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WATER RESOURCES IN THE BLACKSTONE RIVER BASIN, MASSACHUSETTS

By

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TWO SHEETS
1. Surface Water
2. Ground Water

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CONTENTS

SHEET 1

ILLUSTRATIONS

SHEET I

ILLUSTRATIONS (continued)

SHEET 2 (continued)

TABLE

FACTORS FOR CONVERTING INCH-POUND UNITS TO INTERNATIONAL SYSTEM OF UNITS (SI), WITH ABBREVIATIONS

Multiply inch-pound units	By	To obtain SI Units
	Length	
inch (in)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
acre	4047	square meter (^{2})
	0.4047	hectometer (hm^2)
	Volume	
gallon (gal)	3.785×10^{-3}	cubic meter (m^3)
million gallons (Mgal)	3.785×10^{-3}	cubic hectometers (hm^3)
million gallons per square mile ($Mgal/mi^2$)	1.461×10^{-3}	cubic hectometers per square kilometer (hm^3/km^2)
	Flow	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile /($ft^3/s)/mi^2$ 7	0.01093	cubic meter per second per square kilometer /($m^3/s)/km^2$ 7
gallon per minute (gal/min)	0.06309	liter per second (L/s)
	6.309×10^{-5}	cubic meter per second (m^3/s)
gallon per day (gal/d)	3.785	liter per day (L/d)
	3.785×10^{-3}	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	43.81	liter per second (L/s)
	0.04381	cubic meter per second (m^3/s)
million gallons per day per square mile /(Mgal/d)/mi^2 7	16.91	liter per second per square kilometer /(L/s)/km^2 7
	0.01691	cubic meter per second per square kilometer ($m^3/s)km^2$
	Hydraulic units	
foot per second (ft/s)	0.3048	meter per second (m/s)
square foot per day (ft^2/d)	0.0929	square meter per day (m^2/d)
	Temperature	
degree Fahrenheit (°F)	5/9 (°F -32)	degree Celsius (°C)
	Specific Capacity	
gallon per minute per foot /(gal/min)/ft7	0.2070	liter per second per meter /(L/s)/m7
	Specific Conductance	
micromhos per centimeter at 25°C (umhos/cm at 25°C)	1	microsiemens per centimeter at 25°C (uS/cm at 25°C)

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ABSTRACT

The Blackstone River heads in brooks 6 miles northwest of Worcester and drains about 330 square miles of central Massachusetts before crossing into Rhode Island at Woonsocket.

The primary source of the Worcester water supply is reservoirs, but for the remaining 23 communities in the basin, the primary source is wells.

Bedrock consists of granitic and metamorphic rocks. Till mantles the uplands and extends beneath stratified drift in the valleys. Stratified glacial drift, consisting of clay, silt, and fine sand deposited in lakes and coarse-textured sand and gravel deposited by streams, is found in lowlands and valleys.

The bedrock aquifer is capable of sustaining rural domestic supplies throughout the Blackstone River basin. Bedrock wells yield an average of 10 gallons per minute, but some wells, especially those in lowlands where bedrock probably contains more fractures and receives more recharge than in the upland areas, yield as much as 100 gallons per minute.

Glacial sand and gravel is the principal aquifer. It is capable of sustaining municipal supplies. Average daily pumpage from this aquifer in the Blackstone River basin was 10.4 million gallons per day in 1978. The median yield of large-diameter wells in the aquifer is 325 gallons per minute. The range of yields from these wells is 45 to 3,300 gallons per minute. The median specific capacity is about 30 gallons per minute per foot of drawdown.

INTRODUCTION

This report describes streamflow, ground-water resources, and pumpage of water for public supply in the Blackstone River basin in Massachusetts. The report is intended to provide information for development and management of water resources. Current increases in population, per capita use, and industrial activity is increasing demand for water. Water demand is growing most rapidly in the towns outside of Worcester, all of which obtain their water supplies from wells. The report is one of a series of map reports prepared in cooperation with the Massachusetts Water Resources Commission, that describes the water resources of major river basins in the State.

The Blackstone River heads in brooks 6 miles northwest of Worcester and flows southeast to enter Rhode Island just upstream from Woonsocket. The river drains about 330 mi^2 in Massachusetts, which includes parts or all of 29 towns and the city of Worcester.

Kettle Brook, the headwater of the Blackstone River, rises in Paxton on the west slope of Little Asnebumskit Hill at an elevation of about 1,300 feet. The Blackstone River begins in the southern part of Worcester at the confluence of the Mill River, a stream that runs southward through Worcester, and the Middle River formed by Kettle Brook and other brooks from the west and north. At this point, the elevation of the Blackstone River is 490 feet. The river flows southeast 31 miles through a narrow valley surrounded by till and bedrock uplands to the Rhode Island line. There, the elevation of the river is 160 feet. The overall gradient is about 10 feet per mile.

Several streams are tributary to the Blackstone River between Worcester and the Rhode Island State line: the Quinsigamond, Mumford, West, Mill, and, finally, the Peters River, just upstream from the Rhode Island line. Streams draining from the western uplands tend to have steep gradients. The elevation of Singletary Brook, for example, decreases from about 700 feet at its origin in the uplands of Sutton to 385 feet at its confluence with the Blackstone River 5-1/2 miles to the east. The gradient of the brook is 57 ft/mi.

The Blackstone River basin is underlain by granite and metamorphic rocks such as granite gneiss, schist, slate, and quartzite. These rock formations have been deformed and consolidated by folding and recrystallization.

The advance of ice during continental glaciation, which eroded hills and deposited till, produced many drumlin-type elliptical hills whose long axes generally trend north-south. Erosion overdeepened some reaches of south-trending valleys. Stratified drift accumulated in lowlands and valleys during the stagnation and melting of the ice sheet. The stratified sand and gravel deposited by melt-water streams form the principal aquifer of the basin.

Population of the Blackstone River basin in Massachusetts is estimated to have been about 262,000 in 1970 (Massachusetts Department of Commerce and Development, 1971). This represents a decline of about 4,600 from a peak of 266,611 in 1950. A decline of about 26,900 in Worcester in those 20 years was almost balanced by growth in the suburbs and rural towns. Towns on the east and west sides of the basin--Upton, Mendon, Sutton, and Douglas--retain a rural character and have the lowest population densities. At present (1979) only Mendon and Millville remain without population centers large enough to require public water-supply systems.

Caption for figure 1:

LOCATION OF THE BLACKSTONE RIVER BASIN IN MASSACHUSETTS.

Caption for figure 2:

POPULATION DENSITY OF TOWNS AND CITIES IN THE BLACKSTONE RIVER BASIN IN MASSACHUSETTS, 1975.

Caption for figure 3:

ANNUAL CYCLE OF STREAM RUNOFF AND GROUND-WATER LEVELS.

During the growing season, streamflow and ground-water levels decline from a peak in early spring to a low in late summer in direct response to lack of recharge due to high evapotranspiration and from drainage from aquifer storage. Most of the precipitation that infiltrates the soil during this declining period is transpired by vegetation. During the nongrowing season, the period from early fall to early spring, evapotranspiration is minimal and recharge from precipitation raises ground-water levels, which increases discharge thereby increasing stream runoff. During the early spring, snowmelt may also contribute to these increases. These annual cyclical trends in runoff and ground-water levels are typical of the basin.

SURFACE WATER

Caption for figure 4:

FLOW DURATION CURVES FOR SELECTED SITES.

The flow-duration curves for the stream-gaging stations show the percentage of time daily mean discharges were equaled or exceeded. In addition to showing the duration curve for the entire period of available annual records, duration curves for the months of highest and lowest median monthly flows are included. Also, the duration curves for the year of highest and lowest annual runoff within the period of record are shown. The annual period used in the duration curves is the water year, the 12-month period ending September 30 of the year designated.

The geology and hydrology of a basin determine the shape of the duration curve. These characteristics include precipitation, snowmelt, evapotranspiration, topography, channel storage, ground-water storage, and regulation of flow. As an example, the high end of the duration curve for period of record for West River below West Hill Dam, near Uxbridge has a gentle slope. The gentle slope indicates that the stream is not flashy during periods of high flow. This is the result of the attenuation of high flows by West Hill Dam, a U.S. Army Corps of Engineers flood control dam.

High Streamflow

Caption for figure 5:

FLOOD HYDROGRAPHS OF THE 1955 FLOOD ON KETTLE BROOK AND BLACKSTONE RIVER.

Caption for figure 6:

ANNUAL PEAK AND FLOOD VOLUME FREQUENCY CURVES.

Major floods and consequent damage have played a role in the history of the basin. The two largest and most devastating floods in recent times occurred in 1936 and 1955. Flood profiles and high-water marks for the Blackstone, Quinsigamond, and West Rivers and selected tributaries have been published for the March 1936 flood (Massachusetts Department of Public Works, 1936). High-water marks for Kettle Brook and Blackstone River have been published for the flood of 1955 (U.S. Geological Survey, 1960). The hydrographs of the 1955 flood for Kettle Brook and Blackstone River (fig. 5) illustrate the relation of the amplitude and the lag time of the peaks at various sites along the stream reach. The early peak at Woonsocket resulted from failure of Horseshoe Dam on the Mill River. The secondary peak at Woonsocket, in relation to amplitude and lag time, probably corresponds to the other peaks under natural flooding.

Flood control has been steadily improved since 1936. Two flood-control structures, built by the U.S. Army Corps of Engineers, have effectively reduced flood damage. A diversion tunnel on Kettle Brook in Auburn directs major flood flows around the city of Worcester. A dam and reservoir on the West River in Uxbridge reduces major flood flows.

Probability curves of the maximum annual peak discharges and highest average discharges for indicated number of consecutive days are shown for various stream-gaging stations (fig. 6). These flood-frequency curves are used for flood inundation and flood control reservoir-capacity studies. They apply to a specific site, and should not be used at other stream locations.

Information on floods in ungaged streams is essential to designing flood control and riverine structures. Equations have been developed by Wandle (1980) for estimating the magnitude and frequency of floods in the central region of Massachusetts. The equations apply to ungaged sites where floodflows are basically natural. They do not apply to sites where floodflows are significantly affected by diversion, urbanization, or regulation, where the usable manmade storage is 4.5 million ft^3/mi^2 of drainage area above the site.

The equations that follow are the product of multiple-regression techniques that provide estimates of annual peak discharges corresponding to the 0.1, 0.04, 0.02, and 0.01 annual exceedance probabilities.

$$Q_{0.1} = 84.98A^{0.760}St^{-0.166}$$
$$Q_{0.04} = 114.9A^{0.775}St^{-0.195}$$
$$Q_{0.02} = 141.9A^{0.785}St^{-0.217}$$
$$Q_{0.01} = 172.7A^{0.797}St^{-0.237}$$

where,

Q_t is the peak discharge, in cubic feet per second, for the specified exceedance probability, t (0.1, 0.04, 0.02, 0.01);

A is the drainage area, in square miles; and

St is a storage index which is the combined area of lakes, ponds, and swamps expressed as a percentage of the drainage area plus 0.5.

Additional explanation and examples of how to determine estimates are given in Wandle (1980).

The preceding equations are applicable to sites where drainage area is between 0.49 mi^2 and 199 mi^2 and storage index is less than 23 percent.

Low Streamflow

Caption for figure 7:

LOW-FLOW FREQUENCY CURVES.

The annual probability that the average of the daily discharges during the indicated number of consecutive days of lowest flow during a year will be less than a specified value is shown for selected gaging stations in figure 7.

Estimated annual minimum 7-day low flows having a 10 percent annual probability for various sites are shown in figure 8. They were obtained by correlating baseflow measurements with long-term gaging-station records. The 7-day, 10 percent probability low flow is used as an index of dilution capabilities of streams and in water-quality standards. These characteristics are representative of the hydrologic conditions at the time of data collection (1978). The annual period used in the analysis of low flows is the climatic year, the 12-month period ending March 31 of the designated year.

The relation between low streamflow and drainage area varies from one stream to another and between sites on a stream. Consequently, the data on the map should not be used to estimate the 7-day, 10 percent probability low flow for other sites in the basin. The major cause of nonuniformity between natural-flowing streams during low-flow periods is differences of ground-water storage. Other causes include variances of surface storage, evaporation, transpiration, and precipitation. Activities of man, such as ground-water pumping, and regulation and diversion of streamflow, can also result in nonuniformity.

Specific conductance was measured twice in September 1978 at all the streams in the low-flow network. Specific conductance ranged from less than 100 umho/cm at 25^{o}C in the rural areas of Paxton, Holden, and Douglas to more than 250 umho/cm in the urban area of Auburn and towns of Grafton, Mendon, and Upton.

Caption for figure 8:

LOW STREAMFLOW OF DISCHARGE-MEASUREMENT SITES.

EXPLANATION

01112250	Station number, in downstream order, from the data-collection network of the U.S. Geological Survey.
Mill River near Blackstone	Station name
Elm Street	Location
25.6 / 1.5	Drainage area, in square miles / Estimated minimum 7-day mean flow, in cubic feet per second, with an annual 10 percent probability.
Z	Less than 0.1 cubic foot per second
△	Low-flow measurement station
▲	Continuous-record gaging station
—··—	Basin boundary
—··—	Subbasin boundary
— — — —	City or town boundary
— — — —	State boundary

Stream-Gaging Stations

Kettle Brook at Worcester

Drainage area: 31.3 mi^2.

Period of record: August 1923 to September 1978.

Maximum instantaneous discharge for period of record: 3,970 ft^3/s August 19, 1955.

Average discharge for water years 1924-77: 53.4 ft^3/s, (adjusted for diversion).

Quinsigamond River at North Grafton

Drainage area: 25.5 mi^2.

Period of record: October 1939 to 1979.

Maximum instantaneous discharge for water years 1940-79: 820 ft^3/s August 20, 1955.

Average discharge for water years 1940-79: 41.4 ft^3/s.

West River below West Hill Dam, near Uxbridge

Drainage area: 27.9 mi^2.

Period of record: March 1962 to 1979.

Maximum instantaneous discharge for water years 1963-79: 435 ft^3/s February 1, 1979.

Average discharge for water years 1963-79: 46.2 ft^3, (adjusted for change in storage in West Hill Reservoir).

Blackstone River at Northbridge

Drainage area: 139 mi^2.

Period of record: October 1939 to September 1977.

Maximum instantaneous discharge for period of record: 16,900 ft^3/s

August 20, 1955 (greatest since at least 1900).

Average discharge for water years 1940-77: 266 ft^3/s.

Mumford River at East Douglas

Drainage area: 27.8 mi^2.

Period of record: July 1939 to September 1951.

Maximum instantaneous discharge for period of record: 420 ft^3/s

March 22, 1948.

Average discharge for water years 1940-51: 44.8 ft^3/s.

SHEET 2

GROUND WATER

General Hydrogeology

The quantity of ground water that can be developed at a given place in the Blackstone River basin depends on the local geologic formations and the sources of recharge. The two major aquifers in the basin are the bedrock and the sand and gravel of glacial origin in lowlands and valleys. Precipitation is the only source of recharge in the uplands; whereas, in the lowlands, it may be possible to augment recharge from precipitation by inducing infiltration from streams, lakes, or ponds.

The bedrock of the Blackstone River basin consists of consolidated rock which can yield water in various quantities depending on the degree of fracturing. The bedrock is an important aquifer because it usually yields sufficient water to wells for rural domestic supplies in the upland areas. However it is generally not considered to be a source capable of sustaining public supplies.

A nearly continuous sheet of till overlies bedrock, covers uplands and slopes, and extends beneath most valleys. Till is an unstratified glacial deposit of unsorted materials ranging in size from boulders to clay. Some of the till was deposited beneath advancing glacial ice, and some was deposited from within the ice as it melted. In the Blackstone River basin, the known thickness of till ranges from none at outcroppings of bedrock to as much as the 186 feet reported in a well in Douglas. Till generally has a low permeability, and yields from wells dug in till are rarely enough for a modern home. Most of the old wells dug in till have been replaced by deeper, more reliable wells drilled into the bedrock aquifer.

Water in unconsolidated deposits and bedrock of the Blackstone River basin is generally under water-table conditions. Below the water table, water fills the spaces between grains of sediment or the fractures in bedrock. The water table may be many tens of feet below land surface under uplands and hills, and near or intersect land surface at the shores of streams, ponds, and lakes. At a few places, wells tap water that is confined, commonly by a layer of till or clay, and under enough pressure to cause water to rise above the level at which it enters the well or even flow out of the well at land surface.

The stratified glacial deposits may be divided into two general types. The first consists of fine-grained sand, silt, and clay deposited in temporary lakes that formed in valleys as the ice melted. The second consists of medium- to coarse-grained sand or sand and gravel deposited by streams flowing from the melting glacier. Only the coarse-grained deposits contribute significantly to the water supply of the basin.

Well yields of 5 to 50 gal/min can be obtained locally from sand layers in the fine-grained sediments. The coarsely textured deposits of the Blackstone River basin are the principal aquifer tapped by public-supply and industrial wells. Pumpage from most wells in this aquifer induce recharge from streams or lakes, and well yields range from a few hundred to more than 1,000 gal/min.

Caption for figure 9:

AREAS FAVORABLE FOR DEVELOPING GROUND WATER.

EXPLANATION

The map units described in figure 9 indicate the expected quantities of ground water that can be developed from single wells of large diameter (8 inches or more), or groups of six or more small-diameter (2-1/2 inches) wells at individual sites. The different categories are based on saturated thickness and hydraulic conductivity estimated from lithologic logs. This map is intended to guide exploration. It is not a substitute for test drilling and pumping.

All the area is underlain by crystalline bedrock aquifer that usually yields 1 to 10 gal/min from wells less than 300 feet deep. Reported yields for bedrock wells range from 0.2 to 125 gal/min. In general, wells in the lowlands have larger yields than wells in the uplands. Bedrock is the major source of domestic supplies in rural areas.

Areas where unconsolidated deposits are favorable for yields of 250 gal/min or more. The aquifer is medium or coarse sand or sand and gravel near a body of surface water that may provide water for recharge by induced infiltration.

Areas where unconsolidated deposits are favorable for yields of 50 to 250 gal/min. The aquifer may be finer grained than previous map unit or farther from a body of surface water capable of providing water for recharge by induced infiltration.

Areas where unconsolidated deposits are favorable for yields of as much as 50 gal/min from beds of sand recharged mainly by local precipitation. This map unit includes some wetland areas where sandy beds may be found amid finer grained materials.

Areas where unconsolidated till, as thick as 150 feet, are unfavorable for development. Some shallow (less than 30 feet) large diameter (3 feet), dug wells supply single-family homes where yields are generally less than 5 gal/min.

UNCONSOLIDATED DEPOSITS

◎ $\frac{300}{15}$

Public-supply well or field of well points. Upper number is estimated yield, in gallons per minute, when tested. Lower number is specific capacity, in gallons per minute per foot of drawdown, observed when aquifer was tested.

○

Industrial well

Observation well, in Northbridge

BEDROCK

⊙

Public-supply well

●

Industrial well

— — — · · — — — —

Boundary of Blackstone River basin

Caption for figure 10:

WATER-LEVEL FLUCTUATION IN OBSERVATION WELL NORTHBRIDGE 1.

The graph of water levels from observation well Northbridge 1 (Maevsky, 1976) shows annual fluctuation due to changes in rate of recharge. During the cool months of autumn and winter, water consumption by evaporation and transpiration is minimal, and rain and snowmelt exceed the capacity of the soil layer and percolate downward to recharge ground water. In spring and summer, plants grow and transpire and evaporation increases markedly, so that most precipitation is returned to the atmosphere and little or none remains to recharge ground water.

The average annual water-level fluctuation in the sand and gravel aquifer penetrated by Northbridge 1 well is about 1.5 feet. The sand and gravel aquifer has a storage coefficient of about 25 percent, which means that about 25 percent of a given volume of the sand and gravel consists of intergranular space that will store or release water. A 1.0 foot thickness of the aquifer can contain 3.0 inches of water.

Recharge on areas of low relief underlain by sandy soils, as in the vicinity of the Northbridge 1 observation well, may be as much as 0.9 [(Mgal)/d/mi^2] (Williams and Tasker, 1974). Where soils are derived from till, or where bedrock crops out extensively, recharge will be considerably less, perhaps 0.3 [(Mgal)/d/mi^2].

Caption for figure 11:

MOVEMENT OF GROUND WATER NEAR A STREAM AND A PUMPING WELL.

Wells that induce recharge from streams are capable of much higher sustained yields than wells in aquifers for which recharge is obtained only from precipitation. Public-supply wells in the sand and gravel aquifer are located near bodies of surface water, commonly streams, to obtain maximum yields. The first water pumped from wells comes from aquifer storage close by the well, but continued pumping will intercept ground water that is moving toward the stream. Continued pumping may lower the water table sufficiently to reverse the hydraulic gradient and induce water to flow from the stream into the aquifer and to the well.

Caption for figure 12:

YIELDS OF PUBLIC-SUPPLY WELLS IN THE SAND AND GRAVEL AQUIFER.

Public-supply wells in the sand and gravel aquifer have yields ranging from 45 to 3,300 gal/min. The median yield is 325 gal/min. The yields of many wells decline with time because ground water contains iron and manganese that may precipitate and encrust well screens, thereby impeding the entrance of water to the wells.

Caption for figure 13:

SPECIFIC CAPACITIES OF PUBLIC-SUPPLY WELLS IN THE SAND AND GRAVEL AQUIFER.

The specific capacity of a well is largely dependent on the hydraulic conductivity of the aquifer and is obtained by dividing the yield (in gallons per minute) by the drawdown (in feet) in the well. It is commonly determined by pumping a well until the rate of increase in drawdown becomes very slow.

The short-term yield of a well site can be estimated from the product of specific capacity and available drawdown. Long-term yields are affected by aquifer storage, impermeable boundaries such as till and bedrock, recharge boundaries such as streams and lakes or reservoirs, and recharge rates.

Caption for figure 14:

SATURATED THICKNESS OF THE SAND AND GRAVEL AQUIFER AT PUBLIC-SUPPLY WELLS AND WELL YIELDS.

Other factors being equal, the largest yields are obtained where the saturated thickness of the aquifer is greatest. However, yields of up to 580 gal/min have been obtained at sites where the aquifer has a saturated thickness of 9 feet or less because they are near sources of recharge. Yield depends on the hydraulic conductivity and the saturated thickness of the aquifer, closeness of wells to sources of infiltration, rate of recharge from precipitation, and well design.

Potential Yield of the Sand and Gravel Aquifer

The sand and gravel aquifer, along many stretches of the valleys of the Blackstone River basin, is capable of producing much more water than is now pumped from it. In 1978, the average daily pumpage was 10.4 Mgal (table 1). Most of the water that is pumped from the aquifer is released as wastewater and eventually moves into streams and becomes available for reuse downstream. Wastewater from unsewered homes moves through septic tanks and drain fields into the ground and eventually into streams.

A primary constraint on increased development, which involves reuse of water, will be a decline of water quality unless remedial measures are instituted. Surface water in the Blackstone River and its principal tributaries, especially in the upper reaches in Worcester, Auburn, and Millbury, is already degraded so much that ground water obtained, in part, from induced recharge is of marginal quality for public supply. For example, the concentration of sodium in water samples from the Millbury public-supply wells in 1976 ranged from 37 to 70 mg/L and averaged 45 mg/L. The suggested drinking water standard for sodium is 20 mg/L in Massachusetts. Increases in pumpage will have to be accompanied by water treatment if further degradation of water quality is to be prevented. Wastewater, which is disposed of in septic tanks by the growing number of homes in suburban towns, adds dissolved constituents and perhaps contaminants to ground water that flows to ponds, lakes, and streams.

Another effect of inducing recharge from a stream is a decrease in streamflow downstream of the pumping wells. Heavy pumping can reduce streamflow to discharge rates that would be unacceptable to recreation, conservation, and fish and wildlife interests. Heavy pumpage sustained by infiltration from lakes, notably Lake Quinsigamond, could reduce lake levels, more than would be tolerated by owners of lakeshore properties and those who use the lake for boating, swimming, and fishing.

Evaluation of the potential for artificial recharge is part of any assessment of the potential yield of the sand and gravel aquifer. The Cook Allen well field (owned by Northbridge) in the town of Sutton, includes about seventy 2-1/2-inch wells driven into sand and gravel beneath three manmade lagoons. The flow of Cook Allen Brook is diverted to flood the lagoons and recharge the underlying sand and gravel. The infiltration of diverted water provided about 220 Mgal of water in 1978--about 55 percent of the total pumpage.

The rest of the public water supply for Northbridge is drawn from a gravel-packed well and from a well field on the south and northwest shores of Whitins Pond. A large proportion of the yield of these wells results from management of the pond. Whitins Pond was formed by a milldam built in 1847 that raised the surface-water level at the dam about 13 feet. The higher surface-water level brought about a corresponding 13-foot rise in the ground-water table (available drawdown) at the shore of the pond. Whitins Pond, now kept at a virtually constant level, constitutes a large reservoir of water available to recharge the adjacent aquifer.

The aquifers in the valleys of the Blackstone River basin probably could be recharged artificially at many places.

Yields of Wells From the Bedrock Aquifer

Fractures are the source of water to wells in bedrock. They are normally only hundredths or thousandths of an inch wide. The number and width of water-bearing fractures that a well penetrates is difficult to predict. A well may intersect water-bearing fractures 50 feet below the water table, whereas another nearby well may not intersect water-bearing fractures at any depth.

The specific capacities of bedrock wells vary greatly owing to the irregular distribution and size of water-bearing fractures. Data from tests on 49 wells showed specific capacities that ranged from 0.0004 to 6 gal/min/ft of drawdown. The median value was 0.12 gal/min/ft of drawdown. These wells yielded 0.2 to 125 gal/min, and the average yield was about 10 gal/min.

Most bedrock wells are drilled to provide domestic supplies in rural areas; and, with few exceptions, yield sufficient quantities of water for homes. A yield of only 1 gal/min will supply a home if the supply system has a large storage capacity. Water is available from storage within the well casing. The commonly used 6-inch-diameter well stores about 1.4 gallons per foot of depth, so that 100 gallons of water can be obtained by pumping and lowering the water level about 70 feet. The storage is replenished when the pump is off.

Bedrock wells in lowlands generally have larger sustained yields than bedrock wells on uplands. Recharge from precipitation on uplands mantled by till on the average, probably does not exceed 190,000 gal/acre/yr. Recharge on 1 acre of till mantled upland would probably be sufficient to sustain the 300 gal/d (4 persons x 75 gal/d per person) demand of an average single-family household. The bedrock beneath lowlands can receive far more recharge, from ground water flowing in from the uplands, and from ground-water storage in the unconsolidated stratified glacial deposits that overlie bedrock in the valleys. The public-supply wells of Leicester, in Paxton, are examples of bedrock wells in lowlands with large sustained yields (50 to 120 gal/min).

Caption for figure 15:

PUMPAGE OF WATER FOR PUBLIC SUPPLY IN 1978.

All the towns in the Blackstone River basin rely on ground water; Worcester (city) relies mainly on surface water from the following reservoirs: Kettle Brook, Lynde Brook, Holden, Kendall, Pinehill and Quinapoxet.

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vertical lines not used in table headings

Table 1.--Pumpage of water for public supply in 1978

Town or city	Population in 1975	Area in Blackstone River basin, in percent	Source of water	Capacity of system, in million gallons per day	Pumpage, in million gallons per day: Total	Average daily	Maximum daily	Date of maximum daily	Remarks
Auburn	15,626	94	Wells	2.75	344	0.94	2.29	7-7	Auburn Water District received 0.5 Mgal from Worcester.
Bellingham	14,461	50	do.	1.61	192	.52	--	--	Listed pumpage is from the three wells in Blackstone River basin.
Blackstone	6,486	100	do.	.93	150	.41	.67	5-25	
Boylston	3,326	20	do.	3.02	41	.11	--	--	Listed pumpage is from Morningdale wells in Blackstone River basin.
Douglas	3,174	83	do.	.9	68	.19	.28	7-1	
Grafton	10,630	93	do.	1.8	311	.85	--	--	Grafton State Hospital received 6 Mgal from Worcester.
Hopedale	4,014	80	do.	.43	--	--	--	--	Bought some water from Milford in summer.
Leicester	8,887	40	do.	.6	80	.22	.32	6-4	Four wells in Paxton, one well in Leicester. Cherry Valley and Rockdale Water Districts received 3.4 Mgal from Worcester.
Mendon	2,714	100	--	--	--	--	--	--	No public supply.
Millbury	12,121	100	Wells	2	426	1.17	1.61	5-30	Received 0.24 Mgal from Worcester.
Millville	1,744	100	--	--	--	--	--	--	No public supply.
Northbridge	12,165	100	Wells	3.1	399	1.09	1.66	11-11	Wells in Sutton and in Northbridge.
Shrewsbury	21,963	62	do.	5.5	996	2.73	4.60	7-14	Received 2.8 Mgal from Worcester.
Sutton	4,969	98	do.	.5	40	.11	--	--	
Upton	3,777	96	do.	.8	76	.21	.57	7-29	
Uxbridge	8,528	100	do.	2.9	256	.70	.76	4-3	
Worcester	172,342	99.7	Reservoirs	26.8	9,110	24.96	37.06	7-13	Forty-four percent of water diverted from Nashua River basin.
			Well	1.7	426	1.17	1.25	6-11	Well in Shrewsbury. Worcester sold about 13 Mgal to towns in Blackstone River basin.
		Total surface water---			9,110	24.96			
		Total ground water----			3,805	10.42			
		Total water-----------			12,915	35.38			

Part of Worcester. BEK

SELECTED REFERENCES

Alden, W. C., 1925, The physical features of central Massachusetts: U.S. Geological Survey Bulletin 760, p. 13-105.

Hem, J. D., 1970, Study and interpretation of the chemical characteristics of natural water: U.S. Geological Survey Water-Supply Paper 1473, 363 p., 2 pl.

Kingsbury, F. H., and Smith, E. W., 1943, Variability in the normal chloride content of surface and ground water supplies in Massachusetts: New England Water Works Association Journal, v. 57, no. 1, p. 10-14.

Leighton, M. O., 1903, Normal and polluted waters in northeastern United States: U.S Geological Survey Water-Supply Paper 79, 192 p.

Maevsky, Anthony, 1976, Ground-water levels in Massachusetts, 1936-74: U.S. Geological Survey, Massachusetts Hydrologic-Data Report No. 17, 107 p.

Massachusetts Department of Commerce and Development, 1971, Population area density: Massachusetts Department of Commerce and Development, Bureau of Research and Statistics, 9 p.

Massachusetts Department of Environmental Quality Engineering, 1977, Report of routine chemical and physical analyses of public water supplies in Massachusetts, 1976: Massachusetts Department of Environmental Quality Engineering, Division of Water Supply, 85 p.

Massachusetts Department of Public Works, 1936, High water data--Flood of March 1936 in Massachusetts: Massachusetts Department of Public Works, Geodetic Survey, 210 p.

National Academy of Sciences and National Academy of Engineering, 1973, Water quality criteria 1972: Washington, D.C., U.S. Government Printing Office, 594 p.

National Oceanic and Atmospheric Administration, Climatological data, annual summary, New England: National Oceanic and Atmospheric Administration, issued annually.

U.S. Department of Agriculture, 1970, Water and related land resources management, use and development opportunities, in Comprehensive water and related land resources, Connecticut River basin: U.S. Department of Agriculture, v. III, app. E.

U.S. Environmental Protection Agency, 1975, Water programs, national interim primary drinking-water regulations: Federal Register, v. 40, no. 248, Wednesday, December 24, 1975, Part IV, p. 59566-59587.

____1977, National secondary drinking water regulations: Federal Register, v. 42, no. 62, Thursday, March 31, 1977, Part I, p. 17143-17147.

U.S. Geological Survey, 1960, Floods of August-October 1955, New England to North Carolina: U.S. Geological Survey Water-Supply Paper 1420, 854 p.

____1979, Water resources data for Massachusetts and Rhode Island, 1978: U.S. Geological Survey Water-Data Report MA-RI-78-1, 299 p.

____1980, Water resources data for Massachusetts and Rhode Island, 1979: U.S. Geological Survey Water-Data Report MA-RI-79-1, 349 p.

Wandle, S. W., Jr., 1980, Estimating peak discharges of small, rural streams in Massachusetts: U.S. Geological Survey Open-File Report 80-676, 72 p.

Williams, J. R., and Tasker, G. D., 1974, Water resources of the coastal drainage basins of southeastern Massachusetts, Plymouth, to Weweantic River, Wareham: U.S. Geological Survey Hydrologic Investigations Atlas HA-507, 2 sheets.

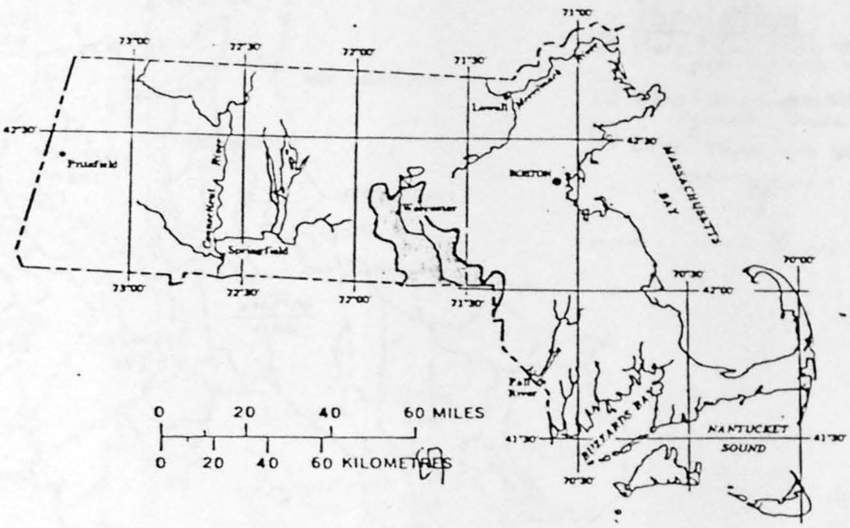
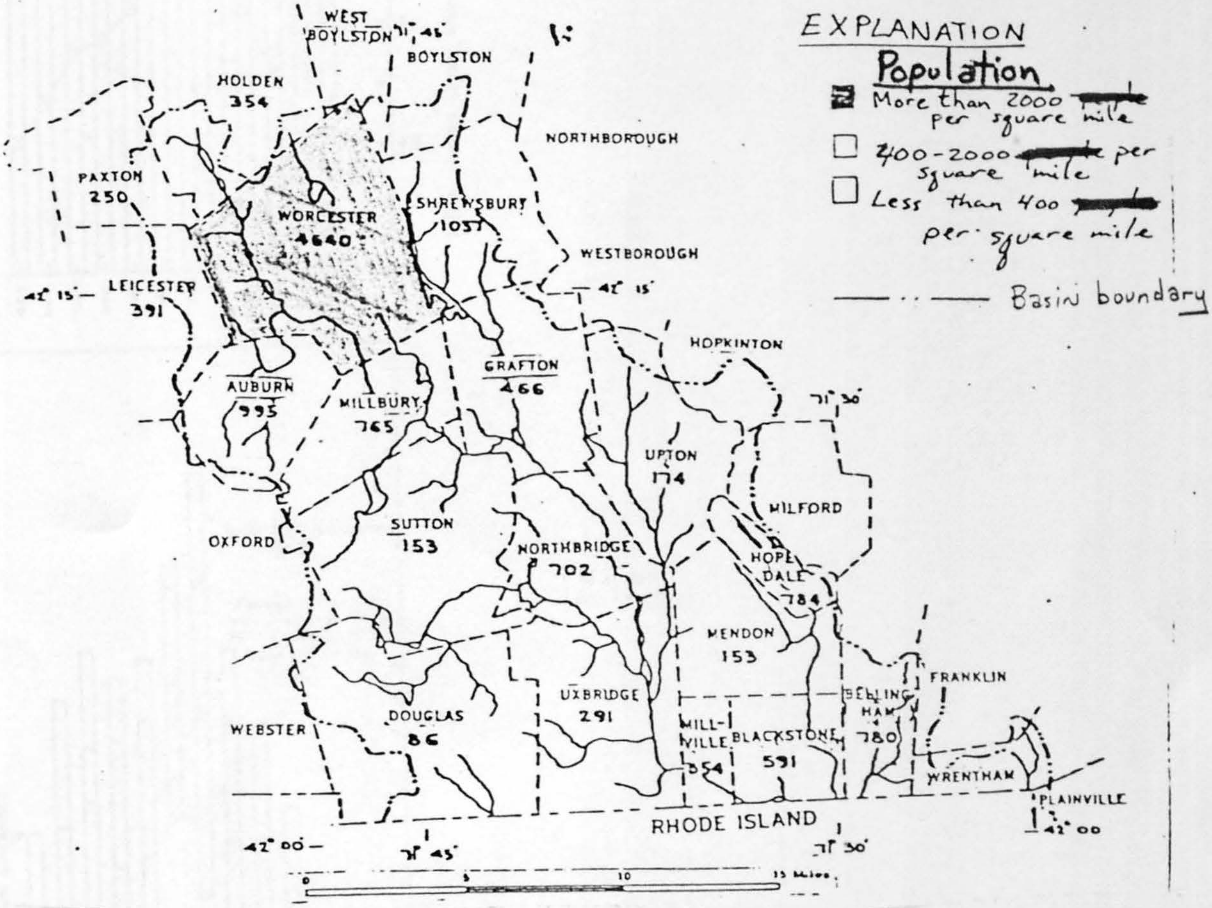


Figure 1.— LOCATION OF THE BLACKSTONE RIVER BASIN IN MASSACHUSETTS.



gure 2.

POPULATION DENSITY OF TOWNS AND CITIES IN THE BLACKSTONE RIVER BASIN IN MASSACHUSETTS, 1975.

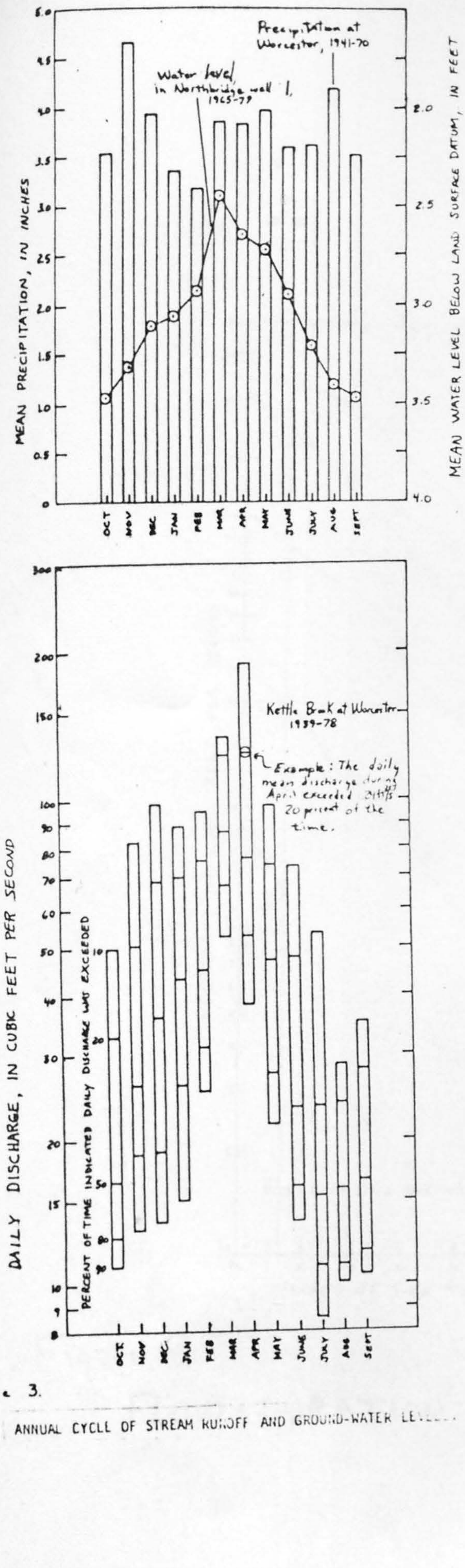


Figure 3.

ANNUAL CYCLE OF STREAM RUNOFF AND GROUND-WATER LEVEL...

Bruce Krejmas
Geological Survey

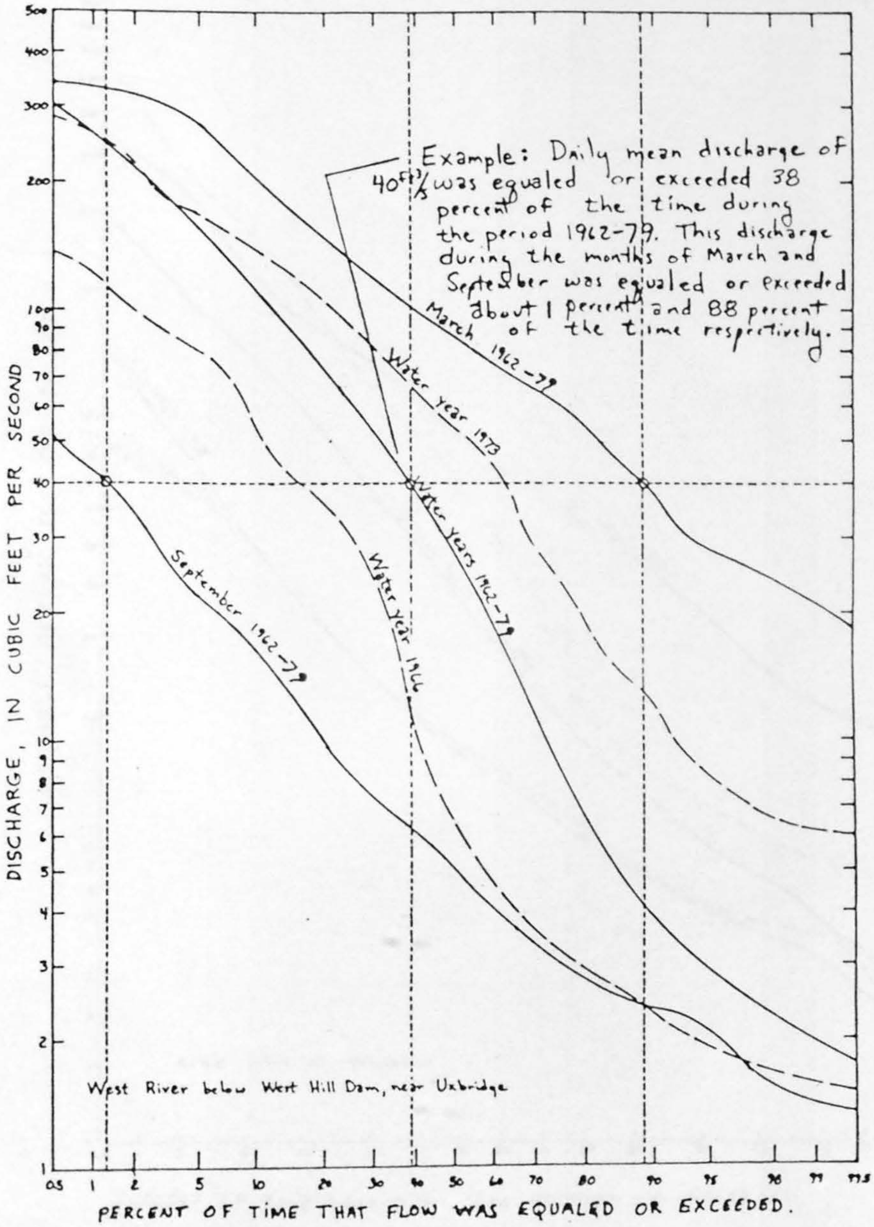
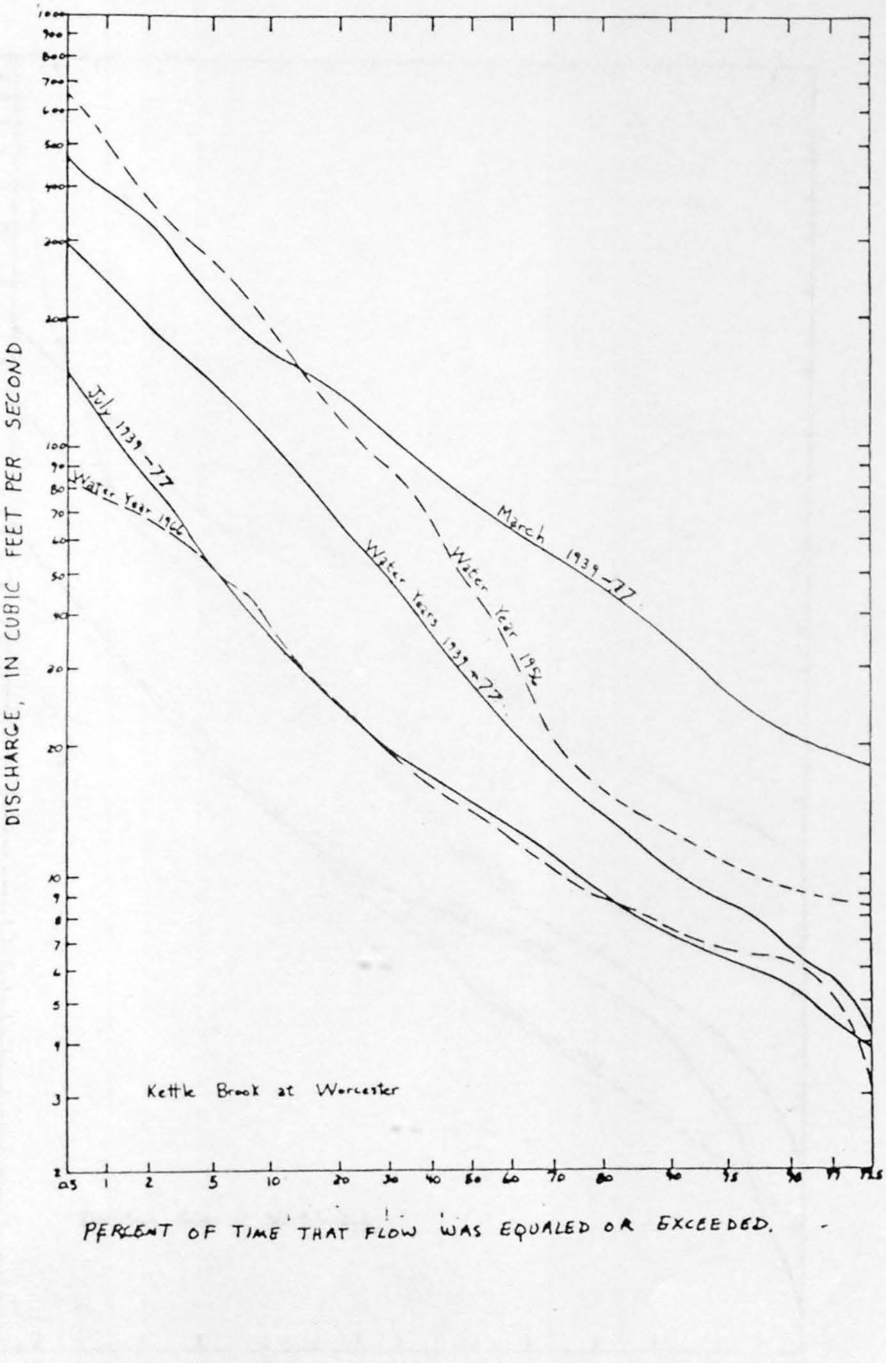


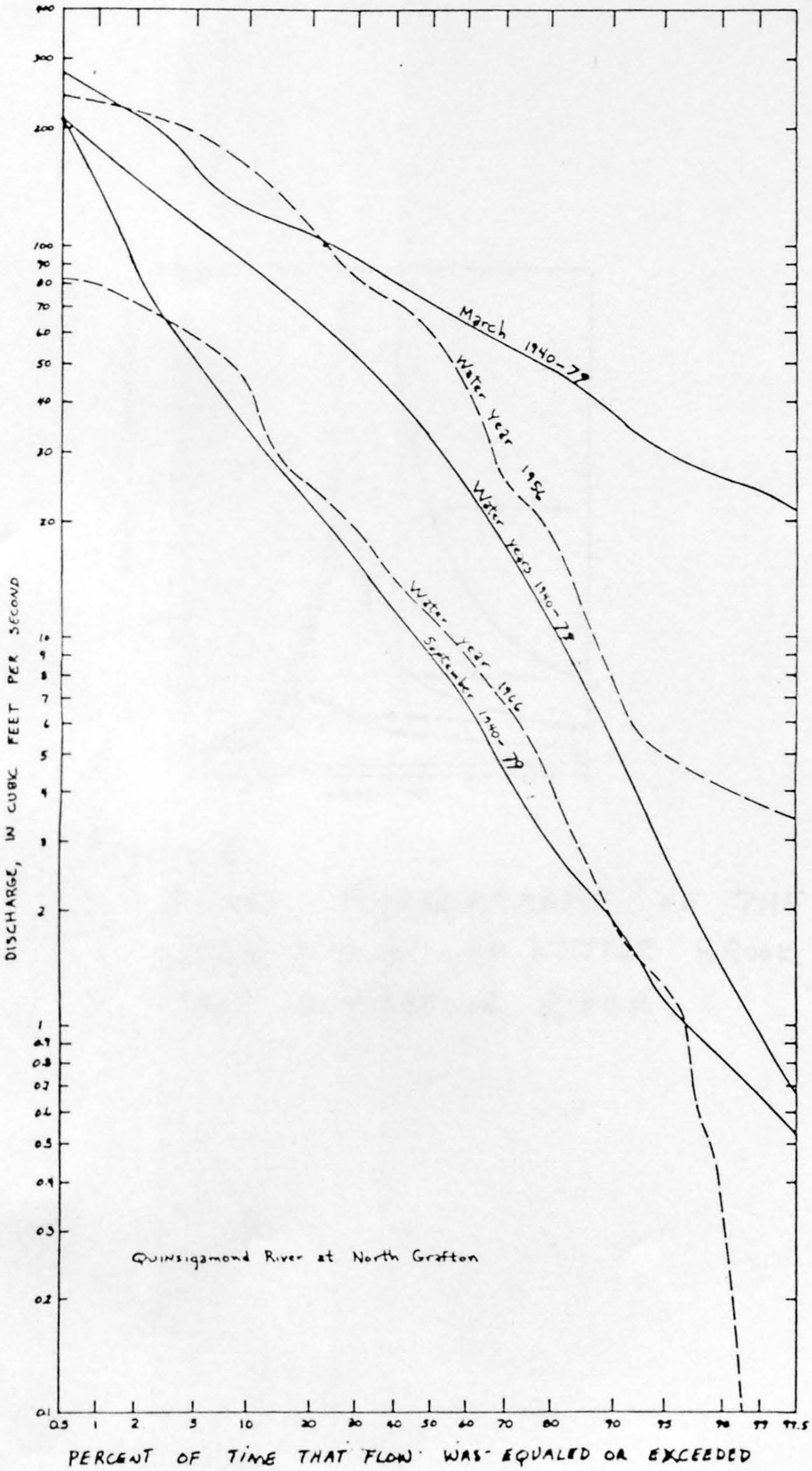
Figure 4.

FLOW-DURATION CURVES FOR SELECTED SITES.



DISCHARGE, IN CUBIC FEET PER SECOND
March 1939-77
Water Year 1952
Water Years 1939-77
July 1939-77
Water Year 1966
Kettle Brook at Worcester
PERCENT OF TIME THAT FLOW WAS EQUALED OR EXCEEDED.

Figure 4.



DISCHARGE, IN CUBIC FEET PER SECOND
PERCENT OF TIME THAT FLOW WAS EQUALED OR EXCEEDED
March 1940-79
Water Year 1956
Water Years 1940-79
Water Year 1966
September 1940-79
Quinsigamond River at North Grafton

Fig. 4

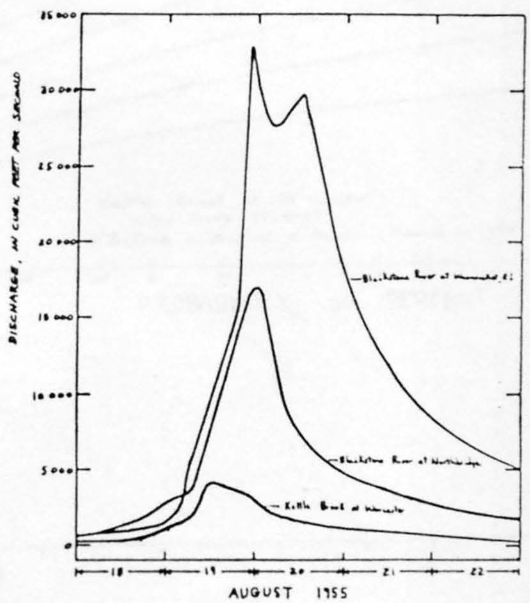
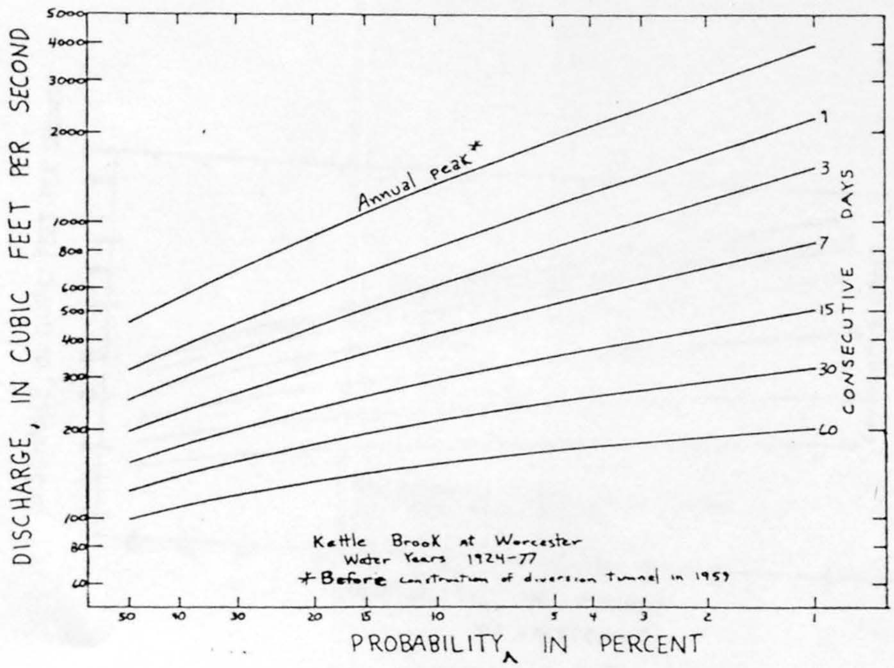


Figure 5.

FLOOD HYDROGRAPHS OF THE 1955 FLOOD ON KETTLE BROOK AND BLACKSTONE RIVER.



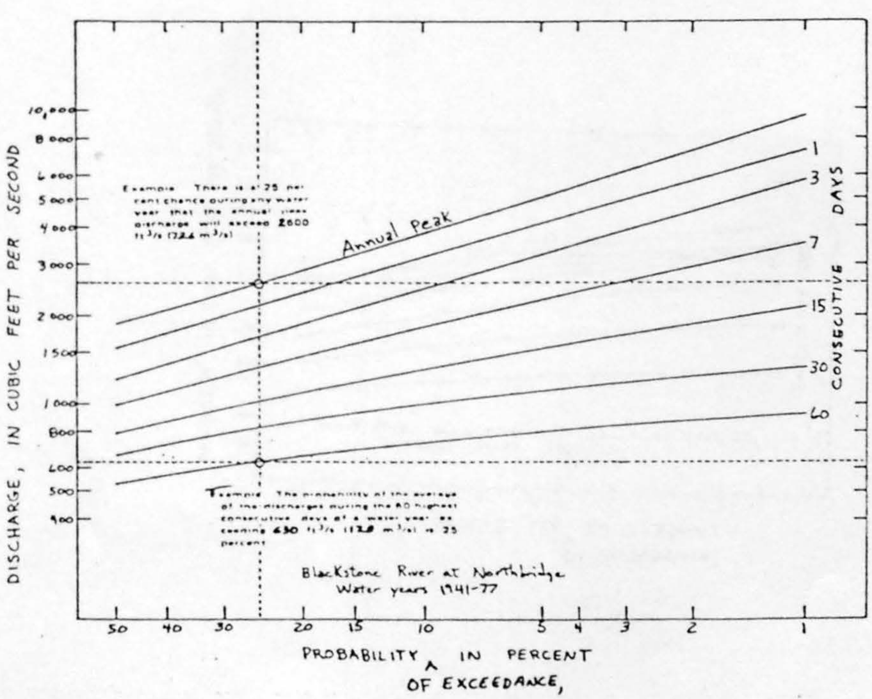
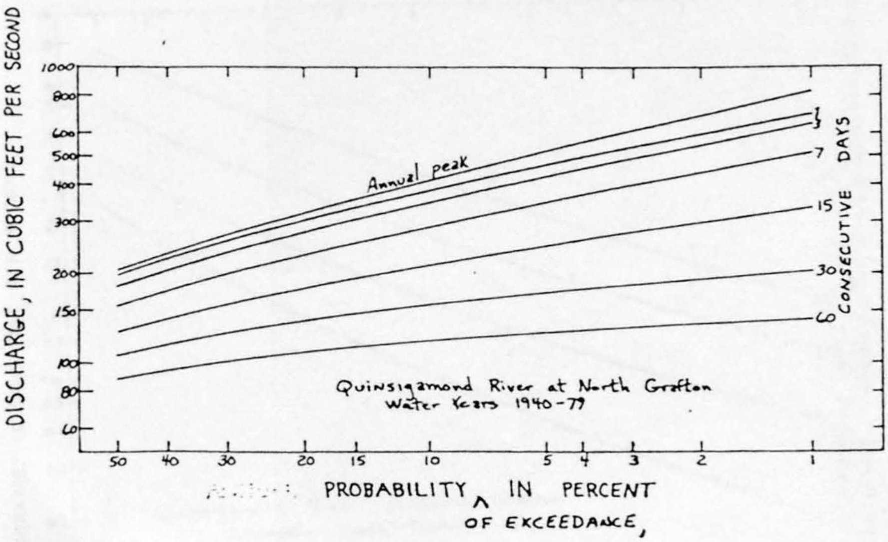
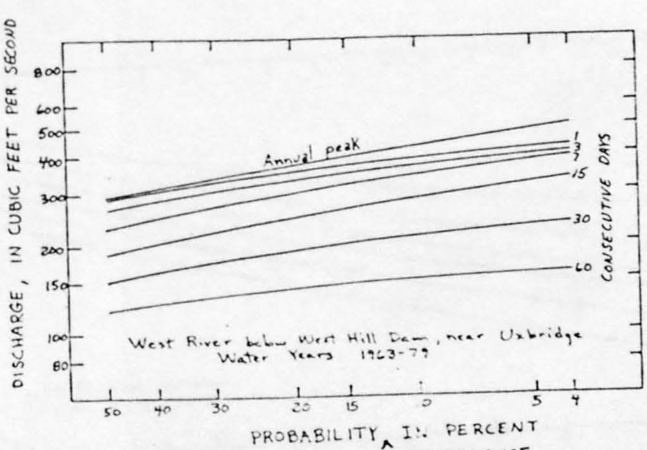


Figure 6. Annual peak and flood volume curves

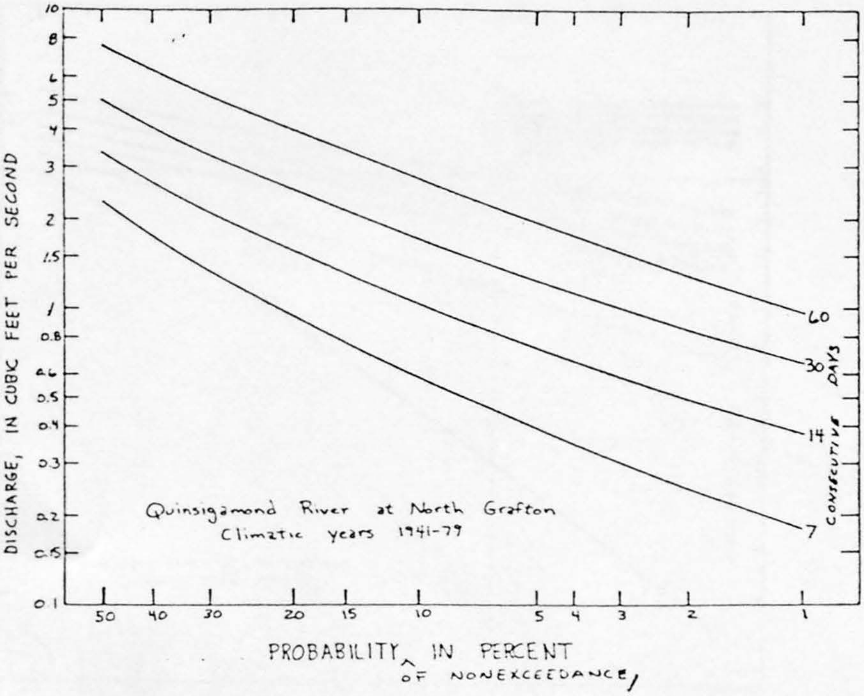


DISCHARGE, IN CUBIC FEET PER SECOND
1000
800
600
500
400
300
200
150
100
80
60
50
40
30
20
15
10
5
4
3
2
1
PROBABILITY OF EXCEEDANCE, IN PERCENT
Annual peak
1
3
7
15
30
60
CONSECUTIVE DAYS
Quinsigamond River at North Grafton
Water Years 1940-79



DISCHARGE, IN CUBIC FEET PER SECOND
800
600
500
400
300
200
150
100
80
50
40
30
20
15
5
4
PROBABILITY OF EXCEEDANCE, IN PERCENT
Annual peak
1
3
7
15
30
60
CONSECUTIVE DAYS
West River below West Hill Dam, near Uxbridge
Water Years 1963-79

Fig. 6



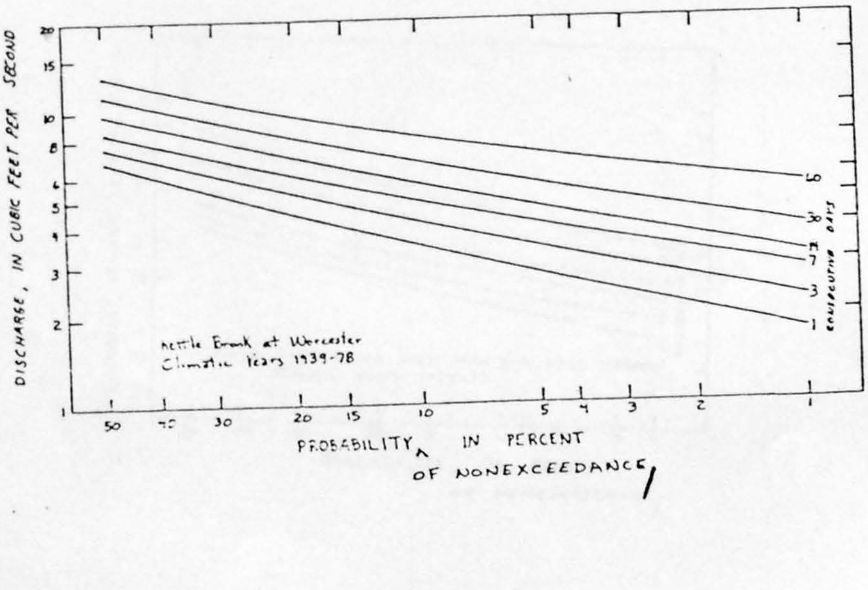
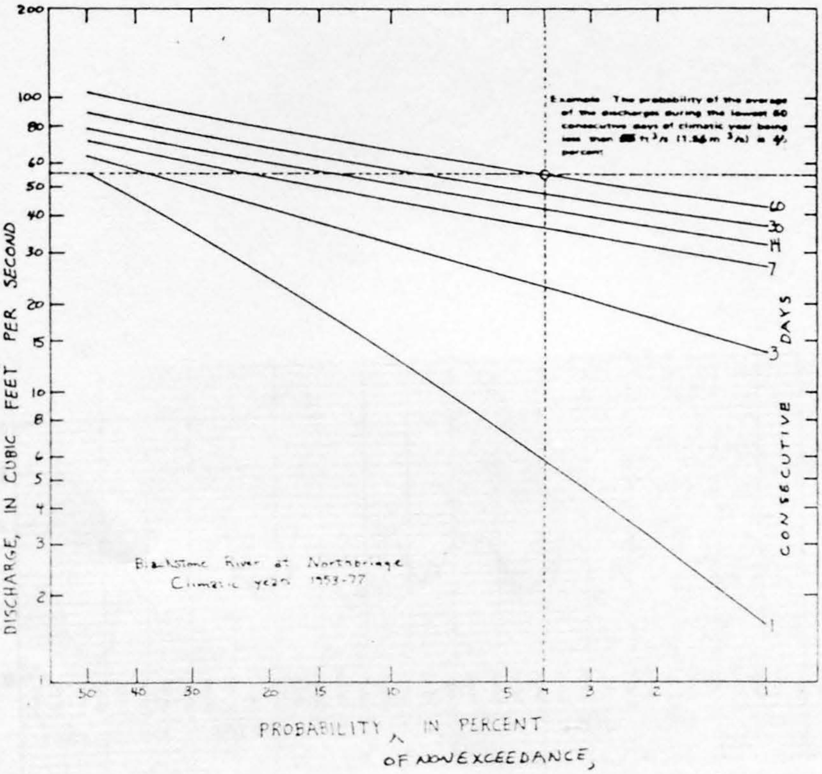
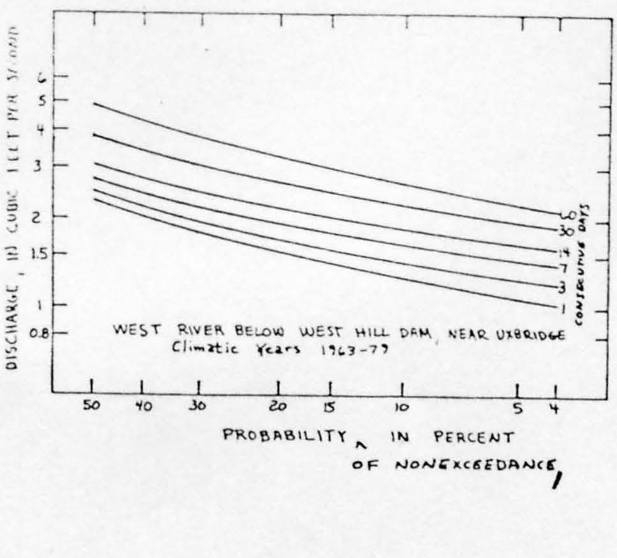


Figure 7. LOW-FLOW FREQUENCY CURVES.



DISCHARGE, IN CUBIC FEET PER SECOND
200
100
80
60
50
40
30
20
15
10
8
6
5
4
3
2
1
Example The probability of the average of the discharges during the lowest 60 consecutive days of climatic year being less than
percent
60
30
14
7
3
1
CONSECUTIVE DAYS
Climatic years 1953-77
50
40
30
20
15
10
5
4
3
2
1
PROBABILITY, OF NONEXCEEDANCE, IN PERCENT



DISCHARGE, IN CUBIC FEET PER SECOND
6
5
4
3
2
1.5
1
0.8
60
30
14
7
3
1
CONSECUTIVE DAYS
WEST RIVER BELOW WEST HILL DAM, NEAR UXBRIDGE
Climatic Years 1963-77
50
40
30
20
15
10
5
4
PROBABILITY, OF NONEXCEEDANCE, IN PERCENT

Fig. 7

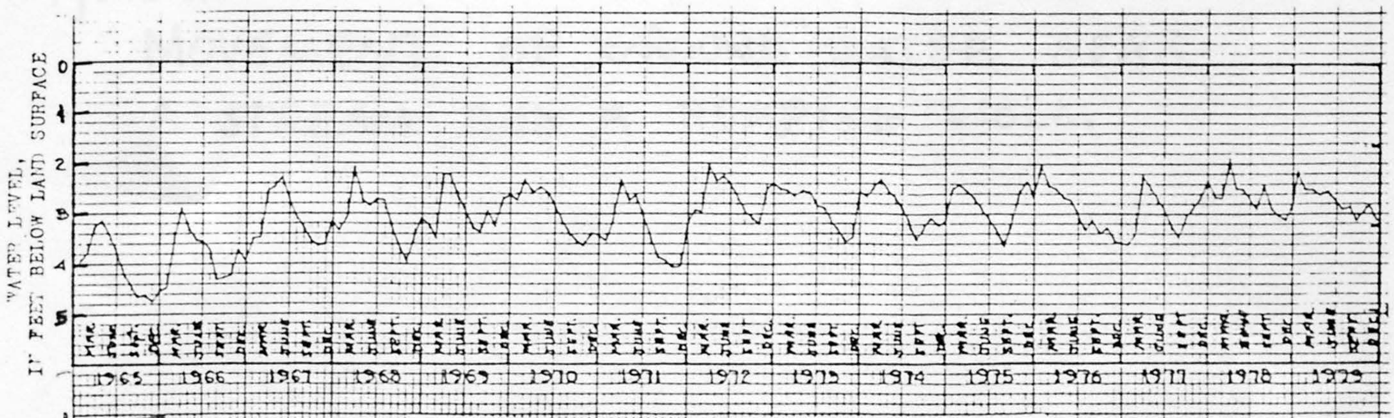


Figure 10. WATER-LEVEL FLUCTUATION IN OBSERVATION WELL NORTHBRIDGE 1.

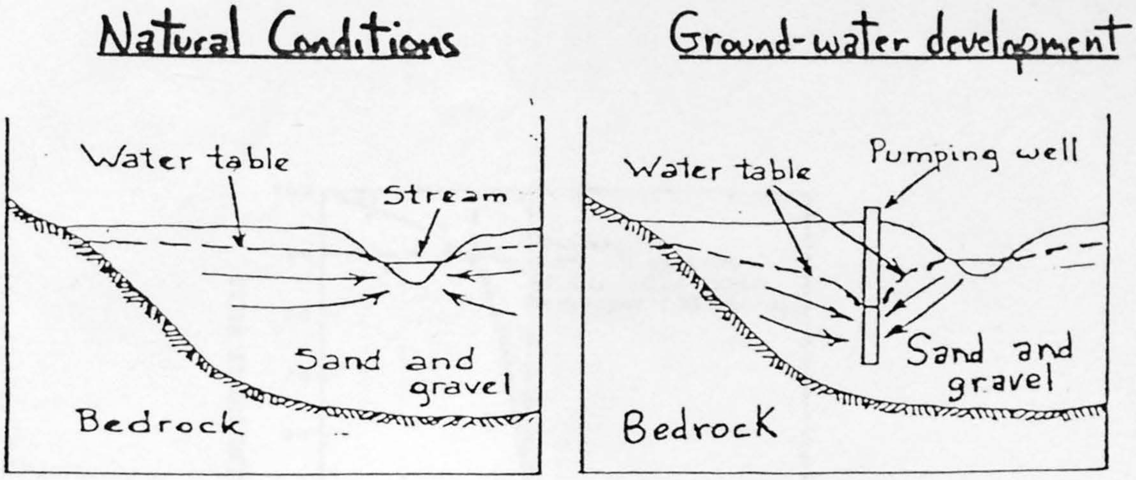


Figure 11.

MOVEMENT OF GROUND WATER NEAR A STREAM AND A PUMPING WELL.

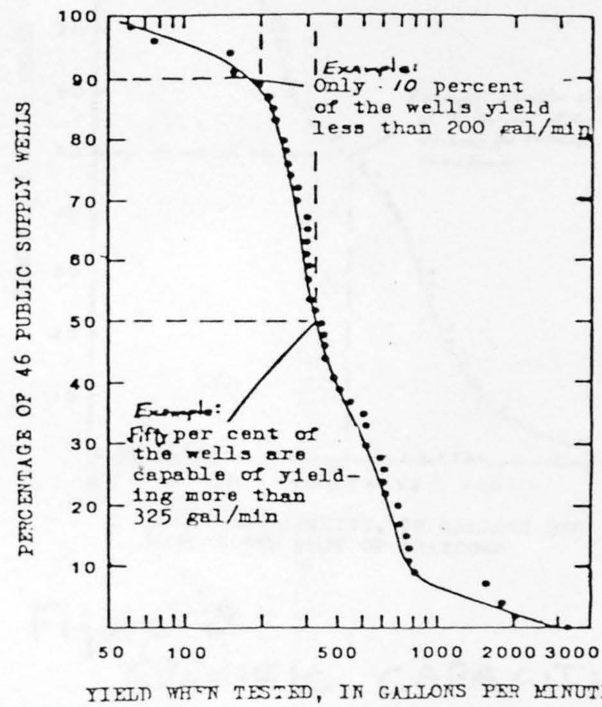


Figure 12.

YIELDS OF PUBLIC-SUPPLY WELLS IN THE SAND AND GRAVEL AQUIFER.

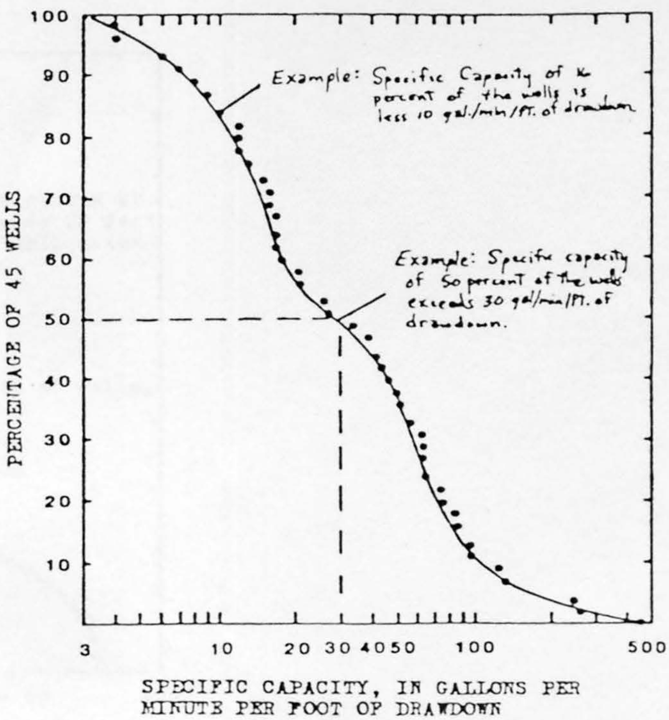


Figure 13.
SPECIFIC CAPACITIES OF PUBLIC-SUPPLY WELLS IN THE SAND AND GRAVEL AQUIFER.

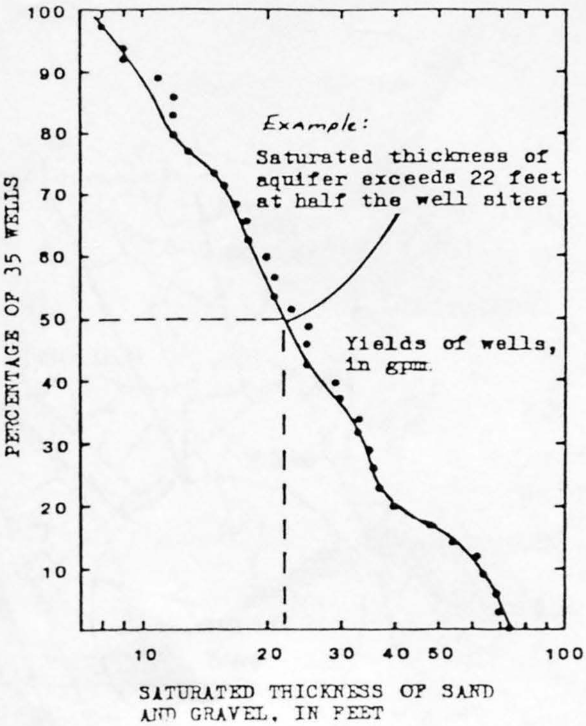


Figure 14.

SATURATED THICKNESS OF THE SAND AND GRAVEL AQUIFER AT PUBLIC-SUPPLY WELLS AND WELL YIELDS.

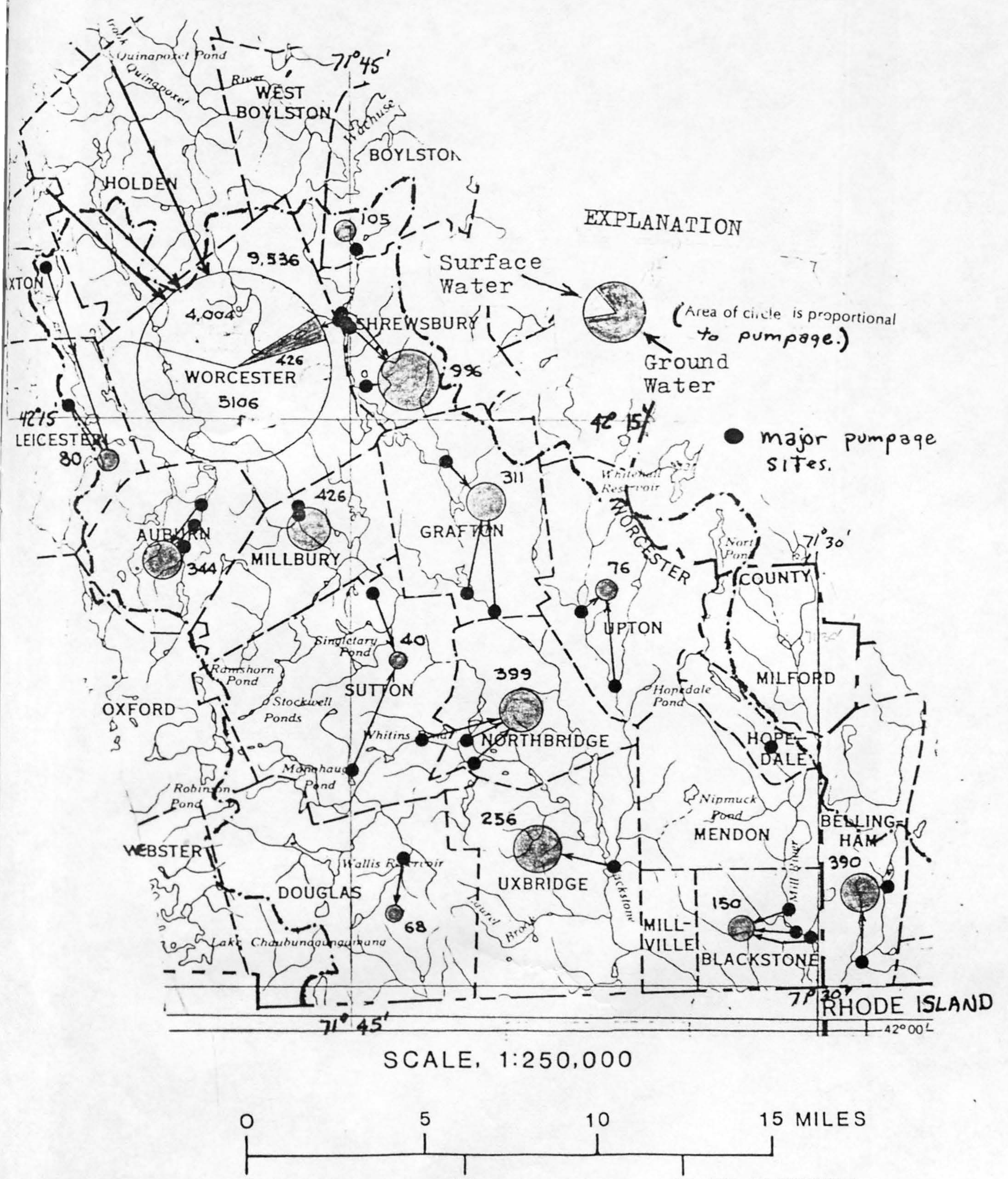


FIG. 15 PUMPAGE OF WATER FOR PUBLIC SUPPLY IN 1978.