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Estimating Surface-Water Runoff to Narragansett Bay, Rhode Island and Massachusetts

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U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 89-4164

Prepared in cooperation with the

RHODE ISLAND DEPARTMENT OF ENVIRONMENTAL MANAGEMENT

ESTIMATING SURFACE-WATER RUNOFF TO NARRAGANSETT BAY, RHODE ISLAND AND MASSACHUSETTS

By Kernell G. Ries III

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CONVERSION FACTORS AND ABBREVIATIONS

The following factors can be used to convert inch-pound units in this report to the International System of units (SI).

Multiply inch-pound unit	By	To obtain SI unit
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
	0.4047	hectare (ha)
square mile (mi^2)	259.0	hectare (ha)
	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	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]	0.01093	cubic meter per second per square kilometer [(m^3/s)/km^2]

Temperature

Temperature in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) as follows: °C = 5/9 × (°F – 32).

Estimating Surface-Water Runoff to Narragansett Bay, Rhode Island and Massachusetts

By Kernell G. Ries III

ABSTRACT

Monthly and annual estimates of mean fresh-water inflow to the 143 square mile Narragansett Bay for water year 1987 (Oct. 1, 1986 through Sept. 30, 1987), and for long-term average conditions were required for use by other investigators. Fresh-water inflow consists of surface-water runoff from streams draining into the bay, and precipitation on the bay itself. About 63 percent of the land area within the 1,820 square mile drainage basin was monitored by streamflow-gaging stations prior to commencement of the study; the remainder was ungaged.

Mean runoff to the basin, which includes the bay, during water year 1987 was estimated to be 4,860 ft^3/s (cubic feet per second), with estimates of monthly mean runoff ranging from a low of 1,060 ft^3/s in August, to a high of 14,400 ft^3/s in April. Long-term mean annual runoff to the basin was estimated to be 3,690 ft^3/s, with long-term mean monthly estimates ranging from 1,820 ft^3/s for July, to 6,540 ft^3/s for March. The estimates were derived by summing the known runoff from gaged areas of the basin with estimates of runoff from ungaged land areas, diversions from gaged areas, and computed runoff equivalents of rainfall on the bay. The estimates of the 1987 water year and long-term mean annual runoff are both considered to be within 10 percent of actual. The estimates of the 1987 water year monthly mean and long-term mean monthly runoff are considered to be within 20 percent of actual and 15 percent of actual, respectively.

The estimates of long-term runoff from ungaged areas of the basin were derived primarily by using multiple regression analyses. Long-term mean annual and mean monthly runoff data from 13 streamflow-gaging stations located within or near the basin were used as the dependent variables in the analyses, which produced separate predictive equations for each month and for the mean annual runoff. Various physical characteristics of the drainage basins for the streamflow-gaging stations were used as the independent variables. Lengths of continuous records for the 13 stations ranged from 21 to 62 years, with a mean record length of 38 years.

Techniques used to estimate runoff from ungaged areas of the basin for the 1987 water year include a previously unpublished method that uses linear regression to relate discharge measurements obtained monthly at an ungaged site to concurrent discharges at a nearby gaged site. Empirical tests of the method using data from gaging stations in the basin indicate that the average accuracy of the method is within 7 percent for annual estimates, and within 13 percent for monthly estimates.

INTRODUCTION

Narragansett Bay, Rhode Island's most important natural resource, is vulnerable to contamination from a large number of point and non-point sources. Effluents from several municipal and industrial wastewater treatment plants and numerous other sources are released directly to the bay and to the streams that provide fresh-water inflow to the bay. Freshwater also enters the bay through direct precipitation on the surface of the bay, and through ground-water seepage. The rate of fresh-water inflow influences, to a large extent, the concentration of contaminants entering the bay at any given time. The inflow of freshwater also affects the salt balance of the bay and the rate at which contaminants are flushed from it to the ocean.

This report is one of several being prepared by various investigators for the Narragansett Bay Project, an organization composed of user groups, scientists, regulators and staff. The goal of the Narragansett Bay Project is to assess the principal factors that affect the environmental quality of the bay and develop recommendations for an overall management plan for the bay. The Project, initiated through a 1984 Congressional amendment to the Clean Water Act, began as a 5-year undertaking in July 1985. It is funded through the U.S. Environmental Protection Agency and administered by the Rhode Island Department of Environmental Management. The Project sponsors several studies that require estimates of the volume and time distribution of fresh-water inflow to the bay. The estimates are needed to accurately determine contaminant loads carried by streams and to calibrate models used to simulate circulation patterns and water quality in the bay effectively.

The 1,820 mi^2 (square mile) drainage area[1] of the Narragansett Bay basin (hereafter referred to as the Basin) includes the 143 mi^2 Narragansett Bay, and land areas that comprise most of northern, central, and southeastern Rhode Island, and large sections of southeastern Massachusetts (fig. 1). Total runoff into the bay includes surface-water inflow from streams draining into the bay, and precipitation that falls directly on the bay. Runoff from 1,054 mi^2, or 63 percent of the 1,677 mi^2 land area in the Basin was measured prior to commencement of this study by continuous-recording streamflow-gaging stations operated and maintained by the U.S. Geological Survey. Knowledge of runoff characteristics from ungaged areas that represented 37 percent of the land area in the Basin, and the contribution of precipitation directly onto the bay, was necessary to determine the total fresh-water input (runoff) to the bay.

Purpose and Scope

The purpose of this report is to provide estimates of the annual and monthly mean runoff into Narragansett Bay during the study period, October 1, 1986, through September 30, 1987 (the 1987 water year), and the long-term means of the annual and monthly runoffs into the bay.

This report describes: (1) the effects of geographic and geologic basin characteristics, land and water use, and climate on basin runoff; (2) the streamflow monitoring network; (3) procedures used to estimate runoff characteristics within the Basin; (4) regulations and diversions and their effects on estimating procedures; (5) the estimates themselves; and (6) an assessment of the accuracies of the estimates.

Acknowledgments

The author would like to thank Peter August and his staff at the University of Rhode Island Environmental Data Center, for digitizing drainage boundaries using their geographic information system computer software. Additional thanks goes to Steven Hale, the Narragansett Bay Project Data Coordinator, and to the Rhode Island Department of Environmental Management, for their support of the digitizing work.

STUDY AREA

Location and Physical Setting

The Narragansett Bay drainage basin encompasses an area of 1,820 mi^2, 143 mi^2 of which comprises Narragansett Bay. Much of the Basin is urban and suburban in character. Major cities within the Basin are indicated on plate 1, and include Worcester, Fall River, Taunton and Brockton, Massachusetts, and Providence, Woonsocket, Pawtucket, Cranston and Warwick, Rhode Island. Fresh-water inflow to the bay comes largely from the Taunton, the Blackstone, and the Pawtuxet Rivers, which together drain 75 percent

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[1] Derivation of drainage areas is discussed in the "Quantification of Variables for Regression Analyses" section.

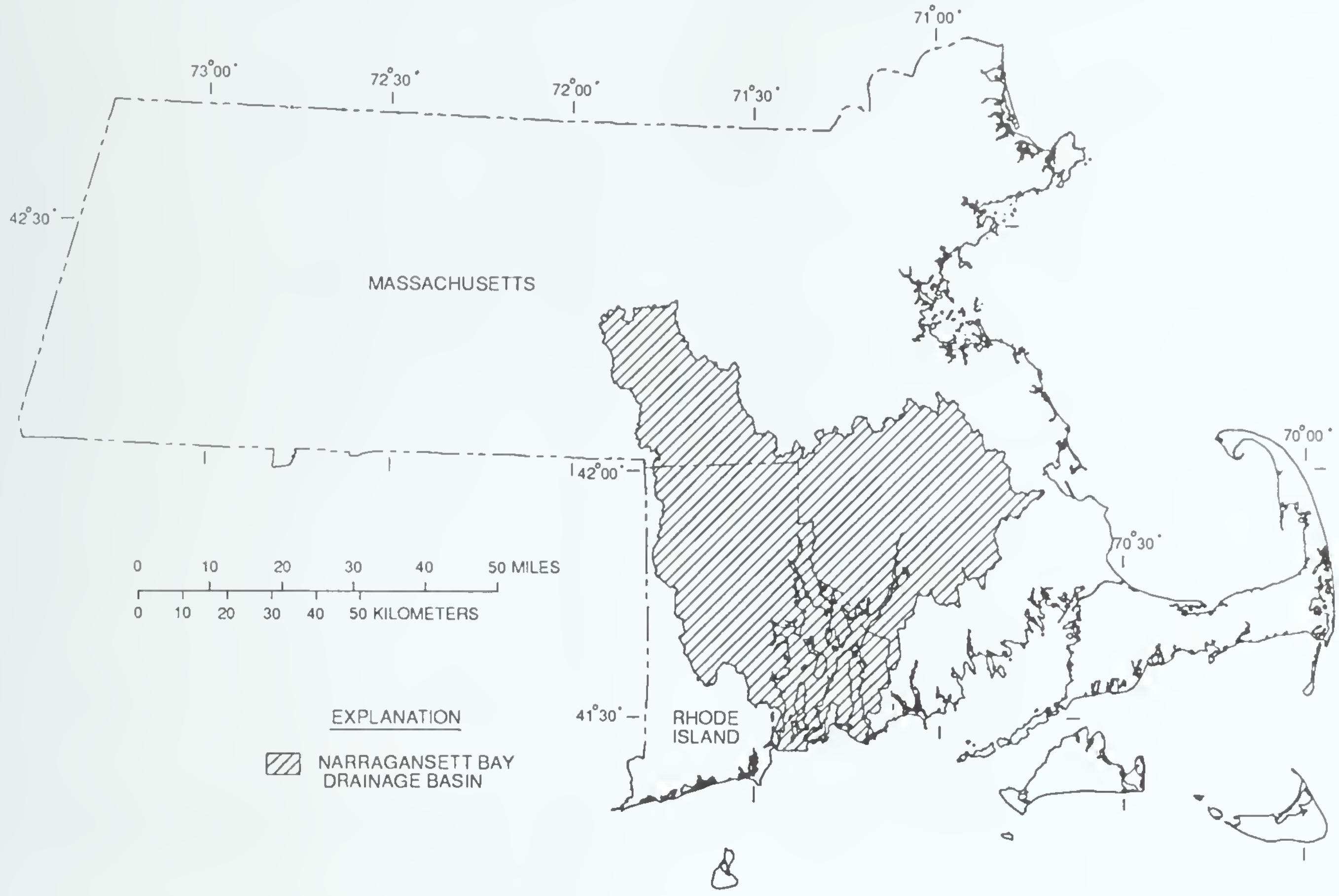

Figure 1.--Location of study area.

of the land area in the Basin. The remainder of the Basin is drained by several smaller rivers and streams, the largest of which are the Woonasquatucket, the Moshassuck, the Ten Mile, the Palmer, and the Hunt Rivers. Runoff from the western half of the Basin enters Narragansett Bay primarily through the Providence River estuary near Providence. Runoff from the eastern half of the Basin flows primarily into Mount Hope Bay, a part of Narragansett Bay, near Fall River.

Narragansett Bay drains into Rhode Island Sound by three routes -- the East Passage, the West Passage, and the Sakonnet River. The boundary line which indicates the mouth of the bay, as used for this report, is indicated on plate 1. This boundary was previously used in investigations by Pilson (1985) and Kremer and Nixon (1978).

The Taunton River, the largest river in the Basin, drains an area of 562 mi^2 comprised primarily of flat to gently rolling terrain. There are several large swamps and ponds within the river Basin. The river is affected by tides for about 15 mi (miles) upstream from its mouth (Williams and others, 1973). The Taunton River enters Mount Hope Bay, a part of Narragansett Bay, at Fall River.

The Blackstone River, the second largest in the Basin, drains an area of 472 mi^2. The headwaters of the Basin are in hilly terrain northwest of Worcester, where the maximum elevation is about 1,300 ft (feet). The topography flattens out as the river flows southward toward its mouth near Old Slater's Mill, in Pawtucket.

The Pawtuxet River, which has a drainage area of 232 mi^2, flows eastward from low hills near the Connecticut-Rhode Island border toward its mouth in Cranston. The Scituate Reservoir, located on the north branch of the Pawtuxet River, is the source of drinking water for the over half of the population of Rhode Island.

Surficial Geology

Bedrock within the Basin is overlain primarily by till and stratified-drift deposits of glacial origin. Till is an unstratified and unsorted deposit of materials ranging in size from clay to boulders. Stratified-drift deposits generally consist of fine sand, silt, or clay deposited in temporary lakes that formed during the glacial retreat, or medium- to coarse-grained sand and gravel deposited by glacial streams. Areas overlain by till and fine-grained stratified drift deposits comprise 51.0 percent of the total land area of the Basin. These areas generally yield greater surface runoff during storm events than areas overlain by coarse-grained deposits because rainfall infiltrates the coarse-grained deposits more rapidly than the fine-grained deposits. Although a large percentage of rainfall on till and fine-grained sediments runs off rapidly and becomes streamflow, much of the rainfall on the coarse-grained sediments recharges ground-water storage in aquifers. Water released from storage in the aquifers can sustain streamflow during periods of little or no precipitation. Coarse-grained stratified drift deposits comprise 35.2 percent of the land area of the Basin.

Lakes and swamps within the Basin provide natural storage for runoff during storm events. Lakes, ponds and manmade reservoirs cover 4.3 percent, and swamps cover 9.5 percent of the land area of the Basin. The stored water is released gradually, sustaining streamflow during dry periods.

River basins draining to the bay from the west to northwest, including the Blackstone, Woonasquatucket, Moshassuck, and Pawtuxet River basins, are generally two-thirds to three-quarters overlain by till. River basins draining from the north and northeast including the Taunton, Palmer, Cole, and Ten Mile River basins, generally have larger proportions of coarse-grained outwash deposits than till, and greater areal percentages of lakes and swamps than river basins draining from the west and northwest. Southwestern land areas in the Basin are predominantly sand, whereas till dominates the southeast and the islands in the bay. Bar-graphs on plate 1 indicate the total areas of till and fine-grained stratified drift, coarse-grained stratified drift, and storage (lakes and ponds) for designated subbasins that contribute runoff to the bay.

Land and Water Use

The Narragansett Bay basin is part of one of the oldest industrialized areas in the country. Land areas characterized as urban and suburban comprise 23.3 percent of the total land area in the Basin (U.S. Geological Survey, 1986). Rhode Island is the second most densely populated state in the Nation. Most of the cities and major towns within the Basin were established along the larger rivers or adjacent to the bay itself. The adjacent water bodies provided convenient transportation, drinking water, power production, industrial cooling and process water, and waste disposal for early municipalities and manufacturing interests. Most of the medium to large streams in the Basin were regulated or diverted or both to accommodate these uses. On the Blackstone River and its tributaries in Rhode Island, for example, dams were constructed, on the average, about 1 mile apart (Johnston, 1985).

Textile mills and other large manufacturing plants that were established during the American Industrial Revolution were once the dominant users of water in the Basin. Since World War II, many mills have ceased operation or no longer use streamflow. As a result, regulations by dams in the Basin have declined. Self-supplied industrial use of streamflow had declined to less than 20 percent of the total freshwater use in Rhode Island during 1980. During this same period, urban land uses such as light industrial and office complexes, roads, parking areas, shopping malls and residential development have greatly increased.

Urban land uses reduce infiltration by reducing the area where precipitation is able to penetrate the land surface. Increased areas of pavement and buildings, and man-made drainage networks transport storm runoff more rapidly to natural channels, producing higher flood peaks. Low flows from urban areas may be diminished due to the reduced infiltration to ground-water aquifers and reduced surface storage. Weiss (1983) suggests that the net effect of urbanization might be a higher mean flow, primarily because of a reduction in evapotranspiration from developed land.

Climate

The climate within the Basin is temperate, with mean annual temperatures ranging from 46.8 °F (degrees Fahrenheit) in Worcester, to 50.3 °F in

Providence, based on records for National Weather Service (NWS) stations located in these cities[2]. Lowest monthly temperatures generally occur in January, with mean January temperatures ranging from 23.3 °F in Worcester to 28.2 °F in Providence. Highest mean monthly temperatures occur in July, ranging from 69.9 °F in Worcester to 72.5 °F in Providence.

Precipitation within the Basin averages about 46 in. (inches) annually with highest amounts occurring in northern and northeastern sections of the Basin. Average annual precipitation for the period 1951-80 at NWS stations within the Basin is 47.60 in. at Worcester, 48.02 in. at Franklin, Mass., and 47.74 in. at Mansfield, Mass. Lowest annual rainfall occurs in central sections of the Basin, with a mean annual rainfall of 45.32 in. at Providence, and 45.77 in. at Taunton, Mass. Precipitation is fairly evenly distributed throughout the year, averaging almost 4 in. per month basinwide, and ranging from about 3 in. per month during June and July, to about 4.5 in. per month during November and December.

Regulations and Diversions

Most large streams in the Basin are affected by reservoir regulations, diversions, or both. Most regulations by dams in the Basin have a negligible effect on monthly and annual streamflows because few reservoirs have large storage capacities. However, three reservoir systems in the Basin have the ability to substantially affect the short-term total runoff to the bay.

West Hill Dam reservoir, on the West River near Uxbridge, Mass. has a usable capacity[3] of 542,000,000 ft^3 (cubic feet). It is a flood control reservoir operated by the U.S. Army Corps of Engineers that retains storm runoff from a drainage area of 27.9 mi^2. The reservoir normally maintains a very small pool. Runoff during flood events is retained by the reservoir and released gradually over a period of days or weeks to mitigate flood damage. These regulations usually affect monthly mean runoff for the West River for only a few months during each year. The annual mean runoff is not affected unless flooding occurs near the end of a water year; this causes a large amount of retained water to be released from the reservoir during the following water year. Records for the streamflow gaging station that is located directly below the dam are adjusted for the monthly change in the reservoir contents to approximate natural flow (flow that is unaffected by regulations of diversions). Both the adjusted and unadjusted monthly runoff figures are published in the annual data report.

The Scituate Reservoir (usable capacity, including five smaller feeder reservoirs, 5,307,000,000 ft^3), on the North Branch Pawtuxet River, and the Flat River Reservoir (usable capacity, 250,000,000 ft^3), on the South Branch Pawtuxet River, maintain large pools and substantially affect streamflow. The reservoirs, although not specifically designed for flood control, can retain runoff during times of high flow. The reservoirs can also augment natural flows during dry periods, although low-flow releases may sometimes only be equal to those required by contractually-arranged agreements with downstream mills. The net long-term effects of the reservoir regulations are that streamflows are smaller than they would normally be during the higher-flow months of March and April, and flows are greater than they would naturally be during summer months. Regulation of the Scituate Reservoir system (drainage area, 92.8 mi^2) affects runoff to a much greater extent than regulation of the much smaller Flat River Reservoir (drainage area 56.7 mi^2). Individual annual mean streamflows can be substantially affected because of the annual changes in contents of the reservoirs. The changes in contents of the Scituate Reservoir have affected annual mean runoff to the Pawtuxet River by as much as 10 percent during some water years (U.S. Geological Survey, 1976-87).

Most of the larger rivers in the Basin are affected by diversions for water supplies of municipalities and manufacturing interests. Diversions by manufacturers are generally limited to short distances along rivers

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[2] References for all temperature and precipitation data in this report: U.S. Commerce Department, National Oceanic and Atmospheric Administration, 1985-1987, Climatological Data, New England, v. 97, no. 13, v. 98, nos. 10-13, v. 99, nos. 1-9 (published monthly).

[3] This and subsequent reservoir capacities are from U.S. Geological Survey, 1976-87.

where water is taken from the river channel, passed through the manufacturing plant, and then returned to the river with little or no loss. Diversions by municipalities affect streamflow distribution to a much greater extent. The consequences vary depending upon the final fate of the diverted water, and inevitably complicate runoff-estimating procedures.

Diversions in the Basin occur in the following ways:

1. Diversions from the Basin, including withdrawals from wells adjacent to streams, to locations outside the Basin, result in a net loss of runoff to the bay. This occurs in the Taunton River basin, from which an average of about 30 ft^3/s (cubic feet per second) of water is diverted outside the Basin to supply the City of New Bedford, Mass.

2. Diversions into the Basin from other river basins result in a net increase in runoff to the bay. This occurs in the Blackstone River basin, where an average of about 20 ft^3/s of water is diverted from the Nashua River basin, and sometimes Quabbin Reservoir, for supply of Worcester, Mass., and in the Taunton River basin, where an average of about 10 ft^3/s of water is diverted from ponds outside the Basin for supplies of Brockton and Abington, Mass.

3. Diversions between river basins within the Narragansett Bay basin produce no net change in runoff to the bay, but may substantially affect the individual rivers. This type of diversion occurs in several river basins, including diversions from the Wading River to the Ten Mile River, and from the Pawtuxet River to the Blackstone, Hunt, and Woonasquatucket River basins.

4. Diversions occur from one location to another within the same river basin. These diversions occur in most of the larger river basins in the Narragansett Bay basin. Water is usually diverted for public supplies from reservoirs or wells adjacent to the river, and returned to the river elsewhere in the form of effluent from sewage treatment plants or through the ground from individual septic systems. This type of diversion causes essentially no net change in the total runoff from the river basin; however, if water is diverted upstream from a gaging station within the river basin and returned to the river downstream, the recorded runoff at the gaging station will be less than that which would occur naturally.

5. Diversions from river basins that are discharged directly to the bay by sewage treatment facilities cause a reduction of flow from the river basin but virtually no net change in runoff to the bay, because consumptive losses are insignificant.

6. Combinations of the above types of diversions also occur.

Diversions have the greatest affect on runoff from the Pawtuxet River basin, where the Scituate Reservoir supplies water to at least 11 major cities and towns in Rhode Island. Water from the reservoir is returned to the Pawtuxet River, transferred to the Blackstone, the Woonasquatucket, and the Hunt River basins, and then released directly to the bay through treatment facilities and septic systems. All of the water that returns to the Pawtuxet River basin is returned to the river upstream from the Cranston gaging station, except sewage-treatment-plant effluent from the City of Cranston that is returned just downstream from the gage.

Diversions from Scituate Reservoir average about 101 ft^3/s on an annual basis, with a low average monthly diversion of about 90 ft^3/s from December to March, and a high average monthly diversion of about 125 ft^3/s during July (City of Providence, Rhode Island, Water Supply Board, 1939-87, annual written communication). About one-fourth of these diversions is returned to the Pawtuxet River upstream from the Cranston gage. Most of the rest of the water is returned below the gage or directly to the bay via sewage treatment facilities.

Additional diversions occur in the Hunt River basin, where an average of about 7 ft^3/s is diverted upstream from the gaging station for supplies of North Kingstown, West Greenwich, and East Greenwich. Most water is returned directly to the bay through the East Greenwich sewage treatment facility, while part of the water is returned to the basin through septic systems.

METHODS OF ESTIMATING SURFACE-WATER RUNOFF

Streamflow Data Base

Fourteen streamflow-gaging stations, listed in table 1, were in operation prior to this study. These gaging stations provided continuous records of streamflow from 1,054 mi^2 of the 1,677 mi^2 land area within the Basin. An additional gaging station was installed near the mouth of the Ten Mile River at the beginning of the study, adding 53.4 mi^2 to the gaged area of the Basin.

Twelve partial-record stations, listed in table 2, were established during August 1986 to augment streamflow records from the continuous-record gages within the Basin. The partial-record stations provide streamflow data for an additional 198 mi^2 of the drainage area. Measurements of discharge, water surface elevation, or both were obtained at each site near the middle of each month throughout the study period. Measurements were obtained twice during months with unusually high runoff.

One additional streamflow-gaging station, Adamsville Brook at Adamsville, R.I., was re-established in a basin adjacent to the Narragansett Bay basin. The Adamsville Brook basin, like most of the southeastern section of the Narragansett Bay basin, is underlain primarily by till. Records from this station provide a good indication of runoff characteristics from till areas within the Narragansett Bay basin. The Adamsville Brook station had been a gaged site from October 1940 to September 1978. Monthly streamflow measurements were obtained at Adamsville Brook beginning in August, 1986. A continuous recorder was reinstalled at the site on February 17, 1987, and operated through September 30, 1987.

About 22 percent (372 mi^2) of the land area in the Basin remained completely ungaged during the study period. Most of this ungaged area is located adjacent to the bay. Flows in most stream reaches near the bay are affected by tides and could not be measured effectively.

The locations of all gaging stations and partial-record stations, and their respective drainage area boundaries, are shown on plate 1. All streamflow and water level data collected for this study, and all data for the periods of record for all gaging stations in the Basin are available from the Survey's National Water Data Storage and Retrieval System (WATSTORE). WATSTORE can provide a variety of products ranging from simple tables to complex statistical analyses (Hutchinson, 1975). Information regarding the availability of data analyses may be obtained from: U.S. Geological Survey, 10 Causeway Street, Room 926, Boston, MA 02222.

Estimating Runoff During the Study Period

Runoff during the study period at ten of the partial-record sites was estimated using a method proposed by Timothy A. Cohn (U.S. Geological Survey, written commun., 1987). The method uses streamflow records from a gaged site A, to estimate the monthly mean flow at a nearby climatologically and hydrologically similar partial-record site B, where discharge measurements are made at least once near the middle of each month during the estimation period.

Cohn's method assumes that at high flows, because of the climatologic similarity and proximity of the basins, the flow at site A will be proportional to the flow at site B. Geologic differences between the basins have less effect on streamflows during periods of high flow than during periods of low flow. High flows usually occur as a result of large storm events, which can be accompanied by significant quantities of snowmelt in colder climates. Soils generally become saturated during large storm events, and runoff is derived primarily from overland flow. As a result, when precipitation intensity exceeds the infiltration capacities of the soils in the individual basins, runoff becomes primarily a function of basin size.

Differences in the geology and physical characteristics of the drainage basins affect streamflow to a much greater extent during dry periods, when streamflow is derived primarily from ground-water storage, than during periods of high flow. Cohn assumes that runoff during dry periods may be substantially different at site A than runoff at site B due to the geologic and physical differences between the basins.

Cohn's method assumes natural flow at both sites, and is explained as follows: in generalized terms, let $Q_{A,t}$ and $Q_{B,t}$ denote concurrent stream-flows at time, t, at continuous-record site A and partial-record site B, respectively. Because the ground-water contribution at the two sites may be substantially different, it would seem reasonable to assume a model of the form

$$Q_{B,t} - \alpha_{B,t} = \beta_1 [Q_{A,t} - \alpha_{A,t}] , \qquad (1)$$

where β_1 is the coefficient of proportionality between the streams at high flows, and $\alpha_{A,t}$, and $\alpha_{B,t}$ are the ground-water contributions at sites A and B, respectively.

Table 1.--*Streamflow-gaging stations in the Narragansett Bay drainage basin*

Basin code[1]	USGS station number	Station name	Location	Period of record	Latitude	Longitude	Remarks
			Massachusetts Gaging Stations				
1212	01108000	Taunton River near Bridgewater	0.1 mi upstream from bridge on Titicut Road	1930-75 1985-87	41°56′05″	70°57′18″	Diversions upstream to and from basin for municipal supplies. Regulated by small powerplants and reservoirs.
1209	01109000	Wading River near Norton	200 ft downstream from Mass. Route 140	1926-present	41°56′51″	71°10′38″	Regulated by lakes and reservoirs. Diversions for municipal supply of Attleboro and small diversions for other municipal supplies.
1208	01109060	Threemile River at North Dighton	800 ft downstream from Warner Boulevard	1967-present	41°51′58″	71°07′24″	Diversions to and from basin may be compensating. Regulated by lakes and reservoirs upstream.
1206	01109070	Segregansett River near Dighton	50 ft upstream from Center Street	1967-present	41°50′25″	71°08′36″	Occasional regulation by ponds. Diversion for Dighton Water District.
0307	01110000	Quinsigamond River at North Grafton	800 ft downstream from Hovey Pond	1939-present	42°13′49″	71°42′41″	Some regulation by Lake Quinsigamond 2.3 mi upstream and by ponds upstream.
0306	01111200	West River below West Hill Dam near Uxbridge	250 ft downstream from West Hill Dam	1962-present	42°06′17″	71°36′28″	Regulated at high flows by West Hill Dam.

Table 1.--*Streamflow-gaging stations in the Narragansett Bay drainage basin*--Continued

Basin code[1]	USGS station number	Station name	Location	Period of record	Latitude	Longitude	Remarks
			Rhode Island Gaging Stations				
0305	01111300	Nipmuc River near Harrisville	on Sherman Road 1.25 mi north of Harrisville	1964-present	41°58′52″	71°41′11″	No significant regulations or diversions.
0304	01111500	Branch River at Forestdale	400 ft downstream from milldam at Forestdale	1940-present	41°59′47″	71°33′47″	Occasional regulation by pond upstream.
0303	01112500	Blackstone River at Woonsocket	50 ft upstream from Peters River	1929-present	42°00′22″	71°30′13″	Regulation by powerplants and reservoirs upstream. Upstream diversions to basin for municipal supply of Worcester, MA.
0402	01114000	Moshassuck River at Providence	800 ft upstream from bridge on U.S. Route 44	1963-present	41°50′02″	71°24′42″	Occasional regulation at low flow.
0503	01114500	Woonasquatucket River at Centerdale	75 ft downstream from bridge on U.S. Route 44	1941-present	41°51′32″	71°29′16″	Some regulation by reservoirs upstream.
0105	01116000	South Branch Pawtuxet River at Washington	150 ft downstream from bridge at Washington	1940-present	41°41′24″	71°33′59″	Regulation by Flat River Reservoir and smaller reservoirs.
0103	01116500	Pawtuxet River at Cranston	0.7 mi upstream from Pocasset River	1939-present	41°45′03″	71°26′44″	Regulation by powerplants, Flat River Reservoir, Scituate Reservoir and smaller reservoirs upstream. Diversion from Scituate Reservoir for municipal supplies.
1301	01117000	Hunt River near East Greenwich	45 ft upstream from Old Forge Dam	1940-present	41°38′28″	71°26′45″	Diversions upstream for municipal supplies.

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[1] The first two digits of the basin code are unique numbers assigned to a particular river basin; the second two digits identify sites within the basin, numbered in upstream order.

Table 2.--*Temporary gaging stations and partial-record stations in the Narragansett Bay drainage basin*

Basin code[1]	USGS station number	Station name	Location	Latitude	Longitude	Remarks
			Temporary Gaging Stations			
0902	01109403	Ten Mile River at East Providence, R.I.	at Pawtucket Avenue bridge	41°49′50″	71°21′05″	Some regulation at low flow by reservoirs upstream.
2001	01106000	Adamsville Brook at Adamsville, R.I.	0.4 mile upstream from Grays Mill Pond outlet	41°33′30″	71°07′47″	Not part of Narragansett Bay basin. Daily flow records available for 1941-78 water years. Recorder reinstalled February 17, 1987.
			Massachusetts Partial-Record Stations			
1211	01108400	Mill River at Whittenton	at Whittenton Street bridge	41°55′23″	71°06′23″	Occasional regulation from ponds upstream.
1204	01109087	Assonet River at Assonet	at Locust Street bridge	41°47′57″	71°03′37″	- -
2102	01109135	Cole River at Hortonville	at Hortonville Road bridge	41°46′30″	71°11′57″	- -
1703	01109220	Palmer River at South Rehoboth	at Reed Street bridge	41°48′33″	71°16′42″	Occasional minor regulation from Shad Factory Pond and fish ladder upstream.
1702	01109225	Rocky Run near Rehoboth	at Davis Street bridge	41°46′52″	71°15′03″	Tidal effect at highest tides.
1802	01109280	Runnins River at Fall River Avenue at Seekonk	at Fall River Avenue bridge	41°48′59″	71°20′10″	- -

Table 2.--*Temporary gaging stations and partial-record stations in the Narragansett Bay drainage basin*--Continued

Basin code[1]	USGS station number	Station name	Location	Latitude	Longitude	Remarks
			Rhode Island Partial-Record Stations			
0302	01113650	Blackstone River at Lonsdale	at Lonsdale Avenue bridge	41°54′40″	71°24′12″	Regulation and diversion above and below upstream gaging station.
0502	01115010	Woonasquatucket River at Providence	at Valley Street bridge	41°49′20″	71°26′25″	Some regulation by reservoirs above upstream gaging station.
0102	01116615	Pawtuxet River at Warwick Avenue at Cranston	at Warwick Avenue bridge	41°46′03″	71°24′20″	Water levels measured at Elmwood Avenue bridge 1 mile upstream after December 1986 due to construction. Regulations and diversions above upstream gaging station.
1601	01116635	Old Mill Creek at Warwick	at Tidewater Road bridge	41°42′43″	71°22′33″	Tidal effect except at low tide.
1401	01116750	Maskerchugg River at Boston Post Road at East Greenwich	at Boston Post Road bridge	41°39′00″	71°27′30″	- -
1501	01117100	Annaquatucket River at Bellville	at Tower Hill Road bridge	41°33′25″	71°27′54″	Occasional regulation by ponds upstream. Daily flow records available for 1962-1964 water years.

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[1] The first two digits of the basin code are unique numbers assigned to a particular river basin; the second two digits identify sites within the basin, numbered in upstream order.

We require an estimate of the flow at site B, $\hat{Q}_{B,t}$ ($\hat{\ }$ signifies estimated), as a function of the flow at site A, $Q_{A,t}$, which is known. The relation can be inverted to yield

$$Q_{B,t} = \beta_1 Q_{A,t} - \partial_t \, , \tag{2}$$

where $\partial_t \equiv \beta_1 \alpha_{A,t} - \alpha_{B,t}$. Thus we need estimates of β_1 and ∂_t ($\hat{\beta}_1$ and $\hat{\partial}_t$, respectively) to obtain

$$\hat{Q}_{B,t} = \hat{\beta}_1 \; Q_{A,t} - \hat{\partial}_t \, . \tag{3}$$

To estimate $\hat{\beta}_1$, ordinary least-squares linear regression[4] is used on the untransformed observations of $Q_{A,t}$ and $Q_{B,t}$. An estimate of $\hat{\partial}_t$ can be obtained for each individual observation by using the differences (residuals) between the predicted values from the regression and the observed values, yielding

$$\hat{\partial}_t \equiv \hat{\beta}_1 \; Q_{A,t} - Q_{B,t} \, . \tag{4}$$

Thus, predictions of flow at site B, $\hat{Q}_{B,t}$ are obtained by changing the intercept, $\hat{\partial}_t$, for regression equation 3 so that a line of slope $\hat{\beta}_1$ passes through each observation point.

In terms of estimating the monthly mean flow, $\hat{Q}_{B,m}$, for month, m, at ungaged site B, given the known monthly mean flow, $Q_{A,m}$, at site A, and concurrent flows $Q_{A,d}$ and $Q_{B,d}$, on day, d, near the middle of the month, the model assumes the form

$$\hat{Q}_{B,m} = \hat{\beta}_1 Q_{A,m} - \hat{\partial}_m \, , \tag{5}$$

where

$$\hat{\partial}_m \equiv \hat{\beta}_1 Q_{A,d} - Q_{B,d} \, , \tag{6}$$

or, combining the equations to obtain

$$\hat{Q}_{B,m} = \hat{\beta}_1 Q_{A,m} - (\hat{\beta}_1 Q_{A,d} - Q_{B,d}) \, . \tag{7}$$

Cohn's method of estimating the regression line slope, β_1, depends to a great extent on the largest observations, especially given the small number of observations available for this study (on average, about 15 per site). As a result, the computed slope tends to be close to the coefficient of proportionality between the two sites at high flows.

Searcy (1960) demonstrates that the relation between two sites, when plotted logarithmically, can often be expressed more satisfactorily by using two lines of different slopes; one for the high-flow range of the relation and another for the low-flow range. The two lines often intersect at from one to two times the mean discharge for streams east of the Mississippi River. Since curvature should be more pronounced with the arithmetic plots used in Cohn's method, than with logarithmic plots, the need for more than one regression line should be greater. The appearance of scatterplots for sites within the Narragansett Bay basin generally supports this conclusion. The scatterplots indicate that estimates of monthly mean flow using Cohn's method could be improved at some sites by determining different regression line slopes for high and low flows.

Figures 2 and 3 provide a graphical representation of the application of Cohn's method to obtain monthly mean streamflow estimates for the partial-record site located on the Cole River at Hortonville, Mass. Figure 2 is a scatter plot of 16 measured discharges at the partial-record site versus the concurrent daily mean discharges for the Segreganset River near Dighton, Mass., gaging station, which is used as the estimator. An examination of the plotted points indicated that separate high- and low-flow regression lines were necessary. Regression lines were determined based on the 4 highest and 12 lowest plotted points, and are indicated in figure 2 by dashed and solid lines, respectively.

Figure 3 shows the observation points of concurrent discharges used in the low-flow regression, the regression line and equation (shown as the solid line in fig. 2), and the estimates of monthly mean runoff. Graphically, the monthly estimates are obtained by drawing a line parallel to the regression line through each observation point. Mean monthly streamflows at the gaging station are entered on the horizontal axis and lines are then drawn vertically to the line that passes through the respective observation point for each month. Monthly mean streamflows at the partial-record site are obtained by drawing a horizontal line from the point at which the two lines intersect for each

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[4] Thorough explanation of statistical methods is outside the scope of this report. References to appropriate statistical texts include: Conover, 1980; Duan, 1983; Iman and Conover, 1975; Riggs, 1967, 1968, 1969; Ryan, Joiner and Ryan, 1985.

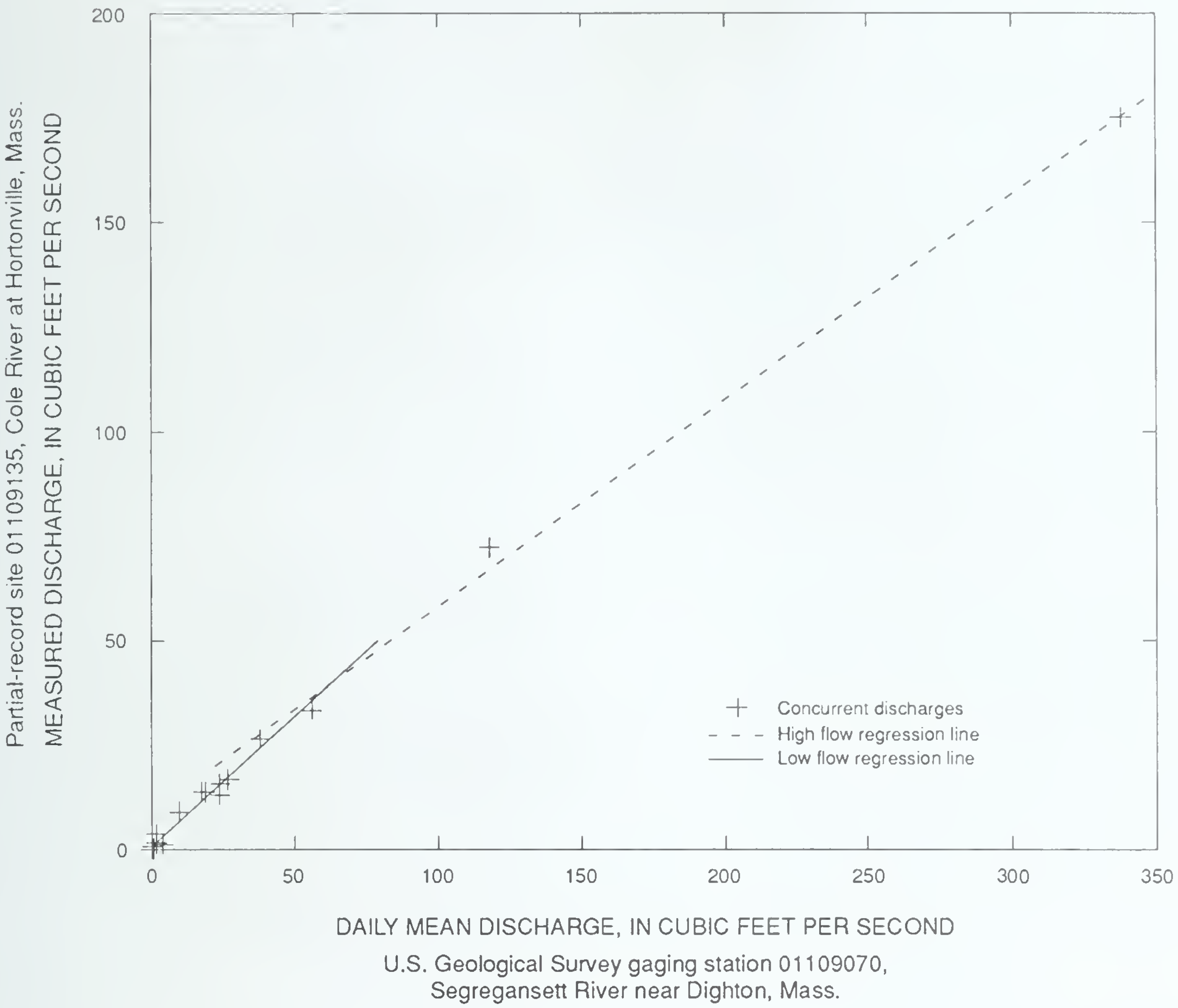

Figure 2.--High flow and low flow regression lines used to relate concurrent discharges at the Cole River partial-record site and the Segreganset River gaging station.

respective month, to the vertical axis, and reading off the monthly value.

In actual applications, the entire method is performed using a computer-software statistical package. The regression line is shifted mathematically through each of the observation points to determine a separate equation for each point that preserves the same slope as the original equation. The known monthly mean flows at the gaged site are then substituted into these separate equations to obtain estimates of monthly mean flows at the partial-record site.

Application of Cohn's method to partial-record sites within the Basin is summarized as follows:

1. For each partial-record site, possible gaged sites to be used as an estimator were selected based on proximity, relative drainage area size, and similarity of the physical characteristics of the subbasins. Highly regulated sites were not used.

2. All available measured discharges at the partial-record site were correlated with, and plotted against, concurrent discharges for each gaged site under consideration.

3. The gaged site with the highest correlation coefficient was chosen unless the scatterplot

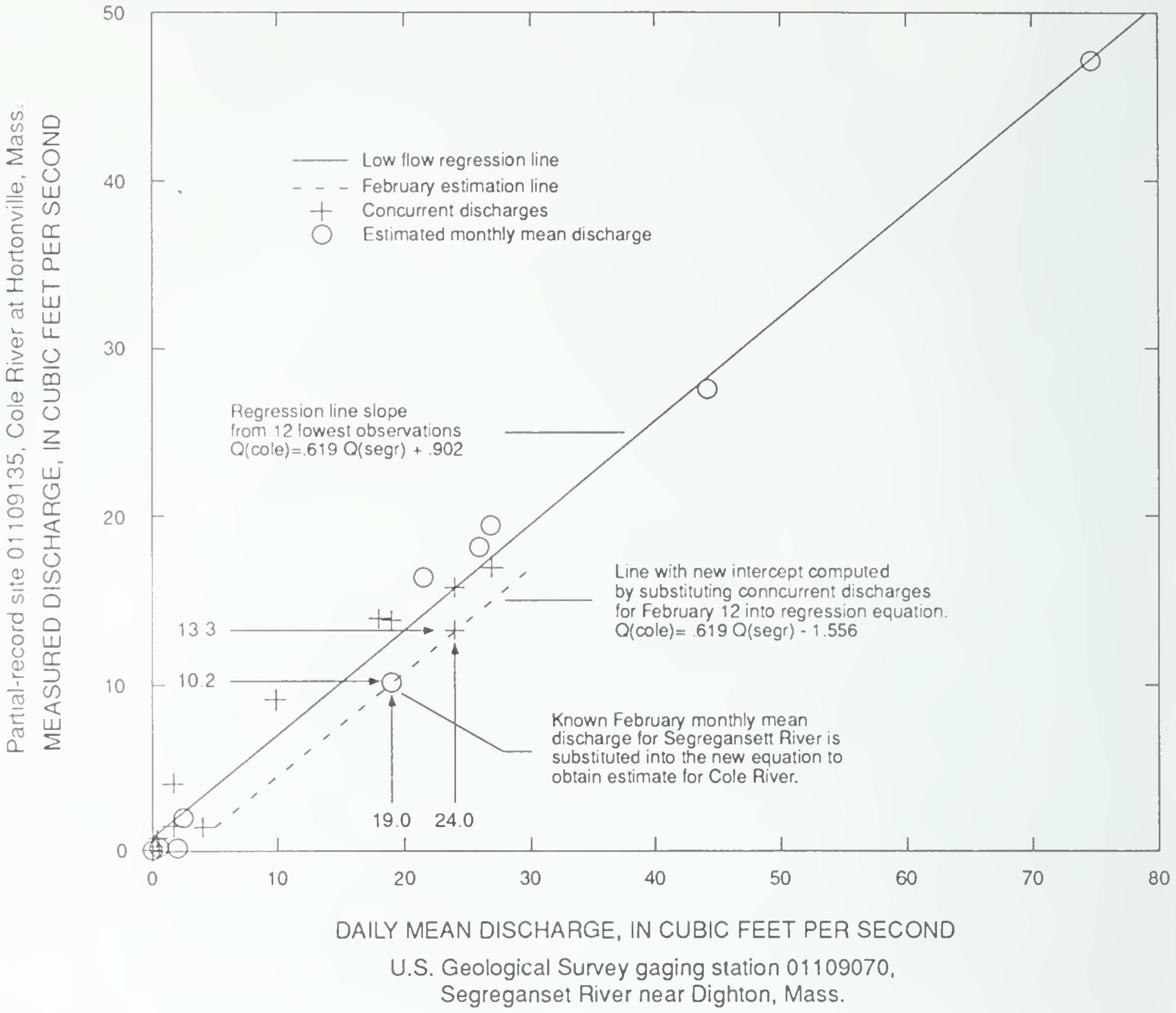

Figure 3. --Representation of Cohn's method of estimating monthly mean runoff at an ungaged site using February, 1987 as an example.

indicated that another site might be preferable. In cases where two sites were found to be equally suitable, estimates were performed separately using each gaged site to estimate flow at the partial-record site. The resulting monthly estimates were averaged to obtain a final estimate.

4. If the plot indicated distinct high-flow and low-flow patterns, regressions were performed to determine separate high-flow and low-flow slopes. The points used in the individual regressions were primarily determined by the appearance of the scatterplots. The intersection between the high-flow and low-flow regression lines averaged 1.24 times the mean for the 1987 water year (1.51 times the long-term mean) for the correlating gaging stations, supporting Searcy's rule of thumb.

5. Estimates of monthly mean flow were determined for each site using equation 7. If separate high- and low-flow slopes were determined at a site, the slope used for an individual monthly estimate was based on

the range of the discharge measurement made during the month. If the observation was in the transition area between flow ranges, separate estimates were made using each slope and their average was used as the final estimate.

6. When more than one discharge measurement was made in a month, monthly estimates were computed for each observation, and then averaged.

Cohn's method of estimating monthly mean discharge at an ungaged site is similar to, and partially based on, a graphical technique proposed by Riggs (1969). Both methods use concurrent discharges near the middle of the month at a gaged site to estimate a monthly mean discharge at the ungaged site.

In Riggs' method, concurrent discharges are plotted logarithmically rather than arithmetically, and a 45 degree line of equivalence is drawn through each point of concurrent discharges. This line of equivalence is based on the assumption that the ratio of the concurrent daily mean discharges of the gaged and ungaged streams near the middle of the month equals the ratio of their monthly means. The known monthly mean discharge at the gaged site is then transferred through the line of equivalence to obtain an estimate for the ungaged site. Riggs, and Parrett and Hull (1986), report that the annual mean discharge, produced by summing and averaging the estimated monthly means, can be estimated within about 10 percent of actual, on average.

There are several advantages to using the method proposed by Cohn over that of Riggs:

1. Cohn uses regression to determine the slope of the line of relation between the two sites rather than assuming that it is 45 degrees.

2. Different lines of relation can be used for high and low flows.

3. Additional concurrent discharges, including observations made outside the estimation period, can easily be included in the regressions to increase the accuracy of the relation by dampening possible large scatter present in the individual measurements.

4. Because the computations are done in normal space rather than logarithmic space, zero flow can be accommodated. (Provided that zero flow is absent, log-transformation of the data may actually improve the results of Cohn's method, although this was not attempted.)

5. Cohn's method is easier to perform on a variety of statistical computer software packages than is Riggs' method.

Three partial-record sites, Blackstone River at Lonsdale, Pawtuxet River at Warwick Avenue, Cranston, and Woonasquatucket River at Valley Street, Providence, are downstream from gaging stations. The drainage areas of these sites are 1.06 times, 1.15 times, and 1.25 times the drainage areas of their respective upstream gaging stations. Plots of the measured discharges at the partial-record sites against the concurrent discharges at their respective upstream gaging stations showed unacceptable scatter in each case. Estimation methods used for these three sites are discussed in the following paragraphs.

Frequent regulation by dams located above and below the gaging station on the Blackstone River caused four of the fifteen discharge measurements obtained at the partial-record site to be unrelated to their concurrent discharges at the gaging station. The regulation affects daily mean streamflows substantially, but monthly mean streamflows are unaffected due to the small storage capacities of the reservoirs. However, Cohn's method could not be used to estimate runoff for months when the discharge measurements obtained at the partial-record site were unrelated to the streamflow at the gaging station.

In addition to regulation by dams located upstream from the gaging station, the Pawtuxet River is affected by shifting control conditions (changing stage-discharge relation) due to aquatic growth at both the gaging station and the partial-record site. A sewage treatment facility also discharges varying amounts of effluent between the gaging station and the partial-record site. These factors create additional uncertainty in the estimates of monthly mean runoff that would be obtained by relating concurrent flows at the two sites.

Measured discharges for the Blackstone and Pawtuxet River partial-record sites were plotted on log-log paper against concurrent discharges at the upstream gaged site. Points that were obviously affected by regulation were omitted and a discharge-versus-discharge (QxQ) relation curve was drawn through the remaining points. Monthly mean discharge estimates at the partial-record sites were read off the relation curve using the known monthly mean discharges at the gaged sites.

Although the Woonasquatucket River is not highly regulated compared to the larger rivers in the Basin, the discharge-versus-discharge estimation method was not used for the Woonasquatucket River partial-record site because the plotted points did not align well. The upstream gaged site has a constantly shifting control (changing stage-discharge relation). Adjustments to correct for the shifting yield reasonable monthly figures but instantaneous and daily discharges may have significant errors. The poor accuracy of the concurrent discharges at the gaged site may have caused the plotted points to scatter unacceptably.

Estimation of runoff during the study period at the Woonasquatucket River partial-record site was performed by using the drainage-area ratio (DA-ratio) method. The method consists of multiplying the known mean monthly discharge at a gaged site by the ratio of the drainage areas of the ungaged and gaged sites, such that

$$\hat{Q}_u = Q_g \left(DA_u / DA_g \right), \qquad (8)$$

where $\hat{Q}_u$ is the predicted monthly mean discharge at the ungaged site, Q_g is the monthly mean discharge at the gaged site, and DA_u , and DA_g are the drainage areas of the ungaged and gaged sites, respectively. Annual runoff estimates were computed by summing and averaging monthly estimates.

The DA-ratio method was used to estimate runoff from the areas between gaged or partial-record sites and the mouths of major rivers in the Basin. The method was also used to estimate runoff at designated locations in ungaged areas where partial-record sites were not established.

Study period monthly and annual precipitation values for the National Weather Service (NWS) weather data collection stations at Kingston, Newport and Providence, Rhode Island, were weighted according to their respective areas of influence determined using a method proposed by Thiessen (1911), to produce averaged precipitation estimates for the entire bay. Monthly and annual discharge equivalents of precipitation directly onto the bay were then computed by multiplying the averaged precipitation estimates by the total area of the bay, and converting the resulting monthly and annual volumes of precipitation to runoff, in cubic feet per second, for each estimated period. The NWS precipitation figures and estimates of mean rainfall on the bay during the study period appear in table 3.

Estimating Long-Term Runoff

Streamflow is derived primarily from precipitation, which varies greatly in time, type, duration and areal distribution. Runoff from separate basins differs due to precipitation variations and differences in the physical characteristics of the basins, such as drainage area, drainage patterns, land-use types, soils, vegetation, evapotranspiration, the amount of natural or man-made storage in swamps, lakes, reservoirs, and storage below the land surface in aquifers.

Multiple-regression analyses that relate streamflow characteristics from gaging stations to measures of the physical characteristics of their basins can be used to produce equations for predicting streamflow characteristics at ungaged sites. These equations, usually referred to as regionalization models in the hydrologic literature, generally utilize basin characteristics derivable from maps, aerial photography, satellite data, and other sources as independent variables for the regression equations. It is usually impractical to include all of the variables that affect streamflow in the models. Selection of variables is limited by time constraints and the availability and complexity of analytical procedures.

Regionalization models produce satisfactory estimates of streamflow characteristics only when the sites where the models are to be applied are within reasonable geographic proximity of those sites used in the model. Use of models to make predictions for ungaged sites with independent variable values outside the ranges of those used in the regression should be avoided because estimation errors increase and become more difficult to evaluate.

Regionalization models of long-term monthly mean flow within the Basin were developed using a stepwise regression analysis procedure. A single model was developed for each month, and used to estimate runoff from most ungaged areas of the Basin. A discussion of stepwise regression analysis procedures, and the selection and quantification of basin characteristics used as independent variables follows.

Stepwise-Regression Analyses

The stepwise procedure tests the relations between the dependent variable (in this case, long-term mean monthly runoff) and the independent variables (basin characteristics), and aids in determining the

Table 3.--*Study period weighted mean monthly and annual precipitation on Narragansett Bay, Rhode Island, and 1987 water year precipitation data for regional National Weather Service stations*

[U.S. Commerce Department, National Oceanic and Atmospheric Administration, 1985-1987]

[Weighted mean precipitation on the bay was computed for the 1987 water year using a method proposed by Thiessen (1911). The precipitation data (in inches) for each weather station was weighted by the bay area (in square miles, mi^2) indicated in parentheses]

	Weather station location			Mean precipitation on the bay ($143\ mi^2$)
Month	Kingston, R.I. ($2.3\ mi^2$)	Newport, R.I. ($83.0\ mi^2$)	Providence, R.I. ($57.7\ mi^2$)	
October 1986	2.71	2.73	2.48	2.63
November	8.11	5.77	7.22	6.39
December	9.78	8.09	7.24	7.77
January 1987	6.19	4.75	4.73	4.76
February	0.91	0.87	0.39	0.68
March	5.09	4.43	5.62	4.92
April	8.26	6.91	7.39	7.13
May	1.81	2.13	1.80	1.99
June	1.46	1.18	2.00	1.52
July	1.05	1.06	1.20	1.12
August	3.15	2.70	2.58	2.66
September	6.11	7.29	7.47	7.34
1987 water year	54.63	47.91	50.12	48.91

best independent variables to include in the model. The procedure begins by computing coefficients of determination, R^2, for all possible single-variable regressions, and choosing the model with the highest R^2 value. The R^2 value is a measure of the proportion of the variation in the dependent variable that is explained by the model. The procedure adds the independent variables to the model one by one, testing for significance after each step. If a variable is found to be significant at a specified level it is added to the model. Independent variables already in the model are then checked to see if they may be deleted. The procedure ends when no variables can be added or deleted at the specified significance levels for inclusion or removal.

When two independent variables are highly related only one is likely to be found significant in the stepwise procedure. Use of highly related variables can sometimes lead to unstable model results. Variables with a small range of values usually are not found to be significant even though they may have a strong theoretical relation to the dependent variable.

Regionalization model variables are commonly log-transformed in order to make the relationship more linear and the sample distribution more normal. Equations produced from the stepwise procedure using natural log-transformed variables take the form of a linear function, such as

$$\ln Y = \ln \alpha + \beta_1 \ln x_1 + \beta_2 \ln x_2 + \ldots + \beta_n \ln x_n + \varepsilon_i \qquad (9)$$

where Y is the dependent variable (mean monthly runoff), $x_1, x_2, \ldots, x_n$ are the independent variables. α is the regression constant, and $\beta_1, \beta_2, \ldots, \beta_n$ are the regression coefficients of the independent variables, ε_i is the residual error, $i = 1, 2, \ldots, N$, and N is the sample size.

The regression equations need to be detransformed (exponentiated, for natural-log transformation) to original units in order to make meaningful predictions. Detransformation of equation 9 yields

$$Y = (\alpha x_1^{\beta_1} x_2^{\beta_2} \ldots x_n^{\beta_n})(\exp(\varepsilon_i)). \qquad (10)$$

In a nontransformed regression the error term is ignored because the sum of the errors is always zero with ordinary least squares regression. However, log-transformed regressions yield residuals that have a log-normal distribution, and have a mean and median that differ when detransformed. A simple detransformation of the regression equation that ignores the error term yields estimates of the median response rather than the mean response of the dependent variable, and causes estimation bias. Duan (1983) provides a method of estimating the mean residual error in order to avoid this bias. Adjusting equation 10 using Duan's "smearing estimate" yields

$$Y = (\alpha x_1^{\beta_1} x_2^{\beta_2} \ldots x_n^{\beta_n})(\Sigma[\exp(\varepsilon_i)]/N). \qquad (11)$$

Duan's smearing estimate of the mean residual error, the final term in parentheses, is performed by summing the exponentiated natural log-space residuals, ε_i, and dividing by the sample size, N. Failure to include this error term can result in underestimation of the dependent variable.

Stepwise regression is a useful tool for exploratory data analysis, but does not guarantee that the final result is the best model for the data. Comparisons of different models that explain the same dependent variable, but use different independent variables, different numbers of stations in the analyses, or different transformations need to be made to determine the best model available. The final model must be consistent with real world hydrologic principles. Tests for possible violations of the assumptions for regression analyses also are needed.

The R^2 value can be adjusted for the number of stations in the regression model, R^2_{adj}, in order to compare models that explain the same dependent variable but use differing numbers of stations in the analyses. The R^2 or R^2_{adj} values, however, cannot be used to compare transformed and untransformed models with the same dependent variables because the proportion of variation in log-space is not the same as it is in normal space.

Comparisons of transformed and nontransformed models with the same dependent variables can be performed by detransforming the predictions from the transformed model and multiplying them by the smearing estimate of the mean residual error. The percentage errors of the predictions from the different models can then be computed and compared. Models with smaller standard errors, s, and smaller averages of the absolute values, $|e_i|$, of the percentage errors of the predictions, are considered to be superior.

Quantification of Variables for Regression Analyses

The basin characteristics initially chosen as independent variables for use in the regression analyses were drainage area, stream slope, stream length, and individual areal percentages of till, coarse-grained stratified drift, storage (swamps, lakes, reservoirs), and urban land use. Areas of fine- grained stratified drift and bedrock outcrops were included in the areal percentage of till since their runoff characteristics are similar. Areas of man-made fill were also included as till although fill could have properties of either till or coarse-grained stratified drift, depending upon its composition. Since fill rarely exceeded one percent of total subbasin area very little error is introduced by simply including fill as part of the total area of till and eliminating field verification. Each of the variables except urban land use were measured from various source maps using an electronic digitizing tablet.

Subbasin drainage boundaries for partial-record sites, the mouths of rivers and the mouth of the bay, were delineated on the latest available U.S. Geological Survey 7 1/2-minute quadrangle topographic maps. Drainage area boundaries for gaging stations within the Basin were transferred to this new set of latest-available maps from previously-delineated drainage divide maps at a scale of 1:24,000 on file in the Massachusetts and Rhode Island offices of the Survey. The Massachusetts maps are part of a series of open-file drainage divide reports (Brackley and Wandle, 1982, 1983, Krejmas, 1982, and Wandle and Frimpter, 1982). The 53 new drainage divide quadrangle maps encompassing the Basin are at a scale of 1:25,000 for Massachusetts, and 1:24,000 for Rhode Island. All subbasin drainage areas were computed in square miles from the new set of maps using the procedures proposed by the U.S. Federal Inter-agency River Basin Committee (1951).

Plate 1 indicates drainage basin boundaries and the locations of gaging stations and partial-record sites in the Basin. The plate also provides the percentage of urban area, stream slope, stream length, drainage area, and a bar graph indicating the total subbasin surficial areas of coarse-grained stratified drift, till (including bedrock outcrops and fine-grained stratified drift), and storage (total of ponds and swamps) for each subbasin.

All surficial features for each individual quadrangle map were measured at one time. Total areas of individual surficial features were computed for each subbasin on a map. Subbasin totals were then compiled by summing the subbasin totals computed for each map. Areal percentages were computed by dividing the subbasin total area of a surficial feature by the total subbasin area. Source maps used to measure surficial features are listed in the Selected References.

Stream length, in miles, was measured horizontally from the gaged site or other point of reference on the topographic maps, upstream to the drainage divide by following the forks that have the longest watercourses. Stream slope, in feet per mile, was computed using the difference in elevation of points 10 percent and 85 percent of the distance from the gaged site or other reference point to the basin boundary, divided by 75 percent of the total stream length above the point of reference. Measurement of stream lengths and slopes were performed according to procedures explained in the "National Handbook of Recommended Methods for Water-Data Acquisition" (NHRM) (U.S. Geological Survey, 1977).

Geographic information system (GIS) computer technology was used to create a digitized data file of the drainage divides for the Basin. This data file was merged with the land use and land cover digital data file from the Geographic Information Retrieval and Analysis System (GIRAS) of the Survey (1986). The GIRAS land-use data files consist of digitized polygons of land surface representing single land use types. The minimum area represented by a polygon is about 9.9 acres. Classification is based upon the system shown in table 4. The land use data were compiled and digitized at a scale of 1:250,000, from enlargements of high-altitude areal photographs taken in 1974. By use of the GIS, the total area of urban-type land use (Level 1, type 1, from table 4) was computed for each subbasin, and converted to areal percentage. Figure 4 is a map indicating the distribution of urban-type land use within the Basin, produced using the GIS to merge the drainage divide data file with the GIRAS land-use data.

Measurement accuracy of the basin characteristics varies. The NHRM states that the relative standard error of estimate for determining drainage area, stream length and stream slope is 5 percent. Map error occurs due to distortion in the aerial photographs used to make the map, transference of three-dimensional information to two dimensions, enlarging or reducing, errors in drawing the map, and map scale. Additional errors can occur in defining the basic variables (delineating drainage divides, and so forth), and instrument and operator errors.

Measurement of surficial geologic features and land use involves errors in addition to those stated above. Surficial features and land use change with time. Swamps and ponds can be created or destroyed, fill can be used to cover natural soil types, and areas of sand or bedrock can be quarried. Land use can change dramatically, usually from nonurban to urban uses such as shopping malls or housing developments being built on farmlands.

Source maps used to measure surficial features were published during 1949-73 (see Selected References). The source maps were compared with the latest available topographic maps to identify changes. Changes, which in most cases were minor, were transferred back to the source maps and included in the measurement of areas of surficial features.

Some of the 1:24,000-scale surficial geology maps used were unpublished and in some cases incomplete. The unpublished surficial geology maps are located in the Massachusetts office of the U.S. Geological Survey, and include those for the Assonet, Assawompsett Pond, Attleboro, Blackstone, Fall River, Fall River East, Franklin, Mansfield, Milford, Norton, Oxford, Somerset, Taunton, and Tiverton quadrangles. These maps were checked against various 1:48,000-scale Hydrologic Atlas maps for accuracy and occasional interpolation (Walker and Krejmas, 1986; Williams, 1968; Williams and others, 1973; Williams and Willey, 1973). For some quadrangles, the atlas maps were used exclusively. Although no rigorous procedure for quantifying the measurement error of this methodology is available, a relative Basin-wide standard error of about 10 percent is probably reasonable.

The measurement error of land use as a percentage of total subbasin area increases slightly as subbasin drainage area decreases. This occurs because the minimum polygon size of the GIRAS data base is 9.9 acres. This error should remain relatively small because the smallest subbasin area for which runoff is being estimated is 5.4 mi^2 (3,456 acres). Land use changes since the data were compiled in 1974 are likely to be a larger source of error. In some subbasins these changes may be significant due to a large amount of development occurring within the past several years. The GIRAS data base is being revised using

Table 4.-- *U.S. Geological Survey land use and land cover classification system for use with remote sensor data (U.S. Geological Survey, 1986)*

	Level I		Level II
1	Urban or built-up land	11	Residential
		12	Commercial and services
		13	Industrial
		14	Transportation, communications and utilities
		15	Industrial and commercial complexes
		16	Mixed urban and built-up land
		17	Other urban and built-up land
2	Agricultural land	21	Cropland and pasture
		22	Orchards, groves, vineyards, nurseries, and ornamental horticultural areas
		23	Confined feeding operations
		24	Other agricultural land
3	Rangeland	31	Herbaceous rangeland
		32	Shrub and brush rangeland
		33	Mixed rangeland
4	Forest land	41	Deciduous forest land
		42	Evergreen forest land
		43	Mixed forest land
5	Water	51	Streams and canals
		52	Lakes
		53	Reservoirs
		54	Bays and estuaries
6	Wetland	61	Forested wetland
		62	Nonforested wetland
7	Barren land	71	Dry salt flats
		72	Beaches
		73	Sandy areas other than beaches
		74	Bare exposed rock
		75	Strip mines, quarries, and gravel pits
		76	Transitional areas
		77	Mixed barren land

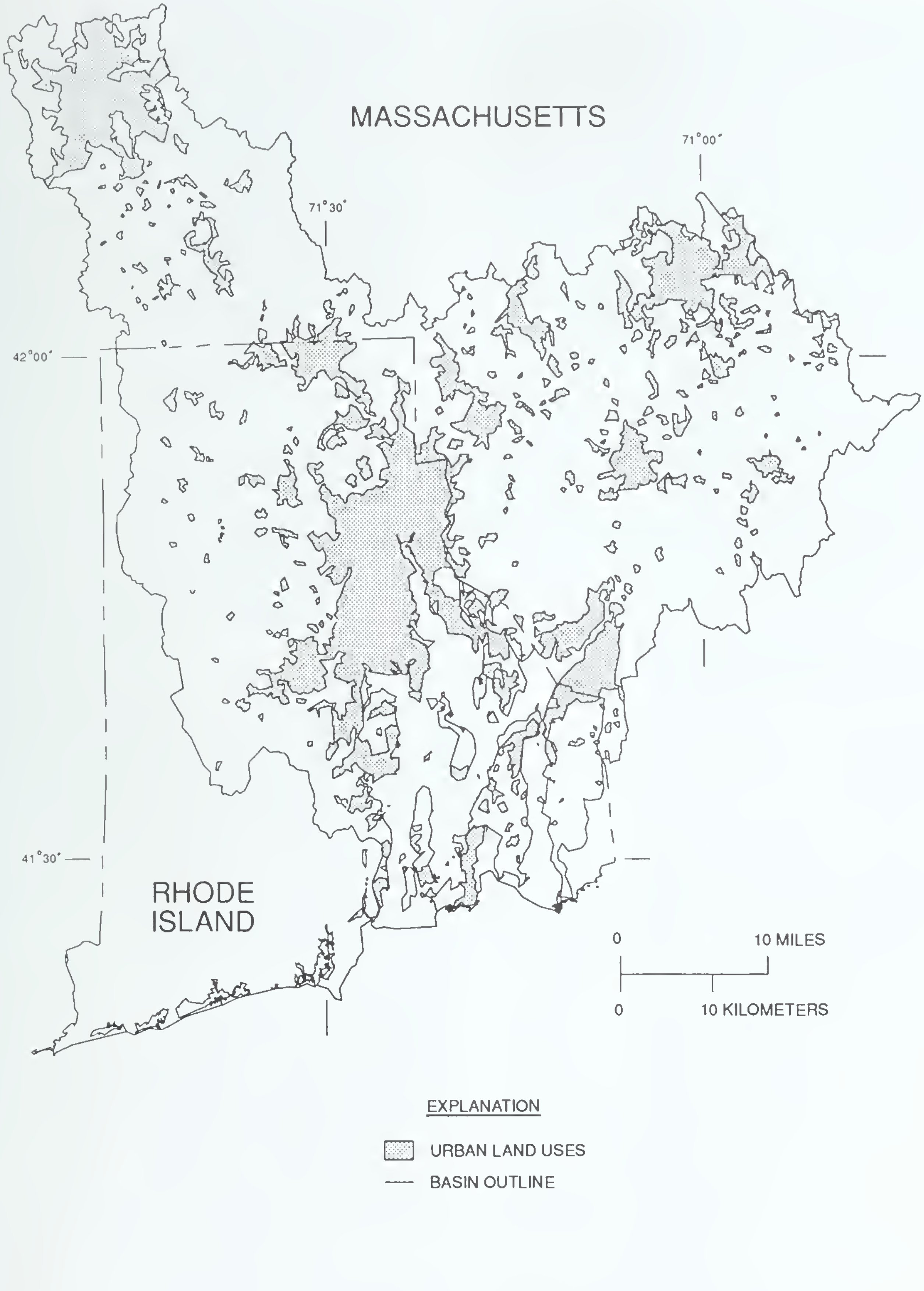

Figure 4.--Distribution of urban-type land use within the Narragansett Bay basin.

land use data compiled during 1980, and digitized at a scale of 1:100,000. The new data base was not available for use during the study period, but should provide a more accurate assessment of urban land use once it becomes available. Although the present GIRAS data base is less accurate than the anticipated revision, it probably provides an adequate relative measure of land use differences between subbasins.

Long-term mean annual and monthly discharge equivalents of precipitation directly onto the bay were computed in the same manner as that used during the study period except long-term precipitation figures were not available for the Newport NWS station. Estimates of precipitation over the bay were obtained by averaging long-term mean precipitation for the years 1951-80 for the Kingston, and Providence, R.I., and the New Bedford, Mass. NWS stations, which were weighted according to Thiessen's method. The NWS long-term precipitation figures and estimates of precipitation on the bay appear in table 5.

ESTIMATES OF SURFACE-WATER RUNOFF TO NARRAGANSETT BAY

Runoff During Water Year 1987

Estimates of the annual and monthly mean runoff to the Basin during the study period are presented in table 6. The table includes data for each gaging station and partial-record site, mouths of rivers, and designated points in ungaged areas, where runoff was measured or estimated. The subbasin for each site has been assigned a four-digit basin code. The first two digits of the basin code indicate the river basin where the site is located. River basin numbers designated by the Rhode Island Department of Environmental Management were used where available, with additional numbers assigned where necessary. The last two digits differentiate sites within the same river basin. Sites are numbered in ascending order according to the distance from the mouth of the river.

Table 6 lists the basin code, site name, location, drainage area, runoff computation method, annual mean runoff, and monthly mean runoff figures for each site. The sites are grouped by major river basins and listed in order of overall river basin size. Sites within each river basin are listed in order of distance from the mouth of the river. Site names for tributary sites appear indented, such that the total runoff for each site includes the entire runoff for any upstream or tributary sites that are indented below it.

Computation methods, explained previously, are indicated for each site in table 6 by the following codes: DA, for the drainage-area ratio method; CM, for Cohn's estimation method; QxQ, for the discharge-versus-discharge method; G, for gaged sites. Annual mean runoff was estimated for each subbasin by weighting the monthly mean runoff estimates by the number of days in the month, summing the weighted estimates, and dividing the sum by 365 days.

Total runoff from the Taunton River basin was estimated by summing the estimated runoff at the mouths of the Quequechan, Assonet, Segregansett, and Threemile Rivers, estimated runoff at the Mill River partial-record site, and the known runoff at the Taunton River gage near Bridgewater, Mass. The drainage-area ratio method was used to estimate flow from the 97.8 mi^2 of intervening drainage area between the mouth of the Taunton River, at the Braga Bridge (Interstate Route I-195) in Fall River, and the summed sites. A basin code was not assigned to the intervening area.

The gaging station on the Wading River at West Mansfield, Mass., was discontinued at the end of the 1986 water year. Runoff for the 1987 water year was not computed at this site. Records from the station were used in the regression analyses to estimate long-term flow from ungaged areas. Long-term flow values for this station are included in table 7, discussed later. The West Mansfield site also is included in table 6, with dashes in the runoff columns, to provide consistency between tables 6 and 7.

Subbasin 0601, indicated on plate 1, consists of all ungaged land areas adjacent to the bay where runoff characteristics cannot be accurately estimated based upon an upstream gaging station or partial-record site. Subbasin 0601 is comprised of several small coastal stream basins, areas adjacent to the bay not drained by streams, ungaged parts of some small river basins, and all of the islands in the bay. Most of the streams within subbasin 0601 are substantially affected by tides, and cannot be measured by normal methods.

The areas included in subbasin 0601 are diverse. Land areas along the western shore of the bay, and a few of the smaller islands, are predominantly composed of coarse-grained stratified drift. The larger islands in the bay, the Bristol area, and land areas along the eastern shore of the bay are primarily composed of till. Attempts to break subbasin 0601 up into smaller geographic areas yields some subbasins that are underlain almost entirely by till and some subbasins that are underlain almost entirely by coarse-grained stratified drift. No gaging stations in the Basin are underlain by either till or coarse-grained stratified drift to the same extent as these small subbasins. Because of this, it is not expected that DA-ratios with individual gaged areas would yield satisfactory results for separated parts of subbasin 0601.

Subbasin 0601, taken as a unit, has percentages of stratified drift, till, and storage that are very close to the mean percentages of these surficial-geologic units for all gaged areas in the Basin. Therefore, it was felt that a reasonably accurate single runoff estimate for subbasin 0601 could be obtained by multiplying the total gaged runoff in the Basin by the ratio of the drainage area of subbasin 0601 to the total gaged drainage area in the Basin.

Indirectly, the DA-ratio estimate for subbasin 0601 at least partially includes the ground-water input from ungaged areas adjacent to the bay that are not drained by streams. The implicit assumption in applying a DA-ratio to these areas is that runoff, which is composed of both overland flow during storm events and ground-water seepage that sustains streamflows (and the bay) during dry periods, is occurring at essen-

Table 5.--*Long-term weighted mean monthly and annual precipitation on Narragansett Bay, Rhode Island, and 1951-1980 precipitation data for National Weather Service stations*

[U.S. Commerce Department, National Oceanic and Atmospheric Administration, 1985-1987]

[Long-term weighted mean precipitation on the bay was computed using a method proposed by Thiessen (1911). Mean precipitation during 1951-1980 (in inches) for each weather station was weighted by the bay area (in square miles, mi^2) indicated in parentheses]

Month	Weather station location			Mean precipitation on the bay (143 mi^2)
	Providence, R.I. (90.4 mi^2)	Kingston, R.I. (50.8 mi^2)	New Bedford, Mass. (1.8 mi^2)	
October	3.75	3.96	3.20	3.82
November	4.22	4.65	4.16	4.37
December	4.47	4.58	4.66	4.51
January	4.06	4.23	4.06	4.12
February	3.72	3.69	3.84	3.71
March	4.29	4.65	4.20	4.42
April	3.95	4.13	3.76	4.01
May	3.48	4.12	3.35	3.70
June	2.79	2.92	2.73	2.84
July	3.01	2.99	2.37	2.99
August	4.04	4.46	4.26	4.19
September	3.54	4.11	3.35	3.74
Mean annual	45.32	48.49	43.94	46.43

Table 6.--*Annual and monthly mean runoff to the*

[Major river basins listed in order of basin size. Indentations indicate subbasin
miles, mi^2; runoff is in cubic feet per second, ft^3/s;

Basin code	Runoff source	Location	Drainage area (mi^2)	Computation method[1]	Annual mean runoff (ft^3/s)
		Taunton River basin			
1201	Taunton River	Mouth (Interstate Route 195)	562	*	1,440
--	Intervening Area	--	97.8	DA	252
1202	Quequechan River	Mouth	30.5	DA	87.4
1203	Assonet River	Mouth	35.1	DA	99.7
1204	Assonet River	Locust Street, Assonet, MA	20.7	CM	59.3
1205	Segreganselt River	Mouth	14.8	DA	42.9
1206	Segreganselt River	near Dighton, MA	10.6	G	30.7
1207	Threemile River	Mouth	85.1	DA	216
1208	Threemile River	North Dighton, MA	84.3	G	214
1209	Wading River	near Norton, MA	43.3	G	96.9
1210	Wading River	West Mansfield, MA	19.5	--	--
1211	Mill River	Whittenton Street, Whittenton, MA	41.1	CM	113
1212	Taunton River	State Farm, near Bridgewater, MA	258	G	634
		Blackstone River basin			
0301	Blackstone River	Mouth (Old Slater Mill dam)	472	DA	1,150
0302	Blackstone River	Lonsdale, RI	441	QxQ	1,070
0303	Blackstone River	Woonsocket, RI	416	G	1,020
0304	Branch River	Forestdale, RI	91.5	G	237
0305	Nipmuc River	near Harrisville, RI	15.9	G	39.5
0306	West River	West Hill Dam, near Uxbridge, MA	27.9	G	62.0
0307	Quinsigamond River	North Grafton, MA	25.6	G	49.6
		Pawtuxet River basin			
0101	Pawtuxet River	Mouth	232	DA	575
0102	Pawtuxet River	Warwick Avenue, Cranston, RI	231	QxQ	573
0103	Pawtuxet River	Cranston, RI	201	G	481
0105	South Branch Pawtuxet River	Washington, RI	62.9	G	156
		Tenmile River basin			
0901	Tenmile River	Mouth	55.4	DA	145
0902	Tenmile River	Pawtucket Avenue, East Providence, RI	53.5	G	140
		Woonasquatucket River basin			
0501	Woonasquatucket River	Mouth	51.9	DA	182
0502	Woonasquatucket River	Valley Street, Providence, RI	47.8	DA	115
0503	Woonasquatucket River	Centerdale, RI	38.2	G	92.1

Narragansett Bay basin during water year 1987

is upstream of, or tributary to, preceding subbasin. Drainage areas are in square dashes indicate data not available or not applicable]

Monthly mean runoff during water year 1987(ft^3/s)											
Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
259	1,200	2,980	2,290	1,160	1,820	4,400	1,680	414	219	120	798
45.0	209	519	399	202	317	766	292	72.1	38.1	20.9	139
10.9	72.9	203	138	53.6	133	249	90.2	22.4	10.7	3.02	58.9
12.5	84.0	224	159	61.8	154	286	104	25.8	12.3	3.47	67.8
7.37	49.5	138	93.9	36.4	90.8	169	61.2	15.2	7.23	2.05	40.0
2.86	37.6	104	61.7	26.5	61.7	148	36.3	3.43	0.88	0.14	30.0
2.05	26.9	74.7	44.2	19.0	44.2	106	26.0	2.46	0.63	0.10	21.5
47.3	174	493	329	156	246	708	242	51.2	28.5	16.4	106
46.9	172	488	326	155	244	701	240	50.7	28.2	16.2	105
18.7	83.0	232	152	67.0	107	323	101	20.4	9.24	4.70	43.4
--	--	--	--	--	--	--	--	--	--	--	--
12.1	104	250	183	72.8	128	344	131	20.2	18.2	5.36	89.7
128	517	1,190	1,020	587	782	1,900	784	219	110	70.6	307
291	910	2,130	1,270	720	1,520	4,120	1,400	474	300	204	377
272	850	1,990	1,190	673	1,420	3,850	1,310	443	280	191	352
247	810	1,930	1,140	637	1,360	3,640	1,260	412	257	172	325
69.0	223	491	253	143	308	877	276	84.5	42.8	23.6	56.6
5.27	33.2	78.2	38.4	25.6	62.8	156	50.1	12.9	5.14	2.16	5.20
7.58	43.1	124	60.2	34.6	87.8	256	82.9	19.5	9.81	5.20	13.0
8.32	29.4	85.1	49.6	27.7	60.2	202	69.8	19.4	13.5	9.44	20.8
151	374	1,260	1,040	537	648	1,530	675	191	154	132	218
150	372	1,250	1,040	535	645	1,520	672	190	153	131	217
126	312	1,050	876	447	541	1,270	562	159	128	109	182
55.1	114	442	252	108	170	370	170	69.4	58.4	32.5	42.0
55.9	126	314	208	106	152	421	152	46.3	31.8	27.0	97.8
54.0	122	303	201	102	147	407	147	44.7	30.7	26.1	94.4
47.9	161	406	228	130	192	643	204	61.4	41.8	27.3	42.7
30.3	102	257	144	82.3	122	407	129	38.8	26.4	17.3	27.0
24.0	81.6	205	115	65.8	97.1	325	103	31.0	21.1	13.8	21.6

Table 6.--*Annual and monthly mean runoff to the*

Basin code	Runoff source	Location	Drainage area (mi^2)	Computation method[1]	Annual mean runoff (ft^3/s)
		Palmer River basin			
1701	Palmer River	Fall River Avenue, North Swansea, MA	47.4	DA	120
1702	Rocky Run	Davis Street, South Rehoboth, MA	7.37	CM	16.4
1703	Palmer River	Reed Street, South Rehoboth, MA	30.9	CM	80.2
		Moshassuck River basin			
0401	Moshassuck River	Mouth	23.7	DA	54.9
0402	Moshassuck River	Providence, RI	23.3	G	53.5
		Hunt River basin			
1301	Hunt River	East Greenwich, RI	22.9	G	62.5
		Small coastal river basins within Narragansett Bay basin			
2101	Cole River	Wilbur Avenue, Swansea, MA	13.4	DA	33.3
2102	Cole River	Hortonville, MA	7.79	CM	19.4
1801	Runnins River	School Street, Seekonk, MA	9.39	DA	21.5
1802	Runnins River	Fall River Avenue, Seekonk, MA	5.92	CM	13.5
1501	Annaquatucket River	Hamilton, RI	6.51	CM	19.2
1401	Maskerchugg River	East Greenwich, RI	5.86	CM	11.2
1601	Old Mill Creek	Warwick, RI	5.40	CM	18.9
		Ungaged area			
0601	Ungaged area	adjacent to bay	169	DA	422
		Adamsville Brook basin**			
2001	Adamsville Brook	Adamsville, R.I.	8.02	CM, G	21.1
		Total runoff to the Narragansett Bay basin			
	Total land area	--	1677	--	4,250
	Additional diversions	--	--	--	90
	Total bay area	--	143	--	515
	Total basin area	--	1820	--	4,860

Narragansett Bay basin during water year 1987--Continued

Monthly mean runoff during water year 1987(ft^3/s)											
Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
8.03	105	304	173	73.3	155	397	111	9.41	1.44	0.95	79.1
1.41	9.32	42.7	25.1	10.2	24.0	52.0	16.8	1.60	0.68	0.21	12.1
5.08	75.1	203	115	49.0	101	269	72.5	6.00	0.48	0.56	51.8
15.2	49.5	135	64.3	33.3	60.8	148	60.2	23.9	17.0	14.2	35.7
14.8	48.2	132	62.7	32.5	59.3	144	58.7	23.3	16.6	13.8	34.8
12.0	56.7	151	106	60.6	89.3	146	72.7	20.9	10.7	7.65	15.5
0.36	33.5	84.2	51.2	17.5	47.4	102	31.3	3.47	0.57	0.27	28.2
0.21	19.5	49.0	29.8	10.2	27.6	59.4	18.2	2.02	0.33	0.16	16.4
2.21	14.5	48.6	34.3	15.5	31.9	66.4	19.9	1.80	1.26	0.48	22.1
1.39	9.13	30.5	21.5	9.74	20.0	41.7	12.5	1.13	0.79	0.30	13.9
10.6	21.7	26.9	22.0	18.2	21.3	36.8	22.0	14.0	11.2	7.87	18.2
1.43	7.77	25.0	16.9	9.72	16.0	30.8	14.6	2.66	3.74	0.50	3.94
12.9	17.3	37.6	19.6	14.6	20.1	38.8	17.2	11.1	8.29	6.46	23.5
95.8	340	827	609	320	526	1,330	492	140	88.4	60.6	194
5.94	31.0	54.1	30.3	16.5	30.0	55.6	20.0	4.45	1.08	0.26	4.40
964	3,420	8,330	6,130	3,220	5,300	13,410	4,950	1,410	889	610	1,950
80	76	77	81	80	78	77	89	114	117	117	90
326	819	964	590	93	610	914	247	195	139	330	941
1,370	4,320	9,370	6,800	3,390	5,990	14,400	5,290	1,720	1,140	1,060	2,980

[1] Computation methods

DA	estimated using drainage-area ratio method with an upstream gaged site.
*	estimated using a summation of runoff in subbasins 1202, 1203, 1205, 1207, 1211, 1212, and DA-ratio method for the intervening area.
**	not part of Narragansett Bay drainage basin October to January estimated using Cohn's method; continuous record thereafter.
CM	estimated using Cohn's regression method (see text, page 8.)
QxQ	estimated using rating curve of measured discharge at an ungaged site versus discharge an upstream gaged site.
G	active gaged site - continuous record.

tially the same rate as runoff from the gaged areas which drain to streams that eventually discharge to the bay. It is possible that additional ground water enters the bay due to underflow beneath rivers entering the bay and upwelling from sources under the bay. Detection and quantification of underflow and upwelling of ground water to the bay would require additional study, and are not within the scope of this report.

The estimates of total monthly mean runoff from land areas within the Basin were computed by summing the known or estimated runoff for each non-indented subbasin listed in table 6. Estimated total annual mean runoff from land areas was computed in the same manner as explained above for the individual subbasins.

Regulations and diversions did not greatly affect estimation of runoff characteristics from ungaged areas and partial-record sites during the study period. Gaging stations chosen as correlating sites for Cohn's estimation method were not highly regulated or diverted.

The gaging station on the West River near Uxbridge, Mass., is located directly below a U.S. Army Corps of Engineers flood-control dam. Streamflow records for this station are adjusted for the change in contents of the reservoir in order to emulate natural flow conditions. The largest monthly change during the study period, an increase of 15.2 ft^3/s during March, results in a difference of about one percent of the monthly discharge at the Blackstone River gaging station at Woonsocket, RI, and is considered negligible.

Streamflow records for the Blackstone and Taunton River gaging stations were adjusted for regulations and diversions to compute natural basin yields for the annual basic data reports published prior to 1975 (U.S. Geological Survey, 1971-1975, 1976-1987). Since 1975 adjustments to the gaging station records for regulations and diversions have not been included in the annual reports. Adjustments for the Blackstone River gage usually resulted in an increase in the annual mean runoff of about 20 to 25 ft^3/s. The annual mean runoff for the Taunton River gage was usually reduced by about 20 to 25 ft^3/s. Assuming that approximately the same pattern still exists, the adjustments amount to 2 to 3 percent of the total annual mean flow in each of the rivers. Because the regulations and diversions in the Taunton and Blackstone River basins are compensating in terms of total natural runoff to the bay, the actual, unadjusted runoff figures were used for both gaging stations.

The total runoff figures for the Narragansett Bay basin were adjusted for diversions from the Pawtuxet and Hunt River basins. The adjustments, which were additions to the total basin runoff, were necessary because most of the water diverted from these river basins is not accounted for by the gaging stations in the Basin. About three-fourths of the diversions from the Scituate Reservoir, in the Pawtuxet River basin, are returned to the Narragansett Bay basin below the gaging stations in the form of effluent from sewage treatment plants. This proportion is based on the latest-available reservoir withdrawal figures for all the cities and towns supplied by the City of Providence, R.I., Water Supply Board (written commun., 1986), which operates the Scituate Reservoir. The reservoir withdrawal figures are for the period July 1, 1984, through June 30, 1985. Because the proportion of diversions received by the individual cities and towns is not likely to vary a great deal over time, the supplied consumption figures were used for both the study period and long-term estimates of the diversions from the Scituate Reservoir that are returned to the Basin in ungaged areas or directly to the bay.

The total adjustments for diversions from gaged areas that are returned to the Basin in ungaged areas or directly to the bay were computed by adding three-fourths of the diversions from Scituate Reservoir during the study period to the average diversions from the Hunt River (about 7.0 ft^3/s). These figures appear as "Additional diversions", near the end of table 6.

Additional adjustments for runoff and diversions from ungaged areas that enter the bay through treatment facilities located within the ungaged areas are not necessary. Estimates of natural yields from these areas are included in the estimated total yield from land areas in the Basin.

Estimates of total runoff to the Basin were computed by summing the individual estimates of total runoff from land areas to the bay. Estimates for diversions from gaged areas that are returned to the Basin in ungaged areas or directly to the bay, and runoff due to precipitation directly onto the bay, were then added to the summed total runoff estimates from land areas.

Long-Term Runoff

Estimates of long-term runoff to the Basin are presented in table 7. The format of table 7 is the same as that for table 6, which was discussed previously, except that there are three additional computation method codes used: R, for regression analyses using basin characteristics as independent variables; DG, discontinued gaged site; and QR, discharge measurement ratio used to estimate runoff at the Old Mill Creek partial-record site, which will be explained below. Cohn's method, CM, was not used to estimate long-term flow.

The final regression equations used to estimate long-term mean monthly and annual runoff from land areas in the basin are listed in table 8, with smearing estimates, Sm, adjusted coefficients of determination, R^2_{adj} , averages of the absolute values and standard errors of the percentage errors of the predictions, $|e_i|$ and s, respectively.

Initial stepwise regressions predicting runoff characteristics were run using drainage area, areal percentages of stratified drift, till, storage (lakes, reservoirs, and swamps), and urban land use, stream lengths, and stream slopes, as the independent variables to be tested. Several of the variables were highly correlated, causing unstable initial results. Drainage area was always present in the initial equations, but small changes in the specified significance levels yielded large changes in the variables that appeared in the regression equations.

New variables were created by combining some of the original variables in order to eliminate some of the high correlation problems, and the stepwise regressions were rerun. The variables entered into the new analyses were the total area of till, A (in mi^2), combined total area of stratified drift and storage, A_{SDS} (in mi^2), percentage of area of urban land use, $\%A_U$, stream length, SL (in mi), and stream slope, SS (in ft/mi). The area of till added to the combined total area of stratified drift and storage equals the total drainage area for each of the stations in the regressions. Combining the areas of stratified drift and storage was considered appropriate because both of these surficial features tend to reduce flood peaks and sustain river flow during dry periods. Stream length and stream slope were not found significant in the new analyses, and were not included in the final equations.

Thirteen gaging stations were used in the final regressions:

Adamsville Brook at Adamsville, R.I
    (discontinued)
Branch River at Forestdale, R.I.
Hunt River near East Greenwich, R.I.
Moshassuck River at Providence, R.I
Nipmuc River near Harrisville, R.I.
Quinsigamond River at North Grafton, Mass.
Segregansett River near Dighton, Mass.
South Branch Pawtuxet River at Cranston, R.I.
Threemile River at North Dighton, Mass.
Wading River near Norton, Mass.
Wading River at West Mansfield, Mass.
    (discontinued)
West River below West Hill Dam,
    near Uxbridge, Mass.
Woonasquatucket River at Centerdale, R.I.

The periods of record for these gaging stations ranged from 21 to 62 years, with a mean record length of 38 years. The gaging stations were corrected for long-term average regulations and diversions where necessary to simulate natural runoff characteristics.

The three gaging stations with the largest drainage areas in the Basin: the Blackstone River at Woonsocket, R.I., the Pawtuxet River at Cranston, R.I., and the Taunton River near Bridgewater, Mass., were not used in the regressions because their records could not be adequately corrected for regulations and diversions. This resulted in a loss in the range of areas in which the models can be confidently applied. The drainage area of the largest station remaining in the regressions, the Branch River at Forestdale, R.I., is 91.5 mi^2.

Subbasin 0601 has a total drainage area of 169 mi^2, with till areas and combined areas of stratified drift and storage larger than those for any of the stations used in the regressions. As discussed previously, this area is mainly composed of many individual small subbasins, including all islands, that drain directly to the bay. Separating subbasin 0601 into smaller geographic areas would produce subbasins that are composed almost entirely of a single surficial-geologic unit. There are no comparable gaging stations used in the regression analyses. Because the proportions of the surficial-geologic units for subbasin 0601 are very similar to the means of the proportions for the gaging stations used in the regressions, the regression equations should produce acceptably accurate estimates for subbasin 0601.

Some of the small coastal river basins adjacent to the bay that were not part of subbasin 0601 had basin characteristic values (areas of till, storage, or percentage of urban land use) that were outside the ranges of those for any of the stations used in the regression analyses. The regression equation estimates for the sites were carefully checked to determine whether their use was acceptable. The mean annual runoff per square mile [$(ft^3/s)/mi^2$], was calculated for all estimated sites and compared with the runoff per square mile for the gaged sites in the Basin. In addition, the

Table 7.--*Long-term mean annual and*

[Major river basins listed in order of basin size. Indentations indicate subbasin
miles, mi^2; runoff is in cubic feet per second, ft^3/s;

Basin code	Runoff source	Location	Drainage area (mi^2)	Computation method[1]	Mean annual runoff (ft^3/s)
		Taunton River basin			
1201	Taunton River	Mouth (Interstate Route 195)	562	*	1,050
	Intervening Area	--	97.8	R	169
1202	Quequechan River	Mouth	30.5	R	63.2
1203	Assonet River	Mouth	35.1	R	71.6
1204	Assonet River	Locust Street, Assonet, Mass.	20.7	R	43.4
1205	Segregansett River	Mouth	14.8	DA	32.0
1206	Segregansett River	near Dighton, Mass.	10.6	G	22.9
1207	Threemile River	Mouth	85.1	DA	174
1208	Threemile River	North Dighton, Mass.	84.3	G	172
1209	Wading River	near Norton, Mass.	43.3	G	73.6
1210	Wading River	West Mansfield, Mass.	19.5	DG	32.5
1211	Mill River	Whittenton Street, Whittenton, Mass.	41.1	R	78.1
1212	Taunton River	State Farm, near Bridgewater, Mass.	258	G	466
		Blackstone River basin			
0301	Blackstone River	Mouth	472	DA	862
0302	Blackstone River	Lonsdale, R.I.	441	QxQ	807
0303	Blackstone River	Woonsocket, R.I.	416	G	770
0304	Branch River	Forestdale, R.I.	91.5	G	173
0305	Nipmuc River	near Harrisville, R.I.	15.9	G	30.7
0306	West River	West Hill Dam, near Uxbridge, Mass.	27.9	G	48.9
0307	Quinsigamond River	North Grafton, Mass.	25.6	G	41.4
		Pawtuxet River basin			
0101	Pawtuxet River	Mouth	232	DA	414
0102	Pawtuxet River	Warwick Avenue, Cranston, R.I.	231	QxQ	412
0103	Pawtuxet River	Cranston, R.I.	201	G	346
0105	South Branch Pawtuxet River	Washington, R.I.	62.9	G	130
		Tenmile River basin			
0901	Tenmile River	Mouth	55.4	R	108
0902	Tenmile River	Pawtucket Avenue, East Providence, R.I.	53.5	R	105
		Woonasquatucket River basin			
0501	Woonasquatucket River	Mouth	51.9	DA	99.6
0502	Woonasquatucket River	Valley Street, Providence, R.I.	47.8	DA	91.7
0503	Woonasquatucket River	Centerdale, R.I.	38.2	G	73.3

monthly runoff to the Narragansett Bay basin

is upstream of, or tributary to, preceding subbasin. Drainage areas are in square
dashes indicate data not available or not applicable]

Long term mean monthly runoff (ft³/s)											
Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
477	864	1,280	1,420	1,510	2,090	1,900	1,180	783	366	332	343
82.9	125	189	213	219	312	296	186	137	62.9	57.4	52.9
28.2	49.8	75.2	78.1	83.2	114	106	70.3	48.3	22.0	20.7	19.5
32.4	55.4	84.5	106	110	154	137	78.9	54.5	18.6	17.2	15.1
18.9	33.9	52.8	67.4	69.6	96.2	83.2	47.3	31.3	9.50	9.06	7.76
12.7	30.3	46.9	48.3	49.1	64.1	53.6	33.4	22.5	7.01	7.69	7.83
9.07	21.7	33.6	34.6	35.2	45.9	38.4	23.9	16.1	5.02	5.51	5.61
74.9	139	231	240	246	339	311	194	148	54.5	56.1	49.7
74.2	138	229	238	244	336	308	192	147	54.0	55.6	49.2
29.5	59.9	91.3	101	105	157	137	82.6	53.0	24.8	21.4	21.5
14.1	25.5	40.4	46.0	48.5	67.6	61.6	37.9	24.3	8.75	8.71	7.22
35.9	58.4	91.5	109	112	156	140	84.0	57.7	21.0	20.0	17.5
210	406	559	621	686	948	853	529	315	180	153	180
451	713	952	1,060	1,100	1,690	1,600	973	706	389	349	385
422	667	890	990	1,030	1,580	1,500	910	660	364	326	360
393	631	848	950	993	1,540	1,440	871	623	336	300	332
87.4	150	209	225	240	346	320	200	134	57.9	53.8	62.8
10.5	24.3	39.5	43.4	45.5	65.4	60.8	35.8	24.8	7.57	5.76	4.52
15.8	36.7	57.2	58.9	73.0	107	102	55.4	46.3	15.6	10.2	8.48
18.7	32.1	43.5	47.9	54.0	79.6	78.3	52.0	39.3	20.4	17.0	15.4
223	309	477	546	583	698	703	472	337	205	211	217
222	308	475	542	580	695	700	470	335	204	210	216
185	264	397	450	481	587	590	394	280	171	175	181
69.5	95.3	154	168	177	229	215	152	113	64.4	62.4	64.3
50.8	82.1	124	130	136	189	180	119	84.7	41.1	38.4	36.1
49.3	80.2	121	127	133	185	175	116	82.6	40.0	37.3	35.1
49.9	76.2	111	126	141	194	179	117	77.6	44.2	39.1	41.4
45.8	69.7	102	115	130	179	165	108	71.4	40.7	36.0	38.2
36.6	55.7	81.6	92.0	104	143	132	86.3	57.1	32.5	28.8	30.5

Table 7.--*Long-term mean annual and*

Basin code	Runoff source	Location	Drainage area (mi²)	Computation method[1]	Mean annual runoff (ft³/s)
		Palmer River basin			
1701	Palmer River	Fall River Avenue, North Swansea, Mass.	47.4	R	94.1
1702	Rocky Run	Davis Street, South Rehoboth, Mass.	7.37	R	16.3
1703	Palmer River	Reed Street, South Rehoboth, Mass.	30.9	R	63.6
		Moshassuck River basin			
0401	Moshassuck River	Mouth	23.7	DA	41.9
0402	Moshassuck River	Providence, R.I.	23.3	G	41.2
		Hunt River basin			
1301	Hunt River	East Greenwich, R.I.	22.9	G	46.4
		Small coastal river basins within the Narragansett Bay basin			
2101	Cole River	Wilbur Avenue, Swansea, Mass.	13.4	R	28.7
2102	Cole River	Hortonville, Mass.	7.8	R	17.1
1801	Runnins River	School Street, Seekonk, Mass.	9.4	R	18.7
1802	Runnins River	Fall River Avenue, Seekonk, Mass.	5.9	R	12.8
1501	Annaquatucket River	Hamilton, R.I.	6.5	DG	18.5
1401	Maskerchugg River	East Greenwich, R.I.	5.9	R	11.6
1601	Old Mill Creek	Warwick, R.I.	5.4	QR	15.8
		Ungaged area			
0601	Ungaged area	adjacent to bay	169	R	319
		Adamsville Brook basin**			
2001	Adamsville Brook	Adamsville, R.I.	8.02	DG	14.3
		Total runoff to the Narragansett Bay basin			
	Total land area	--	1677	--	3,130
	Additional diversions	--	--	--	83
	Total bay area	--	143	--	479
	Total basin area	--	1820	--	3,690

monthly runoff to the Narragansett Bay basin --Continued

Long term mean monthly runoff (ft^3/s)											
Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
43.7	72.0	109	133	137	194	176	104	73.1	27.3	25.1	22.4
6.53	12.9	21.0	26.9	27.8	37.2	30.5	17.4	10.5	2.65	2.69	2.21
28.5	49.4	75.6	90.7	94.3	131	117	70.0	47.8	17.2	16.1	14.3
22.5	37.6	53.5	54.1	55.8	70.3	68.2	46.1	35.0	19.7	19.9	20.2
22.1	37.0	52.6	53.2	54.9	69.1	67.0	45.3	34.4	19.4	19.6	19.9
17.9	35.7	53.4	62.4	71.4	88.6	83.0	60.6	38.7	17.7	15.1	13.5
12.0	22.4	35.8	40.2	42.2	56.7	49.3	30.9	19.7	6.74	6.69	5.87
6.86	13.7	22.1	28.2	29.4	39.5	32.6	18.6	11.3	2.93	2.92	2.43
7.66	13.9	23.8	24.2	25.0	32.9	28.2	19.1	11.5	4.04	4.35	3.74
5.06	9.87	16.7	17.7	18.4	24.0	20.1	13.3	7.78	2.48	2.66	2.27
14.7	20.6	21.6	23.0	20.8	24.7	27.4	19.4	14.9	12.0	10.2	12.3
4.44	9.91	15.4	13.8	15.5	19.7	17.6	13.0	7.85	3.46	3.50	3.35
12.6	17.7	18.5	19.7	17.8	21.2	23.5	16.6	12.8	10.3	8.75	10.5
162	257	346	349	380	546	566	382	308	205	169	177
5.57	13.6	19.5	20.7	23.5	29.2	23.2	17.2	8.84	3.35	3.91	3.83
1,550	2,530	3,620	4,000	4,240	5,920	5,600	3,550	2,470	1,350	1,230	1,290
100	77	75	76	75	75	76	83	95	100	94	87
474	560	559	511	509	548	514	459	364	371	520	479
2,120	3,170	4,250	4,590	4,820	6,540	6,190	4,090	2,930	1,820	1,840	1,860

[1]Computation methods

*	estimated using a summation of runoff in subbasins 1202, 1203, 1205, 1207, 1211, 1212, and intervening area.
**	not part of Narragansett Bay basin - used in regression analyses.
DA	estimated using drainage area ratio method with an upstream gaged site.
G	active gaged site - continuous record.
R	estimated using regression equations.
QR	estimated using ratio of concurrent measured discharges at Old Mill Creek and Annaquatucket River times long term monthly mean runoff at Annaquatucket River.
QxQ	estimated using rating curve of measured discharge at an ungaged site versus discharge at an upstream gaged site.
DG	discontinued gaged site.

Table 8.-- *Summary of regression equations used to estimate long-term mean monthly and mean annual runoff*

Period	Regression equation	Sm_x	R^2_{adj}	$\lvert\bar{e}_i\rvert$	s
October	$\hat{Q}_{10} = (1.670 A_T^{0.487} A_{SDS}^{0.546})\ Sm_{10}$	1.01072	95.8	12.6	16.6
November	$\hat{Q}_{11} = (3.706 A_T^{0.532} A_{SDS}^{0.420})\ Sm_{11}$	1.01026	95.1	12.5	15.1
December	$\hat{Q}_{12} = (3.424 A_T^{0.433} A_{SDS}^{0.456})\ Sm_{12}$	1.01180	94.1	12.0	16.5
January	$\hat{Q}_1 = (8.004 A_T^{0.401} A_{SDS}^{0.527} \%A_U^{-0.0813})\ Sm_1$	1.00566	97.0	9.3	11.1
February	$\hat{Q}_2 = (8.331 A_T^{0.441} A_{SDS}^{0.486} \%A_U^{-0.0717})\ Sm_2$	1.00478	97.4	8.3	10.1
March	$\hat{Q}_3 = (10.697 A_T^{0.451} A_{SDS}^{0.510} \%A_U^{-0.0805})\ Sm_3$	1.00259	98.7	6.0	7.4
April	$\hat{Q}_4 = (8.248 A_T^{0.508} A_{SDS}^{0.501} \%A_U^{-0.0613})\ Sm_4$	1.00159	99.2	4.7	5.7
May	$\hat{Q}_5 = (4.807 A_T^{0.533} A_{SDS}^{0.452})\ Sm_5$	1.00446	98.0	8.2	9.6
June	$\hat{Q}_6 = (2.601 A_T^{0.602} A_{SDS}^{0.471})\ Sm_6$	1.00512	98.0	8.4	10.7
July	$\hat{Q}_7 = (0.547 A_T^{0.818} A_{SDS}^{0.393} \%A_U^{0.127})\ Sm_7$	1.00907	97.0	9.7	13.8
August	$\hat{Q}_8 = (0.594 A_T^{0.736} A_{SDS}^{0.406} \%A_U^{0.136})\ Sm_8$	1.02072	92.8	17.2	22.2
September	$\hat{Q}_9 = (0.466 A_T^{0.817} A_{SDS}^{0.360} \%A_U^{0.163})\ Sm_9$	1.02778	90.4	20.4	29.3
Mean annual	$\hat{Q}_{Year} = (4.665 A_T^{0.464} A_{SDS}^{0.491})\ Sm_{Year}$	1.00376	98.6	6.9	9.2

NOTES

$\hat{Q}_x$ Estimated mean runoff for period x, in cubic feet per second.

$\%A_U$ Subbasin areal percentage of urban land use.

R^2_{adj} Coefficient of determination adjusted for the number of stations in the regression.

$\lvert\bar{e}_i\rvert$ Mean absolute percentage error of predictions in normal space;
$\lvert\bar{e}_i\rvert = (\mathrm{sum}[\lvert(\hat{Q}_i - Q_i)/Q_i\rvert]/N) \times 100$,
where i = 1, . . . , N, and N = 13, the number of stations used in the regression.

s Standard error of estimate, in percent.

A_T Subbasin total area of till, in square miles.

A_{SDS} Subbasin total area of stratified drift and storage (lakes and swamps), in square miles.

Sm_x Smearing estimate for month x,
$= \mathrm{sum}[\exp(\varepsilon_i)]/N$, where $\varepsilon_i =$ log space regression residuals for i = 1, . . . , N,
and N = 13, the number of stations used in the regression.

mean runoff per square mile calculated from all discharge measurements made during the study period at each of the partial-record sites was compared to the mean runoff per square mile calculated from the concurrent discharges for each gaged site. These comparisons indicated that, in most instances, use of the regression equations yielded reasonable estimates of long-term runoff in the small coastal basins.

The mean runoffs per square mile for discharge measurements made at the Annaquatucket River and Old Mill Creek partial-record sites were greater than those for all other sites in the Basin. The discharge measurements also exhibited less variability than for most other sites, probably because their basins are relatively flat and their underlying sediments are composed primarily of course-grained sand. The regression equations appeared to underestimate long-term runoff for the two sites, and the regression estimates were not used. Both of the sites have basin-characteristic values that are outside the ranges of those used in the regressions.

The Annaquatucket River site was operated as a continuous-record station during the 1962-64 water years. The site was not used in the final regression analyses because of the short length of record available. Values for the site appeared as outliers when included in earlier trial regression analyses. Runoff throughout the Basin during 1962 was normal, whereas 1963 and 1964 were drought years. Basin-wide runoff during the study period was higher than normal. The 1962-64 water year monthly mean flows were averaged with the study period estimates to obtain long-term flow estimates for the Annaquatucket River. These estimates appear to be more reasonable than the regression equation estimates, which are lower, and are probably more accurate than estimates obtained using the drainage-area ratio method.

An attempt was made to improve the long-term Annaquatucket River estimates by computing averages of the ratios of the combined 1962-64 and 1987 water year means to the long-term means for the gaged sites in the Basin, and multiplying the 4-year means for the Annaquatucket River site by the computed averaged ratios. This method produced monthly estimates for July and September that were greater than the estimates for March and April; a condition which is highly unlikely in this area of the country. As a result, the 4-year averages were used for the long-term estimates.

Regression equation estimates for Old Mill Creek were much less than expected. The Old Mill Creek basin is composed almost entirely of sand, and is highly urbanized. These characteristics are unlike those for any of the sites used in the regression analyses. The study period discharge measurements indicate that runoff from Old Mill Creek is most similar to runoff characteristics for the Annaquatucket River site. Old Mill Creek runoff was estimated by multiplying the long term monthly mean flow estimates at Annaquatucket River by the ratio of the means of the concurrent discharge measurements made during the study period at the two sites. This method partially accounts for differences in the runoff per square mile between the two sites, and is likely to be more accurate than using a simple drainage-area ratio method.

The QxQ method was used to estimate long-term mean runoff for the partial-record sites located on the Blackstone and Pawtuxet Rivers. The drainage areas of the two sites are much larger than the drainage areas of any of the gaging stations used in the regression analyses. The DA-ratio method was used to compute runoff between the furthest downstream gage or partial-record site and the mouths of the Blackstone, Pawtuxet, Threemile, Segregansett, Woonasquatucket, and Moshassuck Rivers. The results obtained using the QxQ and DA-ratio methods should be superior to those obtained from the regression equations. Ungaged areas comprise only 14 percent, on average, of the total areas of the above-named river basins.

Additions to the estimated total long-term mean monthly and annual runoff from land areas in the Basin for diversions from the Scituate Reservoir and the Hunt River basin were estimated in the same manner as was used during the study period. The diversion estimates and estimates of runoff due to precipitation directly onto the bay, both of which appear near the bottom of table 7, were then added to the summed total estimates of runoff from land areas in the Basin to obtain estimates of the total long-term runoff to the Basin.

Accuracy of Runoff Estimates

Study Period

Study-period annual mean runoff at most gaging stations in the Basin was in the highest 25 percent of recorded annual means. Monthly means at most gaging stations also exhibited unusually large fluctuations from normal.

Runoff at the Wading River at Norton, Mass. gaging station is typical of the Basin response during the 1987 water year. The study period annual mean runoff at the Wading River gaging station was the eighth highest of 62 years of record. Monthly mean runoff for December, January, April, and September was in the highest 25 percent of recorded monthly means for the gaging station, with a new record high April mean flow. Mean runoff for the months of February, March, and June through August, was in the lowest 25 percent of recorded monthly means. In comparison, annual mean runoff for the 1986 water year was forty-eighth highest of record, with three monthly means in the highest 25 percent of record and three monthly means in the lowest 25 percent of record.

Figure 5 is a plot of record high, record low, long-term mean monthly, and study period monthly mean runoff for the Wading River gage. The daily hydrograph is also included to illustrate the variations of daily discharges during the period.

Tests of the estimation methods of Cohn, and Riggs, and the DA-ratio method were performed using data from gaged sites within the Basin. The Riggs method estimates were used in these tests as a frame of reference for comparing the methods, since Riggs' method has been shown to adequately estimate the annual mean runoff in the studies mentioned previously. Although the tests are not a rigorous measure of reliability, they provide an empirical measure of the comparability of the methods and an indication of their performance for purposes of this study. The tests were performed by selecting a gaging station to represent an ungaged or partial-record site and using a second gaging station as the index site for correlation. Records of daily discharges on the fifteenth of each month during a water year were considered as discharge measurements at the assumed ungaged or partial-record test site for both Cohn's and Riggs' methods. The discharges for the assumed ungaged site were then related to the concurrent daily discharges at the gaged index site according to the requirements of the individual methods. Each test produced an estimate of annual mean runoff and 12 estimates of monthly mean runoff for the test site.

The estimates obtained using the techniques of Cohn and Riggs, and those obtained using the DA-ratio method, were compared to the known monthly and annual mean runoff for the test site and the percentage errors of the estimates were computed. Twelve tests of Cohn's method, 11 tests of Riggs' method, and 18 tests of the DA-ratio method were performed using data for water years 1984-87. Of these, 12 tests were common (used the same gaging stations and water year) to Cohn's method and the DA-ratio method. Eleven tests were common to Riggs' method and the DA-ratio method, and five tests were common to all three methods. The means of the absolute errors (absolute differences between the known and estimated values, in percent) of all the estimates made using each method were computed. In addition, the means of the absolute errors of all the estimates that were common to the three methods, and that were common to each pair of methods (Cohn's-method tests were compared with the 12 common DA-ratio method tests, and so forth) were also computed. In general, the means of the absolute errors obtained for the common tests did not differ substantially from the means of the absolute errors obtained for all tests of each method. Figure 6 shows bar-graphs comparing all tests of the three methods.

The comparisons indicate that each of the methods works reasonably well in estimating annual mean runoff. The mean absolute error of the annual mean runoff estimates was about 7 percent for Cohn's method, about 10 percent for Riggs' method, and about 12 percent for the DA-ratio method.

The comparisons also indicate that estimates of monthly mean runoff are not as accurate as the estimates of annual mean runoff. The accuracies of the estimates of monthly mean runoff determined from the three methods (fig. 6), compared using the means and standard deviations of the absolute errors, in percent, were: for Cohn's method, 13 and 11 percent; for Riggs' method, 30 and 35 percent, and for the DA-ratio method, 40 and 86 percent, respectively. The worst absolute errors of the estimates of monthly mean runoff were 40 percent (Cohn), 80-90 percent (Riggs), and substantially greater than 100 percent (DA-ratio).

Wilcoxon-Mann-Whitney ranked-sum tests were performed to determine whether the observed differences in the overall mean absolute errors of the computation methods were statistically significant. The ranked sum tests do not require equal sample sizes for comparison. The results indicated that there was no statistical difference between Cohn's and Riggs' methods for estimating annual mean runoff. Both Cohn's and Riggs' methods were statistically better than the DA-ratio method (at levels of significance of $\alpha = 0.03$, and $\alpha = 0.10$, respectively) at estimating the annual mean runoff. Cohn-method average monthly mean runoff estimates and average worst monthly mean runoff estimates were superior to Riggs' method and the DA-ratio method at levels of significance of $\alpha = 0.02$, or less. Riggs' method appeared to be better at estimating monthly mean runoff than the DA-ratio method, but the difference was not statistically significant. Larger sample sizes probably would show that Riggs' method is superior.

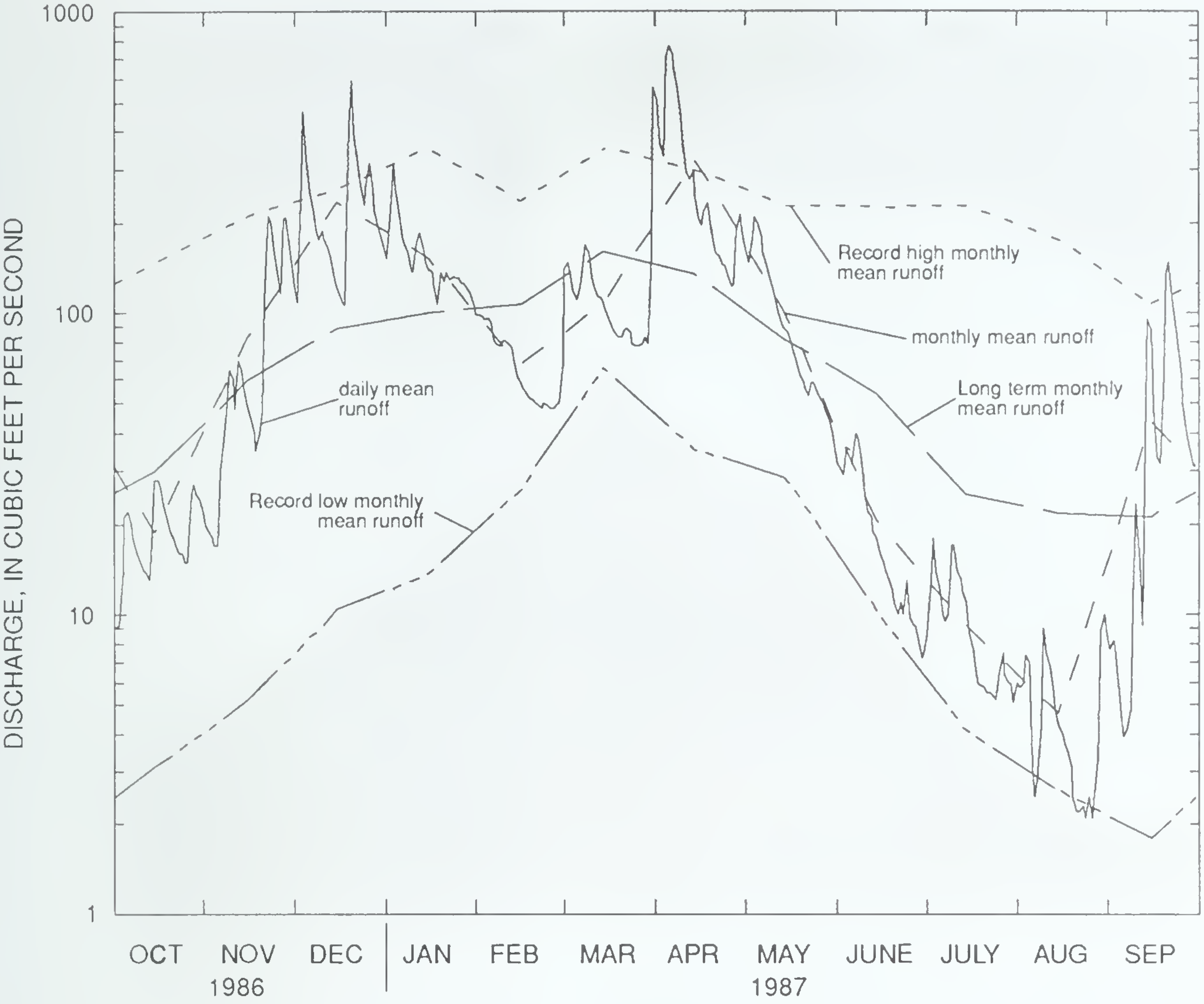

Figure 5. -- Daily mean and monthly mean runoff at U.S. Geological Survey gaging station 01109000, Wading River near Norton, Mass. 1987 water year with long-term statistics plotted for comparison.

The Cohn-method and DA-ratio method tests made with 1986 water year data were compared with study period tests using Wilcoxon-Mann-Whitney ranked sum tests. The tests revealed no significant differences between the 1986 water year and study period errors using either of the methods. This indicates that the unusually large variability in runoff during the study period did not affect the quality of the runoff estimates to a great extent.

Cohn's method was used to estimate runoff from 7.2 percent of the total Basin area, which also contributed 7.2 percent of the estimated total annual mean runoff to the Basin. Cohn's method is the only method of the three discussed that provides reasonably good estimates of monthly mean flow for ungaged basins. The largest error of estimated monthly mean flow for all tests, based on a total of 144 individual estimates, was -51.0 percent. The method appears to have no significant overall bias when all of the tests are taken as a whole. Of the twelve estimates of mean annual flow, half were greater and half were less than actual, with a range of -14.2 to +13.7 percent. The bias and accuracy of estimates for individual ungaged sites is highly dependent on the suitability of the chosen correlating gaged site. Most estimates of monthly runoff at an individual ungaged site may be either underestimated or overestimated, depending upon the gaged site chosen for correlation.

Twelve of the 18 DA-ratio-method tests estimated runoff characteristics from sites located in separate river basins from the estimating sites. The remaining six tests estimated runoff characteristics for sites located on the same river either upstream or downstream from the gaged estimating sites. The results of these six tests were significantly better than those for the 18 tests as a whole, with an estimate of mean annual runoff within 6 percent of actual. The mean absolute error of the monthly estimates for the six tests was 23 percent, with a standard deviation of 29 percent, and average worst absolute error for each test of 62 percent.

The DA-ratio method was used to estimate runoff from 21.3 percent of the total Basin area during the study period. Of the total Basin area, 9.1 percent was estimated using the DA-ratio method for sites located downstream from gaging stations. Estimates for this area are considered to be similar to estimates for the six tests with assumed ungaged sites located either upstream or downstream from a gaged site. The assumed ungaged sites in the six tests had drainage areas that were, on average, about 4.5 times larger or smaller

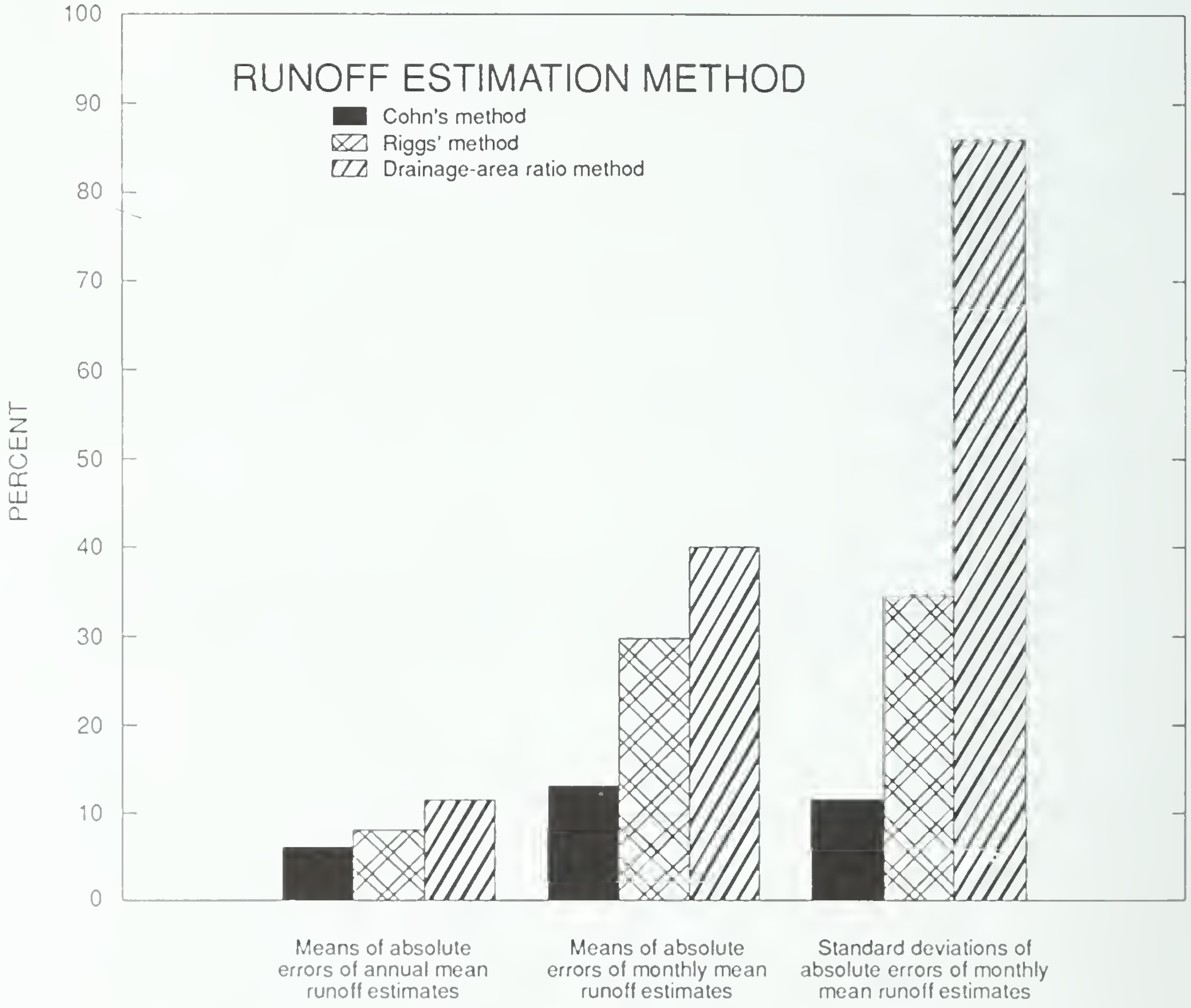

Figure 6. --Accuracies of annual and monthly mean runoff estimates obtained using Cohn's, Riggs', and the drainage-area ratio methods based on tests using data from gaging stations located within the Narragansett Bay Basin.

than the gaged sites used for estimating runoff. In contrast, the drainage areas of the ungaged sites estimated for the study were on average only about 1.5 times larger than their upstream gaged sites. Because the proportion of the drainage areas being estimated below the gaged sites during the study period is much less than those used in the tests, the study-period errors should be smaller than those for the tests. The average error of estimates of annual mean flow from ungaged areas below gaging stations should be within about 5 percent, whereas most estimates of monthly mean flow should be within about 15 to 20 percent of actual. These estimates comprised 9.2 percent of the estimated total annual mean runoff to the Basin. The DA-ratio method estimates of runoff from separate ungaged subbasins probably have accuracies similar to those observed for the 18 DA-ratio tests as a whole, and comprised 12.2 percent of the estimated total annual mean runoff to the Basin.

No rigorous measure of the reliability of the discharge-versus-discharge method of estimating runoff at a partial-record site located below a gaged site is available. The accuracy of the QxQ relation curve is a function of the accuracy of the discharge ratings for each of the sites, and the degree of correlation between the sites. However, because the proportions of the river basins that were estimated using this method are small, the error in the total should remain relatively small. The drainage areas of the Blackstone River and Pawtuxet River partial-record sites are 1.06 times, and 1.15 times the drainage areas of their respective upstream gaging stations. The QxQ estimates were applied to 3.0 percent of the total Basin area, contributing 2.9 percent of the estimated total annual mean runoff to the Basin. These estimates should be at least as good as the DA-ratio estimates used in the study for the ungaged sites located below gaging stations.

Study-period estimates of adjustments to the total basin yield for diversions comprise 2.0 percent of the estimated total annual mean runoff to the Basin. Runoff equivalents of precipitation on the bay comprise 10.6 percent of the estimated total annual mean runoff to the Basin. Annual runoff estimates derived from these two sources are probably within about 20 percent of actual. The monthly estimates are considered to be within about 30 percent of actual.

The estimates of the total annual and monthly mean runoff during the study period obtained using the methods explained above are estimated to be within about 10 percent and 20 percent of actual, respectively. These accuracy figures were obtained by (1) multiplying the estimated accuracy reported above for each runoff estimation technique by its proportion of the estimated total runoff to the Basin, (2) summing the weighted accuracies, (3) dividing by 100 to obtain percent, and (4) rounding to the next highest 5 percent. A mean error of 5 percent was assumed for all gaging-station records. This assumed error was also added to the estimated accuracy of each technique used to estimate runoff from land areas in the Basin prior to weighting. It was necessary to weight the estimation methods by the proportion of the total Basin runoff rather than the proportion of the total Basin area because a drainage area cannot be directly attributed to runoff derived from diversions from gaged areas that are released to the Basin in ungaged areas.

Estimates of annual mean runoff for ungaged sites are likely to be more reliable than estimates for individual months. Additionally, estimates of runoff for the entire basin are likely to be more reliable than estimates of runoff for individual ungaged sites. This is true because errors in a mean tend to decrease with increasing time periods and additional data (Winter, 1981).

Long-Term Runoff Estimates

The final equations shown in table 8 provided 156 estimates of long-term mean monthly runoff and 13 estimates of long-term mean annual runoff for the gaging stations in the regressions. The standard errors of the regression equations used for estimating mean monthly runoff ranged from 6 to 29 percent (see table 8), and the average was about 15 percent. Errors in individual estimates obtained for the gaged sites used in the regressions ranged from -30.9 percent to +78.5 percent, with only two estimates in error by greater than 40 percent. The regression equation used to estimate long-term mean annual runoff yielded an mean absolute error and standard error of 6.9 percent and 9.2 percent, respectively.

The means of the absolute values of the estimation errors obtained from the monthly regression equations ranged from a low of 4.7 percent in April, to a high of 20.4 percent in September, with standard errors of 5.7 percent and 29.3 percent, respectively. The equations for months of relatively high flow generally had regression statistics that were superior to those for low-flow months.

The regression equations were used to estimate runoff from ungaged areas comprising 27.7 percent of the total Basin area. These ungaged areas accounted for 26.1 percent of the estimated total mean annual runoff to the Basin. Runoff estimates that were obtained from the regression equations for the ungaged areas probably have somewhat higher errors than those indicated in table 8 for the stations used in the regressions.

Methods of estimating long-term mean annual and monthly runoff for the Annaquatucket River and Old Mill Creek sites, which together comprise 0.7 percent of the total Basin area, and 0.9 percent of the estimated total mean annual Basin runoff, were discussed previously. The annual estimates for the two sites are likely to be accurate within 25 percent, whereas monthly estimates are probably accurate within 50 percent.

Long-term estimates of runoff from ungaged areas using the DA-ratio method and the QxQ method, adjustments to the total basin yield for diversions, and runoff equivalents of precipitation on the bay should be more accurate than similar estimates for the study period. This is because of the reduction of error in a mean value with increasing amounts of data, as discussed previously. The DA-ratio and QxQ methods were used to estimate runoff from 5.8 percent of the Basin area, which contributed 5.4 percent of the estimated total mean annual runoff to the Basin. Most DA-ratio and QxQ method estimates of long-term mean annual and monthly runoff should be accurate to within about 5 percent and 15 percent, respectively for both methods. Annual adjustments to the total Basin yield for diversions and for runoff equivalents of precipitation on the bay are probably within about 15 percent of actual. Monthly runoff estimates are probably within about 25 percent. Diversions and runoff equivalents of precipitation on the bay respectively contributed 2.2 percent and 13.0 percent of the estimated total mean annual runoff to the Basin.

Estimates of the total long-term mean annual runoff to the Basin obtained using the methods explained above are considered to be within about 10 percent of actual. The estimates of the total long-term mean monthly runoffs to the Basin are considered to range from within about 10 percent of actual for April, to within about 15 percent of actual for September. These estimates were obtained by weighting each estimation method by its proportion of the total long-term runoff to the Basin, as discussed in the previous section. Gaging station records were again assumed to have a mean error of 5 percent.

CONCLUSIONS

The annual mean runoff to the Narragansett Bay basin during the study period, water year 1987, is estimated to be 4,860 ft^3/s. Estimated monthly mean runoffs to the Basin during the study period range from a low in August of 1,060 ft^3/s, to a high in April of 14,400 ft^3/s. Long-term mean annual runoff to the Basin is estimated to be 3,690 ft^3/s, with long-term mean monthly runoffs ranging from 1,820 ft^3/s in July, to 6,540 ft^3/s in March. The estimates were derived by summing the known discharges from gaged areas of the Basin with estimates of runoff from ungaged areas, diversions from gaged areas, and runoff equivalents of precipitation on the bay.

Study period estimates of total annual and monthly mean runoff to the Basin are considered to be within 10 percent and 20 percent of actual, respectively. Techniques used to estimate runoff from individual ungaged areas varied in accuracy. Empirical tests of the concurrent-discharge regression technique proposed by Cohn produced mean absolute errors for the estimates of the mean annual and monthly mean runoff from individual subbasins of 7 percent and 13 percent, respectively. Empirical tests of the drainage-area ratio method for ungaged sites located upstream or downstream from a gaging station produced mean absolute errors of 6 percent and 23 percent, respectively for estimates of annual mean and monthly mean runoff. The discharge-versus-discharge graphical method is expected to yield similar results. When the drainage-area ratio method was applied to ungaged basins using a gaging station in an adjacent basin for relation, average estimation errors for annual mean and monthly mean runoff increased to 12 percent and 40 percent, respectively.

The estimates of the total long-term mean annual and mean monthly runoff to the Basin are considered to be within about 10 percent and 15 percent of actual, respectively. The regression equation used to estimate long-term mean annual runoff from ungaged areas yielded a mean absolute error and standard error of 6.9 percent and 9.2 percent, respectively. The monthly regression equations had mean absolute errors and standard errors ranging from 4.7 percent and 5.7 percent, respectively for April, to 20.4 percent and 29.3 percent, respectively for September. The regression equations for months of high flow generally had lower standard errors than those for months of low flow.

Regulations and diversions affected estimation accuracies for both long-term and study period runoff because estimating procedures normally assume natural conditions. Insufficient knowledge of the ultimate fate of diversions to, from, and within the Basin leads to greater uncertainties in the estimates. Fortunately, diversions are usually not a large percentage of flow within the Basin. Regulation and diversions limited the application and accuracy of the estimation procedures used in several subbasins and prevented use of some gaging stations in the regression analyses for estimating long-term runoff.

The sources for measuring the surficial features used as independent variables in the long-term regression analyses were generally of sufficient accuracy; however, the regression results could possibly be improved if a more recent, and larger scale, GIRAS land use data base had been available.

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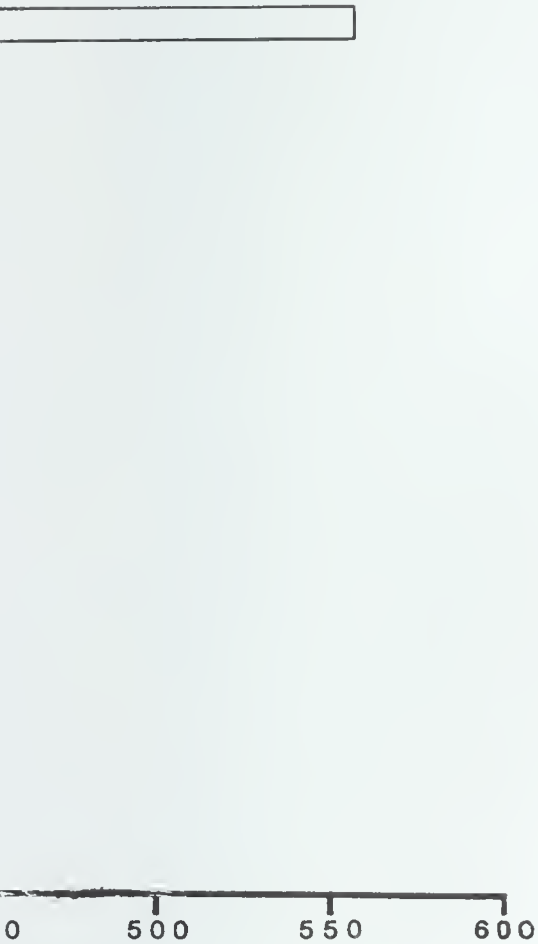
WATER RESOURCES INVESTIGATIONS

REPORT 89-4164 PLATE 1



ON WITH THE

VIRONMENTAL MANAGEMENT

n	Stream Length (miles)	Drainage Area (square miles)
	60.4	562.0
	--	97.8
	9.0	30.5
	11.5	35.1
	7.7	20.7
	9.9	14.8
	6.9	10.6
	30.4	85.1
	29.0	84.3
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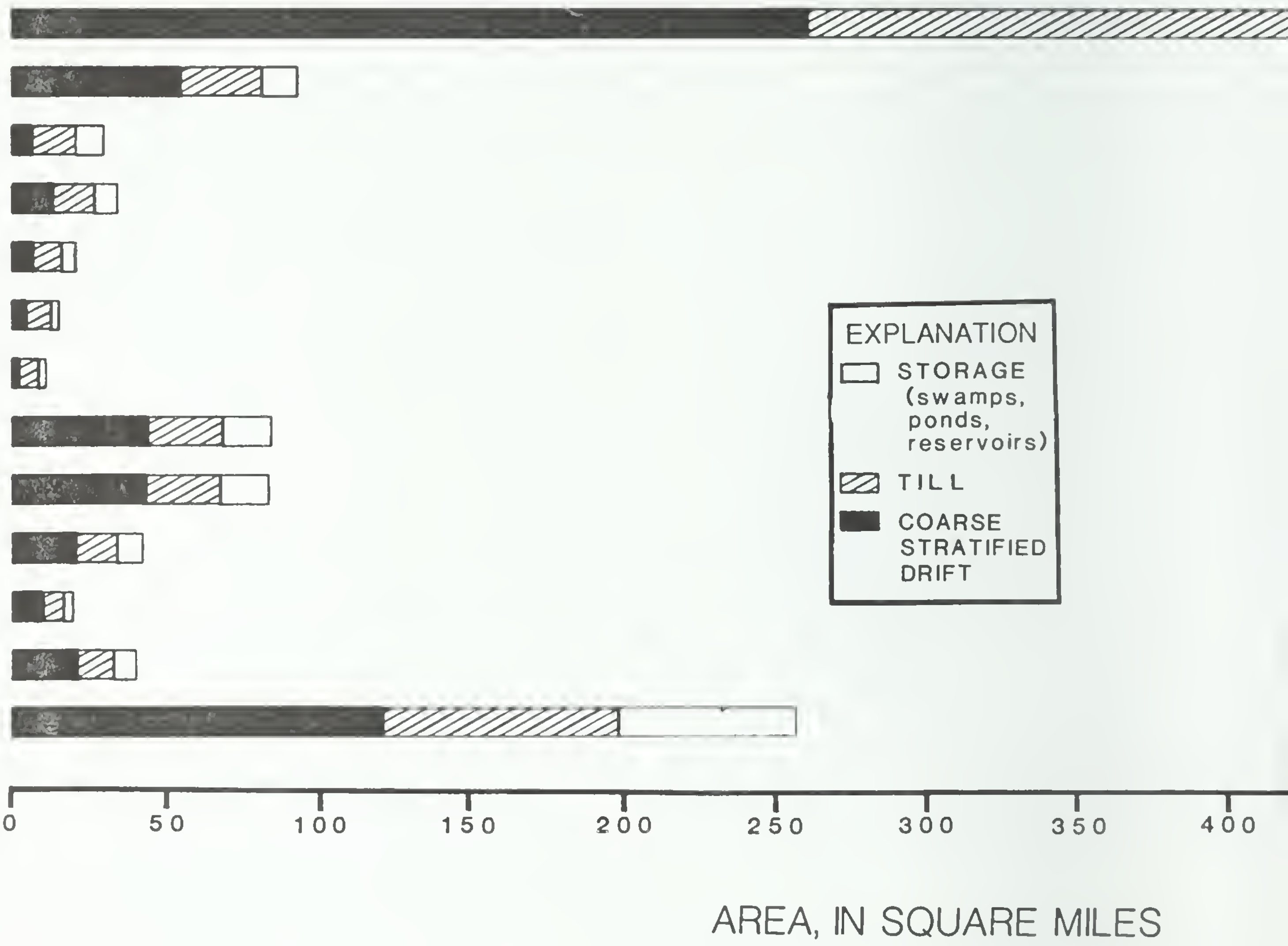
	9.0	19.5
	21.3	41.1
	30.8	258.0



Ries -- Estimating Surface-Water Runoff to Narragansett Bay, Rhode Island and Massachusetts -- WRIR 89-4164

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