreading methods may require a considerable area of relatively flat land for infiltration, depending upon the method used. Recharge wells, pits, etc., require relatively little land area in themselves, but may not be able to recharge as large volumes of water without some temporary surface storage. Fourth, since the most efficient means of collecting excess runoff for artificial recharge is in the natural drainage channels, the recharge facility often must be a part of, or adjacent to, the main rivers or streams. If this cannot be the case, some means of diverting the water to the recharge facility will be required. This will entail additional expense. Finally, if induced infiltration is to be used there must be one or more wells adjacent to a body of surface water and withdrawing water from a formation that is hydraulically connected to that body of water.

With these conditions in mind, let us consider the possibilities for artificial recharge in the study area. At various times of the year excess runoff flows through the study area. This water is unused and may cause damage by flooding. Most of this excess runoff is carried in the Connecticut, Westfield, and Scantic Rivers. It may also become desirable in time to purify and recycle sewage and other waste water. Either, or both, of these sources of water might be considered for recharge into the ground. The most important question is whether or not

there is a geologic unit in the study area that could be artificially recharged. The answer to this question is not simple. Artificial recharge is a method of increasing ground-water yields and must be used in conjunction with ground-water development. In this area only induced infiltration would be feasible on a large scale until ground-water development reaches the point that withdrawal exceeds natural recharge, because the favorable formations are naturally saturated to the extent that there is little unused storage capacity.

The most favorable units for the application of artificial recharge are the unconsolidated sand and gravel units, especially the outwash and some kame deposits. These deposits are most feasible for large-scale ground-water development and are favorable for recharge by most of the methods discussed above.

Most of the bedrock aquifer is naturally saturated except in the recharge areas, which are very hilly and not particularly suitable for artificial recharge by any method except pumping into wells or other excavations. Such recharge would be most suitable for the storage of treated waste water because the excess runoff collects well below these recharge areas. An additional problem with the bedrock aquifer is the development of a well of sufficient capacity to recharge significant amounts of water into the bedrock.

Many of the water-bearing units in the study area are connected hydraulically at some point with a surface-water body from which infiltration could be induced. The most advantageously situated deposits from the point of view of potential municipal supply are the alluvial deposits of the Westfield and Connecticut River flood plains and the outwash of

Hampden adjacent to the Scantic River. However, the alluvium is mostly fine-grained material and even with induced infiltration may not yield suitable quantities of water to a well, or wells, for municipal purposes. It must be pointed out also that during dry weather when induced infiltration would be most desirable and most effective, the amount of water that can be taken from a river might be limited by the physical and legal considerations of maintaining a minimum low flow.

CONCLUSIONS

1. The most important aquifers in the study area are the buried sand and gravel deposits and the outwash deposits, both of Quaternary age. Secondary aquifers are some kame and delta deposits of Quaternary age and the bedrock aquifer, particularly the Triassic portion. All geologic units, except the glaciolacustrine clay deposits, will yield water in sufficient amounts to supply domestic wells.
2. The bedrock aquifer is recharged by precipitation primarily in the uplands of Hampden, the hills of East Longmeadow, and Provin Mountain in Agawam. Regional movement of ground water in the bedrock is toward the Connecticut River from both the east and west. The bedrock discharges into the outwash deposits of Hampden and East Longmeadow. It is doubtful that significant discharge from the bedrock into the Connecticut River occurs in the study area because of the confining clay deposits of glacial Lake Hitchcock.
3. The Quaternary deposits are recharged primarily by the direct infiltration of the precipitation that falls on them. The outwash deposits of Hampden and East Longmeadow and the buried sand and gravel deposits of

Agawam and Longmeadow are also recharged at least in part by discharge from the bedrock aquifer. Ground water moves through the Quaternary deposits toward the local surface drainage where it discharges, except that the buried sand and gravel deposits are not known to discharge naturally within the study area.

4. Ground water in the bedrock aquifer in Longmeadow and most of Agawam occurs under confined conditions, as does the ground water in the buried sand and gravel deposits of Agawam and Longmeadow. The confining stratum is the clay deposits of glacial Lake Hitchcock. Ground water in all other units and the remainder of the bedrock aquifer occurs under unconfined conditions.

5. A study of the well records indicates that the yield to a bedrock well should not be expected to increase significantly if the well is drilled deeper than 250 feet into the Paleozoic bedrock, or 500 feet into the Triassic bedrock. Wells in the Quaternary deposits should be drilled through the entire thickness of the water-bearing unit. Yields to be expected are 5-10 gpm from the Paleozoic bedrock, 30 gpm from the Triassic bedrock, and more than 200 gpm from the Quaternary sand and gravel deposits. There are indications that much higher yields could be obtained from the Triassic bedrock and Quaternary deposits with proper location, construction, and development of wells.

6. The chemical quality of the ground water in all water-bearing units in the study area is generally excellent except that iron and manganese content may be troublesome in any unit. Also, the ground water in the bedrock aquifer, especially in Longmeadow, may have excessive content of total dissolved solids, hardness, or sulfate. All units with ground

water occurring under unconfined conditions are subject to contamination or pollution from road salt, sewage and other wastes, fertilizer, etc.

7. The ground-water resources of Agawam, Longmeadow, East Longmeadow, and Hampden are essentially undeveloped. Proper development and management of these resources could provide sufficient quantities of water to satisfy the requirements of these four towns well into the 21st century at present rates of population growth and water use. Assuming a popula-growth rate of 30 percent every 10 years, a water-use rate of 70 gpcd, and that the study area remains basically residential, this study indicates that the buried sand and gravel deposits and the outwash deposits are capable of supplying water in amounts sufficient to satisfy the requirements of the four towns until at least the year 2010.

8. Artificial recharge is not feasible in the study area at this time. However, if the ground-water resources are developed, artificial recharge will become feasible and desirable as a means of augmenting natural recharge to the developed aquifers using either excess surface runoff or purified sewage and other waste water.

9. If the ground-water resources of the Springfield region are not developed efficiently, a large part of the region's water resources will remain unused, and water shortages will become more of a problem in an area of relatively abundant water resources.

RECOMMENDATIONS

1. Since aquifers do not conform to political boundaries, I think it advisable that some type of regional organization be effected to deal with the surface and subsurface water resources of the Springfield region.

This organization should have the power not only to plan but to regulate the development and distribution of the water resources of the region. For the most effective use of the water resources of the region it is imperative that the cities and towns of the region cooperate in the development of these resources.

2. A detailed hydrogeologic investigation should be made of the buried sand and gravel deposits and outwash deposits under the direction of a competent ground-water geologist. Such an investigation should include an extensive test drilling and test pumping program that would provide sufficient data to determine the physical extent of these aquifers, to determine the hydrologic boundaries of these aquifers, to determine the safe yield of these aquifers, and to recommend the number and locations of wells for the most efficient development of these aquifers. Such an investigation should also consider the desirability of developing these aquifers on a municipal basis as opposed to the private basis on which the outwash in Hampden is being utilized at present. This is a large order and is all the more reason for regional cooperation.

3. The continued development of areas such as Hampden that are underlain by productive aquifers poses a serious threat to the quality of the ground water in these aquifers. This is particularly true if on-lot methods of sewage disposal are employed in areas poorly suited to them. I think it very important that a municipal sewerage system be installed in Hampden if the underlying outwash and bedrock aquifers are to continue to provide a high quality water supply either to individual wells or to municipal water supply wells that could be developed here.

4. The present extensive use of ground water and the potential for even

more extensive development of the ground-water resources in the study area should be kept clearly in mind in the planning and conduct of other activities such as the land disposal of wastes by landfilling or other means, the storage and spreading of salt for road de-icing in the winter months, and the storage and handling of petroleum products, pesticides, and other hazardous materials that may easily enter and pollute the ground-water system.

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Plate 1

BEDROCK GEOLOGIC MAP

and

DATA POINT LOCATION MAP

Explanation

Geology

Triassic Sedimentary Rocks

Ⓡp — Portland Arkose. Shades and combinations of gray, brown, and red arkosic shale, sandstone, and conglomerate at least 6000 feet thick.

Ⓡha — Hampden Basalt. Dark-gray basalt about 120 feet thick consisting of a lower flow about 50 feet thick and an upper flow about 70 feet thick.

Ⓡeb — East Berlin Formation. Gray, reddish-brown, and dark-red arkosic siltstone and shale 700 to 1200 feet thick.

Ⓡho — Holyoke Basalt. Dark-gray basalt in a single flow 250 to 400 feet thick.

Ⓡnh — New Haven Arkose. Light-to dark-reddish-brown arkosic siltstone, sandstone, and conglomerate at least 5000 feet thick. This unit does not crop out in the area mapped.

Paleozoic Crystalline Rocks

Pz — Metamorphic and igneous rocks of the Central Upland. Includes schist, amphibolite, granulite, gneiss, and granite.

- - - - - Inferred contact.

- - U/D - - Inferred fault. U, upthrown side; D, downthrown side.

— — Generalized contour on the bedrock surface. Contour interval 50 feet; datum is mean sea level. Contours above 300 feet along the west border and above 400 feet along the east border are not shown as they closely approximate the surface contours.

Note: The contact between the Portland Arkose and the Paleozoic rocks is a zone of normal faulting of variable width referred to as the Triassic Border Fault.

Triassic bedrock descriptions, contacts, and western faults from Colton and Hartshorn (1966).

Data Points

● 154/(-51) Well or test boring ending in bedrock or at refusal. Upper figure is identification number. Lower figure is elevation of bedrock surface or refusal; minus sign signifies below sea level; parentheses indicate refusal.

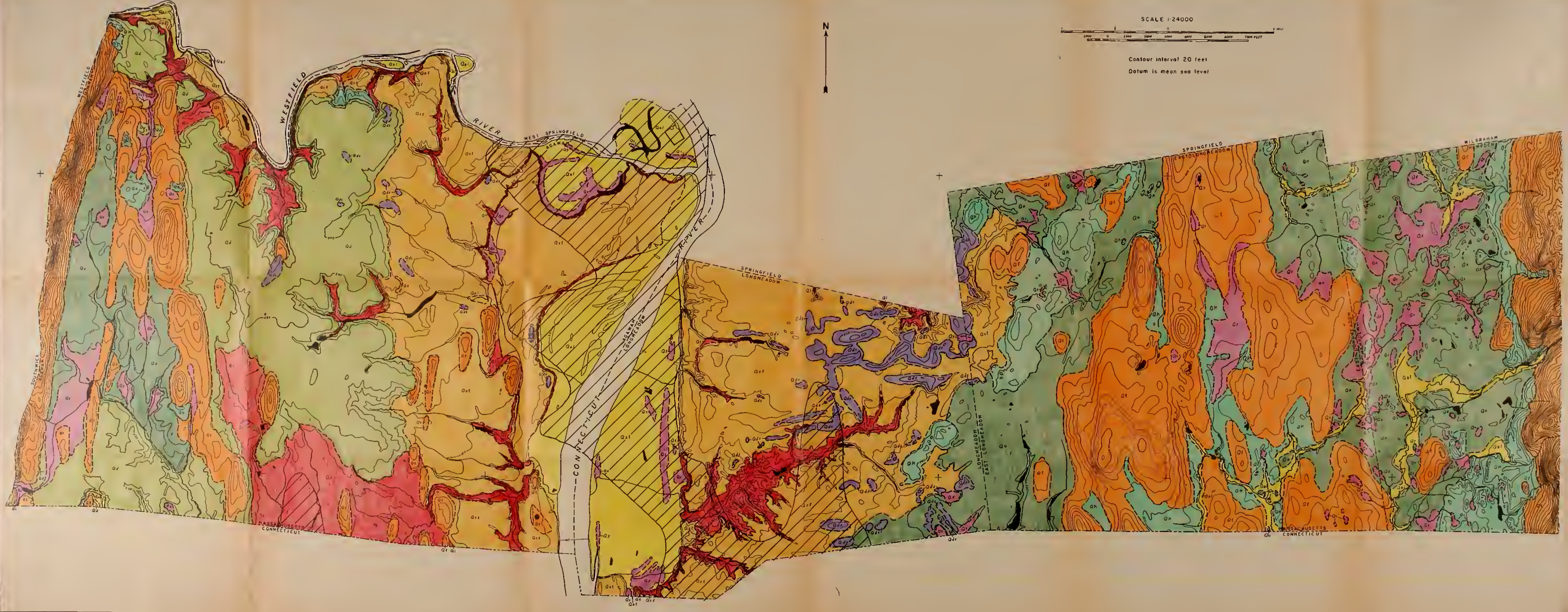
○ 149/61 Well or test boring ending above bedrock. Upper figure is identification number. Lower figure is elevation of bottom of hole; minus sign signifies below sea level.

⚲ 21 Spring. Figure is identification number.

□ A5f/48 Seismic data. Upper figure is identification number; the first letter signifies the source of the data--A is Tighe and Bond (1964) and B is Hartshorn and Koteff (1967); the number and letter following the source letter relate to designations in the report from which the data was obtained. Lower figure is the calculated elevation of the bedrock surface; minus sign signifies below sea level.

△ 7 Gravity data. Figure is identification number.

SURFICIAL HYDROGEOLOGIC MAP



Explanation

Excellent Aquifer Potential

These units have high transmissibility and large areal extent. They are capable of yielding more than 100 gallons per minute and possibly more than 1000 gallons per minute.

Qo — Outwash deposits. High-permeability deposits consisting mainly of sand, gravel, and boulders, but locally silty and rarely clayey. Generally recharged by the bedrock aquifer as well as by direct infiltration.

(diagonal hatching) — Buried sand and gravel. High-permeability deposits of sand and gravel occurring in the deeper bedrock valleys and generally covered by clay. Their extent may be large, but is undefined. Recharge to this unit may be from the bedrock aquifer only.

Good Aquifer Potential

These units have moderate to high transmissibility and moderate to large areal extent. They are capable of yielding as much as 100 gallons per minute.

Qk — Kame deposits. Moderate-to high-permeability deposits consisting in large measure of sand and gravel with lesser amounts of silt and some clay. They are primarily ice-contact stratified drift, but include some sand and gravel deposits of uncertain origin. They are recharged mainly by direct infiltration, but are recharged in part by the bedrock aquifer as well. Their potential is limited by relatively small saturated thickness.

Qd — Delta deposits. Moderate-permeability topset and foreset beds of the Westfield River and Harts Pond Gap glacial deltas. They consist of a complex mixture of interstratified gravel, sand, silt, and clay. They are recharged by direct infiltration. Their potential is limited by small saturated thickness.

Fair Aquifer Potential

These units have low to moderate transmissibility and varying areal extent. They are generally capable of yielding only as much as 20 gallons per minute.

Qal — Alluvium. Low-to moderate-permeability flood-plain deposits consisting of silt and sand with gravel, clay, and some organic matter. They are recharged by direct infiltration of precipitation and flood waters. Their potential is best along the Connecticut and Westfield Rivers where they are most extensive and where infiltration from the rivers may be induced.

Qst — Stream-terrace deposits. Moderate-permeability deposits of sand, silt, and clay, with some gravel. They are recharged by direct infiltration. Their potential is limited by very small saturated thickness.

Qt — Till. Low-permeability deposits consisting of a compact mixture of poorly assorted materials ranging in size from clay to boulders. Their potential is limited by their low permeability.

Poor Aquifer Potential

These units have practically no transmissibility and varying areal extent. They yield little or no water.

Qds — Dune sand. High-permeability wind-deposited fine to medium sand. These deposits generally lie above the water table, and thus they have no saturated thickness.

Qs — Swamp deposits. Low-to moderate-permeability deposits consisting of silt with considerable amounts of clay, muck, and organic matter, and with some sand. They are thin and discontinuous.

Ql — Lake deposits. Low-permeability deposits of clay and silt to fine sand, in large part varved, of glacial Lake Hitchcock. They are most important as an aquaclude, confining the water in part of the bedrock aquifer, the buried sand and gravel deposits, and other underlying units.

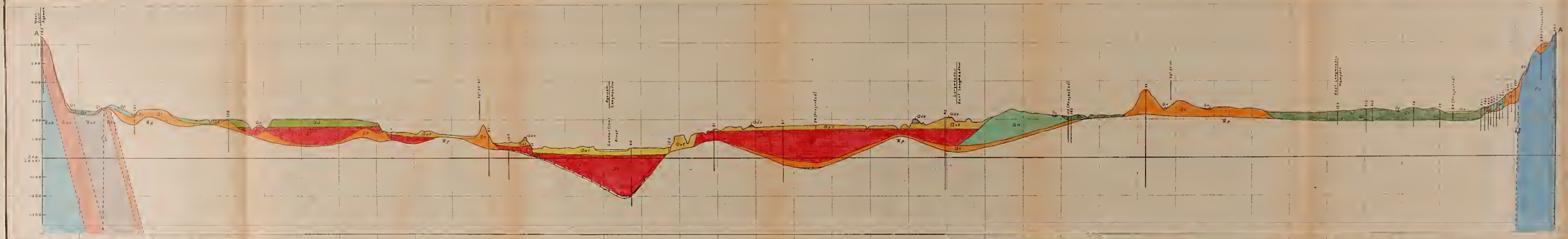


Plate 3

GEOLOGIC CROSS SECTIONS

Explanation

Geologic units are as described in Plates 1 and 2.

Well or test boring. Figure is identification number.

Scale

Vertical Exaggeration X10

BEDROCK HYDROLOGIC MAP

Explanation

Data Points

Well or test boring. Upper figure is identification number. Lower figure is elevation of static water level at time of drilling; datum is mean sea level. Figures in parentheses indicate a boring finished in unconsolidated deposits that are in hydrologic connection with the bedrock.

Spring. Figure is identification number.

Potentiometric Surface

Isopotential lines. Contour interval is 50 feet; datum is mean sea level. This map shows only the general configuration of the potentiometric surface as the contours are based on water-level measurements made at various points in time.

Boundary line between confined conditions and unconfined, or water-table, conditions. Ticks are on the confined side. Boundary is approximate, and is queried where in doubt.

Water Quality

Total hardness, as calcium carbonate, expressed in milligrams per liter.

Stiff diagrams. Three major cations--calcium, magnesium, and sodium--and three major anions--bicarbonate, sulfate, and chloride--are plotted according to the scale shown, and the points are connected to form a polygon. The resulting shape reflects the dominant ions. The size of the diagram reflects the magnitude of the total dissolved solids.