A Precipitation-Runoff Model for Analysis of the Effects of Water Withdrawals on Streamflow, Ipswich River Basin, Massachusetts

Water-Resources Investigation Report 00-4029

Prepared in cooperation with the
MASSACHUSETTS DEPARTMENT OF ENVIRONMENTAL MANAGEMENT, and the
MASSACHUSETTS DEPARTMENT OF ENVIRONMENTAL PROTECTION

U.S. Department of Interior
U.S. Geological Survey

Cover Photos: View of the Ipswich River between Russell Street and the South Middleton Dam. Normal streamflow in this reach is shown in the bottom left photo. Dry riverbed photo taken during the summer drought of 1999.

Photo courtesy of David Armstrong and Timothy Driskell, U.S. Geological Survey, Northborough, Mass.

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By PHILLIP J. ZARRIELLO and KERNELL G. RIES, III

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Northborough, Massachusetts
2000

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
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Denver, CO 80225-0286

CONTENTS

FIGURES

TABLES

CONVERSION FACTORS AND VERTICAL DATUM

CONVERSION FACTORS

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
Hydraulic gradient		
foot per mile (ft/mi)	0.1894	meter per kilometer
Area		
acre	4,047	square meter
acre	0.4047	hectare
acre	0.004047	square kilometer
square mile (mi^2)	259.0	hectare
square mile (mi^2)	2.590	square kilometer
Volume		
million gallons (Mgal)	3,785	cubic meter
gallon per day (gal/d)	0.003785	cubic meter per day
inch per hour per acre (in/h/acre)	10.28	meter per hour per hectare
Flow rate		
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
million gallons per day (Mgal/d)	0.04381	cubic meter per second
inch per hour (in/h)	0 .0254	meter per hour
million gallons per day per square mile [(Mgal/d)/mi^2]	1,461	cubic meter per square kilometer
inch per year (in/yr)	25.4	millimeter per year
Hydraulic conductivity		
foot per day (ft/d)	0.3048	meter per day
Diffusivity		
foot squared per second (ft^2/s)	0.09290	meter squared per second

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F = (1.8 × °C) + 32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C = (°F - 32) / 1.8

VERTICAL DATUM

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Altitude, as used in this report, refers to distance above or below sea level.

A Precipitation-Runoff Model for Analysis of the Effects of Water Withdrawals on Streamflow, Ipswich River Basin, Massachusetts

By Phillip J. Zarriello *and* Kernell G. Ries, III

Abstract

Water withdrawals from the 155-square-mile Ipswich River Basin in northeastern Massachusetts affect aquatic habitat, water quality, and recreational use of the river. To better understand the effects of these withdrawals on streamflow, particularly low flow, the Hydrological Simulation Program-FORTRAN (HSPF) was used to develop a watershed-scale precipitation-runoff model of the Ipswich River to simulate its hydrology and complex water-use patterns.

An analytical solution was used to compute time series of streamflow depletions resulting from ground-water withdrawals at wells. The flow depletions caused by pumping from the wells were summed along with any surface-water withdrawals to calculate the total withdrawal along a stream reach. The water withdrawals, records of precipitation, and streamflow records on the Ipswich River at South Middleton and at Ipswich for the period 1989–93 were used to calibrate the model. Model-fit analysis indicates that the simulated flows matched observed flows over a wide range of conditions; at a minimum, the coefficient of model-fit efficiency indicates that the model explained 79 percent of the variance in the observed daily flow.

Six alternative water-withdrawal and land-use scenarios were simulated with the model. Three scenarios were examined for the 1989–93 calibration period, and three scenarios were examined for the 1961–95 period to test alternative withdrawals and land use over a wider range of climatic conditions, and to compute 1-, 7-, and 30-day low-flow frequencies using a log-Pearson Type III analysis. Flow-duration curves computed from results of the 1989–93 simulations indicate that, at the South Middleton and Ipswich gaging stations, streamflows when no water withdrawals are being made are nearly identical to streamflows when no ground-water withdrawals are made. Streamflow under no water withdrawals at both stations are about an order of magnitude larger at the 99.8 percent exceedence probability than simulations with only ground-water withdrawals. Long-term simulations indicate that the differences between streamflow with no water withdrawals and average 1989–93 water withdrawals is similar to the difference between simulations for the same water-use conditions made for the 1989–93 period at both sites. The 7-day, 10-year low-flow (7Q10, a widely used regulatory statistic) at the South Middleton station was 4.1 cubic feet per second (ft^3/s) with no water withdrawals and 1991 land use, 5.8 ft^3/s no withdrawals and undeveloped land, and 0.54 ft^3/s with average 1989–93 water withdrawals and 1991 land use. The 7Q10 at the Ipswich station was about 8.3 ft^3/s for simulations with no water withdrawals for both the 1991 land use and the undeveloped land conditions, and 2.7 ft^3/s for simulations with average 1989–93 water withdrawals and 1991 land use. Simulation results indicate that surface-water withdrawals have little effect on the duration and frequency of low flows, but the cumulative ground-water withdrawals substantially decrease low flows.

INTRODUCTION

Water use in the Ipswich River Basin has been a subject of contention since the early 1900's, when several surrounding towns were first granted rights by the Commonwealth of Massachusetts to transfer water from the 155-square-mile basin for municipal supplies. The debate over water intensified during the 1990's as development and demand for water increased. The debate centers on whether water withdrawals have decreased or will decrease flows of the Ipswich River enough to cause degradation of water quality, loss of wildlife habitat and diversity, and diminished capacity for use of the river as a recreational and scenic resource. The debate is particularly focused on conditions during summers, when at times nearly half of the 45-mile-long river goes dry.

Dry conditions during the summer of 1997 may have prompted the national environmental organization, American Rivers, to designate the Ipswich River as one of the 20 most threatened rivers in the United States during that year. American Rivers cited water withdrawals, development, and pollution as reasons for the designation, stating that "so much water is removed from the Ipswich River watershed for municipal water supply, industry, and irrigation that the river can literally run dry" (American Rivers, http://www.amrivers.org/). The river is listed under Section 303(d) of the Federal Clean Water Act as a water body that is not in compliance with the Massachusetts Water Quality Standards. The reasons for the listing are impairment of flow, low concentrations of dissolved oxygen, high concentrations of nutrients, and the presence of pathogens (Massachusetts Department of Environmental Protection, 1999). The U.S. Environmental Protection Agency (USEPA) requires Massachusetts to develop management plans for the Ipswich River to address non-compliance with water-quality standards.

Recognizing that any solution to bring the river into compliance with water-quality standards will require cooperation among the many stakeholders, a group of representatives from several Federal, State, and local environmental agencies, non-governmental environmental groups, water suppliers, and private citizens formed the Ipswich River Task Force in 1996, herein referred to as the Task Force. The goals of the Task Force are to assess the water-resource problems in the basin and to facilitate solutions.

The Task Force determined that a watershed model was needed to serve as a basis for water-resources-management decisions in the basin (Peter Phippen, Massachusetts Department of Environmental Management, written commun., 1997). A watershed model would allow State planning and regulatory agencies to: (1) determine potential effects of actions associated with increased human development on water resources, (2) make decisions on permitting of existing and new water withdrawals, (3) set streamflow standards to protect biota in the river, (4) determine safe yields of water-supply reservoirs in the basin, and (5) develop a management plan that will lead to compliance of the river with the Massachusetts Water Quality Standards.

The U.S. Geological Survey (USGS), in cooperation with the Massachusetts Departments of Environmental Management (MADEM) and Environmental Protection (MADEP), began developing a watershed model for the Ipswich River Basin in September 1997. The goal of this effort was to provide a tool that could be used by the various stakeholders to assess water-resources issues in the basin.

Problems associated with water use and urbanization in the Ipswich River Basin are not unique. Recent State legislation (Senate Bill No. 2006 and House Bill No. 4791) established 'A Water Resources Conservation Act and Efficiency Program' and identified the Ipswich River Basin water-management program as a model for other basins throughout the State in recognition of the efforts already undertaken by the Task Force. This legislation requires water-management programs for estimating long-term water needs and determining discharges sufficient to protect aquatic life. The development of watershed simulation models will help address these issues.

Purpose and Scope

This report describes the development, calibration and limitations of a precipitation-runoff model of the Ipswich River Basin, and simulations made with the model to determine the effects of water-use and land use patterns on streamflows. The report also describes the study area, which consists of the 150-square-mile drainage area above the Sylvania Dam in Ipswich; the data used in the model and the methods used to obtain those data; and the methods used to estimate the effects of the pumping of wells on streamflow. Results of the simulation of six scenarios that test different water-withdrawal operations and land-use patterns are described; three scenarios were simulated for the 1989–93 calibration period and three were simulated for the 1961–95 period to examine the effects of withdrawals and land-use change over a wider range of climatic conditions.

Previous Investigations

Numerous reports have been written on the water resources of the Ipswich River Basin by State environmental agencies, regional-planning agencies, non-governmental environmental organizations, and the USGS. Relevant reports are summarized below.

Baker and others (1964) described the geology and ground water of the Wilmington-Reading area. They identified areas within the towns where there was potential for installing municipal wells with substantial yields, and they also described potential negative effects on well yields of a then-proposed draining of adjacent wetlands.

Sammel and others (1964) provided a synopsis of the water resources in the basin. Their synopsis included information on precipitation, streamflows, ground-water levels, and water use, and a map showing availability of ground water and locations of municipal wells in the basin. In a later report, Sammel and others (1966), provided a more detailed analysis of the water resources than in the earlier report. The later report included a revised map of ground-water availability and locations of municipal wells, and maps of surficial geology and depth to bedrock. They indicated that the basin could sustain water withdrawals of about five times the 1960 rate of 7.6 ft^3/s, but that these withdrawals would need to come primarily from downstream reaches of the river. They also noted that a basin-wide approach to the hydrologic problems of the basin was needed along with a better understanding of the hydrologic connection between ground- and surface-water resources.

Burns and James (1972) developed a streamflow-accounting model of the basin to address many of the same issues described in this report. The model was simplistic by comparison with current standards, however, and its ability to address complex hydrologic problems was limited. For example, the model calculated streamflow in subbasins with the streamflow per unit drainage area that was measured at the gaging stations, and thus, the model did not account for differences in the land use or physical properties of the subbasins. Further, the model simulated streamflow with a monthly time step that is inadequate for evaluating the magnitude and frequency of low flows.

Reports by state agencies include those by the MADEM (1987a, 1987b, and 1999), which produced a three-volume management plan for the Ipswich River Basin in the late 1980s. Volume I of the plan contained an inventory and analysis of current and projected water use. Volume II contained hydrologic analyses and recommendations for minimum streamflow thresholds. The report recommended a streamflow of 0.14 $(Mgal/d)/mi^2$ of drainage area. This translates to flows of 9.6 ft^3/s at the South Middleton gaging station, 27 ft^3/s at the Ipswich gaging station, and 33.5 ft^3/s at the Sylvania Dam in Ipswich. Volume III of the plan recommended alternatives for meeting water demands. Relevant reports by regional planning agencies included those by the Metropolitan Area Planning Council (1977) and the New England River Basins Commission (1975).

The Ipswich River Watershed Association has released several reports on water-resources conditions in the basin. The Association releases an annual report on activities of the River Watch volunteer monitoring program, which monitors flow and water quality at about 25 locations. In the summer of 1997, the Association documented the absence of flow along large stretches of the river, reversed flow toward upstream municipal wells in some areas, and depleted dissolved oxygen at several locations (Ipswich River Watershed Association, 1998).

Bratton (1991) summarized water use by town for the Commonwealth of Massachusetts, including that for towns that obtain water from the Ipswich River Basin (p. 53, 56–59). Simcox (1992) summarized water resources and streamgaging activities in the state including those in the Ipswich River Basin (p. 31–33). In addition, nearly all the towns in the area have reports by consulting engineers describing potential water supply and distribution alternatives.

Acknowledgments

The authors would like to thank water suppliers that provided water-use information. The authors are also very grateful to the numerous individuals who provided information or comments during the study including Peter Phippen and Victoria Gartland of the MADEM, Arthur Screpetis, Duane LeVangie, Thomas Lamonte, and Stephen Hallem of the MADEP, Kerry Mackin and Daniele Lantagne of the Ipswich River Watershed Association, and Richard Tomczyk of the Massachusetts Executive Office of Environmental Affairs. Robert Lautzenheiser supplied precipitation information and Luc Claessens of the Marine Biological Laboratory, Woods Hole, Mass., obtained and processed most of the climate data used in the study. Tom Jobes of Aqua Terra, Inc., answered numerous questions about the HSPF model code and developed the procedure to account for water withdrawals in excess of streamflow. In addition, the authors would like to thank employees of the USGS who helped to collect and analyze data for the study, and who helped to prepare this report. The authors are especially grateful to Paul Barlow of the USGS for developing the STRMDEPL program that was used to calculate the effects of ground-water withdrawals on streamflow.

DESCRIPTION OF THE BASIN

The Ipswich River Basin encompasses a 155-square-mile area in the Atlantic coastal plain in northeastern Massachusetts about 20 miles north of Boston (fig. 1). The western headwaters of the Ipswich River begin in northern town of Burlington in the Mill Brook tributary, about 25 miles southwest of its mouth at the Atlantic Ocean near the southern tip of Plum Island (fig. 2). The basin is generally 5 to 10 miles wide in the north-south direction. The Ipswich River is affected by tide below the Sylvania Dam (fig. 2); this reach of the river and its associated drainage area were not included in the study area.

A number of constructed features affect the hydrology of the basin. Most of the large water bodies in the basin were built for water-supply storage near the headwaters of several small tributaries (fig. 2). Several moderate-size reservoirs were built along the major tributary streams to supply water or power to former mills, or for recreation. These impoundments store waters during periods of high flow and increase the potential for evaporation.

Climate: The climate in the basin is humid with an average annual air temperature of 49˚F for the period 1961–95. Monthly mean temperatures during this period ranged from 25˚F in January to 71˚F in July. During the study period of 1989–93, the average air temperature was also 49˚F; the monthly mean temperatures for this period ranged from 28˚F in February, to 70˚F in July and August.

Precipitation during the period 1961–95 averaged 45 in/yr. Precipitation was distributed fairly evenly throughout the year, with average monthly precipitation ranging from 3.2 inches in July to 4.8 inches in November. Precipitation during the study period was very similar. Annual precipitation during 1989–93 averaged 46 inches, and monthly precipitation ranged from 3.0 inches in May and July, to 4.8 inches in October. Annual snowfall during 1989-93 averaged 37 inches, and ranged from 22 inches in 1991 to 83 inches in 1993.

Towns: The Ipswich River Basin includes all or parts of 22 municipalities (fig. 2). Of these, only three (Middleton, North Reading, and Topsfield) are entirely within the basin. Boxford, Hamilton, Ipswich, Lynnfield, North Andover, Wenham, and Wilmington are mostly within the basin. About half or less than half of Andover, Beverly, Burlington, Danvers, Peabody, and Reading are in the basin, and less than 1 mi^2 of Billerica, Essex, Georgetown, Rowley, Tewksbury, and Woburn are in the basin. These municipalities obtain water supplies from various sources both inside and outside of the basin.

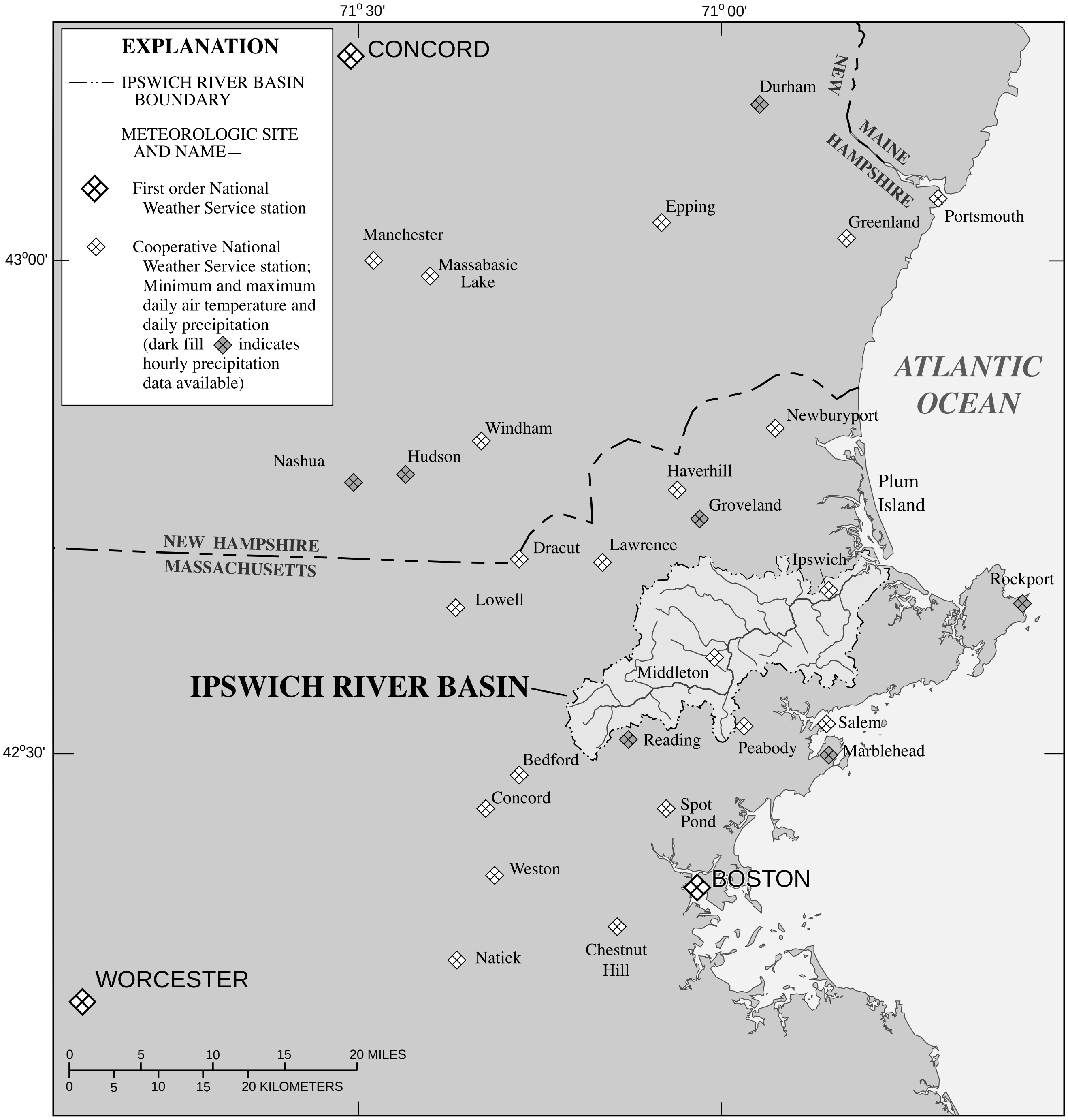


Figure 1. Location map of the Ipswich River Basin and meteorologic sites in northeastern Massachusetts and southern New Hampshire and Maine.

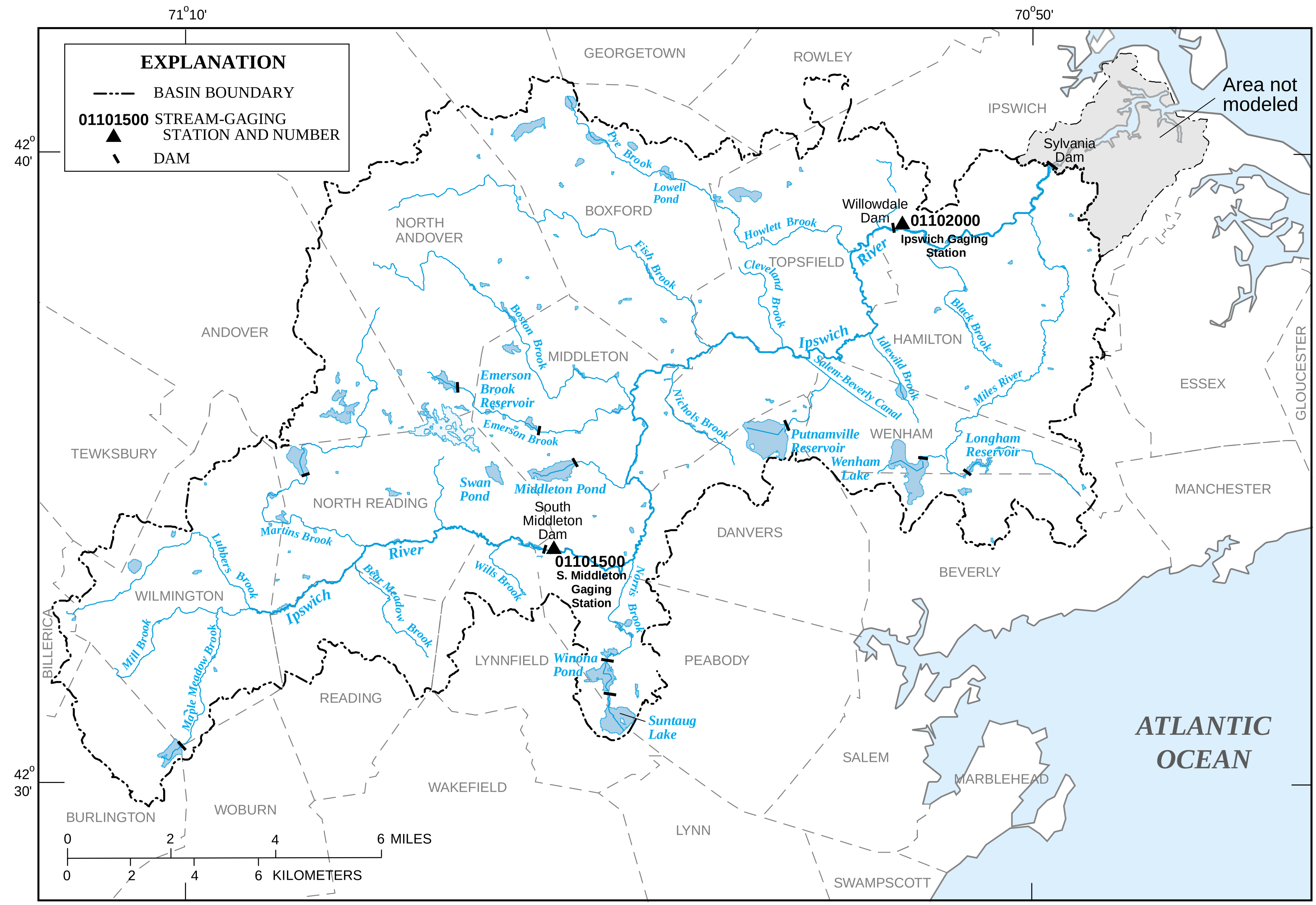


Figure 2. Towns, drainage network, and stream-gaging stations in the Ipswich River Basin, Mass.

Drainage and Gaging Stations: The USGS has operated two streamgaging stations in the basin since the 1930's (fig. 2). The upstream station at South Middleton (station no. 01101500), operated since 1938, is a few hundred feet below the South Middleton Dam and has a contributing drainage area of 44.5 mi^2. This station is referred to in this report as the South Middleton station. Major tributaries above the station include Maple Meadow Brook, Lubbers Brook and Martins Brook. Average river slope above this station is about 6.0 ft/mi. Mean annual streamflow at South Middleton for the period of record is 63.7 ft^3/s (Socolow and others, 1998).

The downstream station at Ipswich (station no. 01102000), operated since 1930, is a few hundred feet below Willowdale Dam and has a contributing drainage area of 125 mi^2. This station is referred to in this report as the Ipswich station. A small area (about 0.6 mi^2) drains directly to a supply reservoir that exports water from the basin. Major tributaries between the South Middleton and Ipswich stations include Boston Brook, Fish Brook, and Howlett Brook. The average river slope between stations is about 1.5 ft/mi. The mean annual streamflow at Ipswich for the period of record is 189 ft^3/s (Socolow and others, 1997).

The drainage between the Ipswich station and the Sylvania Dam (25 mi^2) is ungaged. Contributing drainage to Sylvania Dam is 150 mi^2 and includes inflows from Miles River. Average river slope below the Ipswich station is 2.8 ft/mi.

Topography: The Atlantic coastal plain is characterized by low relief. The Ipswich River elevation drops from about 110 ft at its headwaters to sea level at its mouth, and has an average slope of 3.1 ft/mi. Stream gradients are influenced by numerous wetlands and three low-profile dams that create flat-water conditions in many reaches along the river's 36-mile length. Wetlands and dams also affect tributary stream gradients. Upland areas of the basin are generally low-rounded hills with a maximum elevation of 420 ft, but most hills are under 300 ft.

Surficial Geology: Glacial till covers about 54 percent of the basin, stratified sand and gravel deposits cover about 43 percent of the basin, and alluvial deposits cover about 3 percent of the basin (fig. 3). Upland areas of the basin are mostly underlain by till, which consists of unsorted and unstratified materials ranging in size from clay to large boulders that were transported and spread over the land surface by glaciers (Sammel and others, 1966). Tills are highly variable in their material content and compactness and, thus, the permeability will also differ widely. Melvin and others (1992) report that the median hydraulic conductivity of tills derived from crystalline-rock in southern New England range from 2.7 ft/d for loose surface till to 0.6 ft/d for compact drumlin till. Till deposits also vary in depth but generally are thin, and bedrock is at or near the surface in some areas mapped as till (fig. 3).

Lowland areas of the basin are generally underlain by stratified drift, which consists of well-sorted fluvial sands and gravels deposited from glacial meltwater streams. The permeability of stratified drift typically is larger than that of till. Baker and others (1964) report a median hydraulic conductivity of 53 ft/d for coarse-grained sand and gravel. Precipitation generally infiltrates rapidly into stratified drift and then is slowly released to streams as base flow. Stratified drift forms the major aquifers in the basin, many of which are developed for municipal water supply.

Post-glacial alluvial deposits are found mainly along stream channels. These deposits are typically fine-grained and have a low to moderate permeability. Melvin and others (1992) report hydraulic conductivities of 0.82 to 0.0001 ft/d for fine-grained drift deposits, which are probably similar to the range in hydraulic conductivities of the alluvial deposits because their particle size distributions are similar.

Wetlands: Wetlands cover about 21 percent of the Ipswich Basin (fig. 4), of which 6 percent is nonforested and 15 percent is forested. The wetland distribution is nearly the same for the drainage areas of the two streamgaging stations and for the entire basin. The largest of the wetlands is Wenham Swamp, which occupies an area of about 3 mi^2 along the Ipswich River near the border of Hamilton and Wenham.

Wetlands, especially those along the Ipswich River, play an important role in the hydrology of the basin. Wetland soils generally have a high organic content, high porosity, and low permeability, thus they can store large volumes of water but do not transmit it easily to underlying deposits. Wetlands generally become inundated during floods and in the spring, retarding the magnitude and timing of peak discharges. Wetlands in the Ipswich Basin are typically densely vegetated with a water table within a few feet of the land surface; these factors maximize the potential for evapotranspiration.

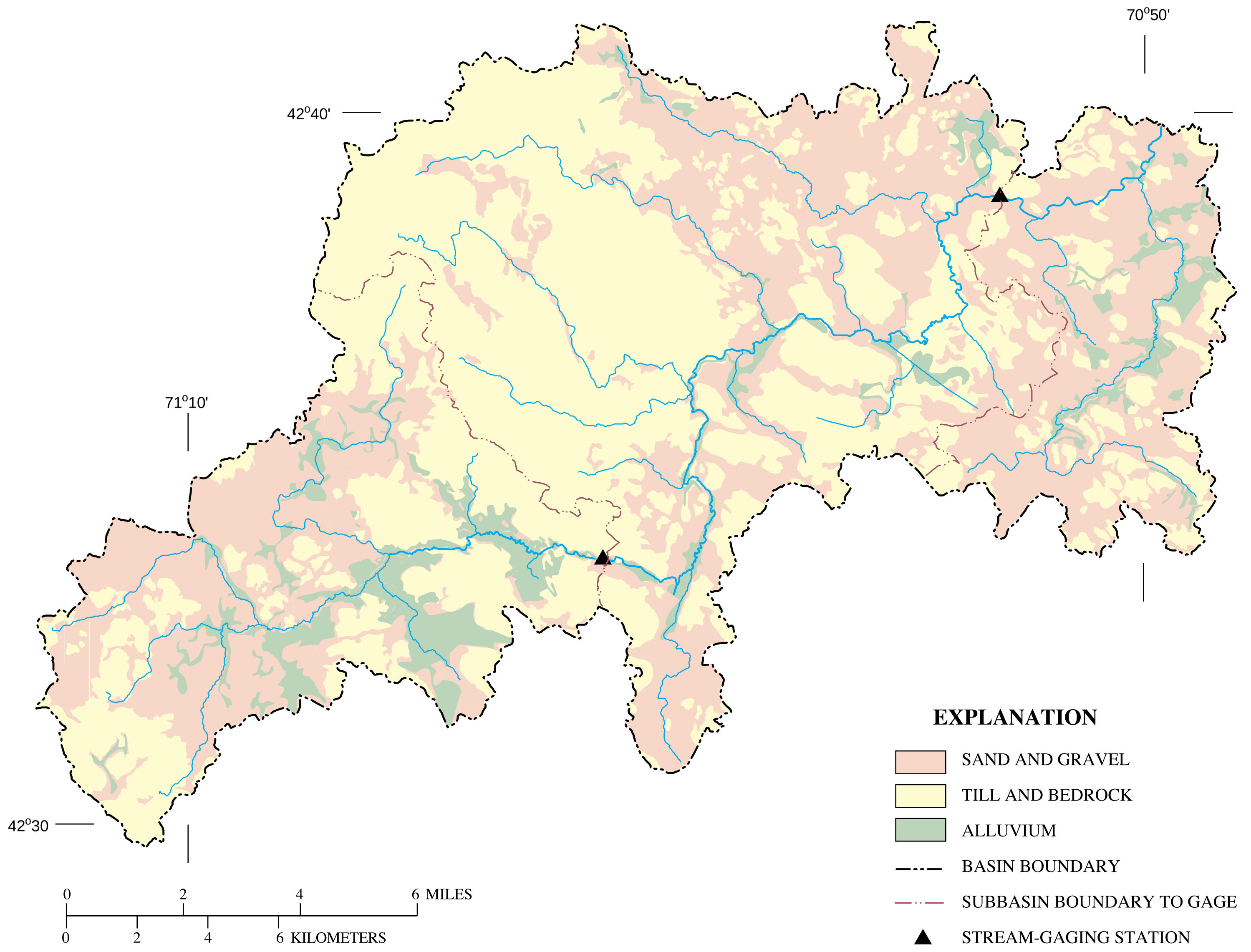


Figure 3. Generalized surficial geology of the Ipswich River Basin, Mass. (Location is shown in fig. 1).

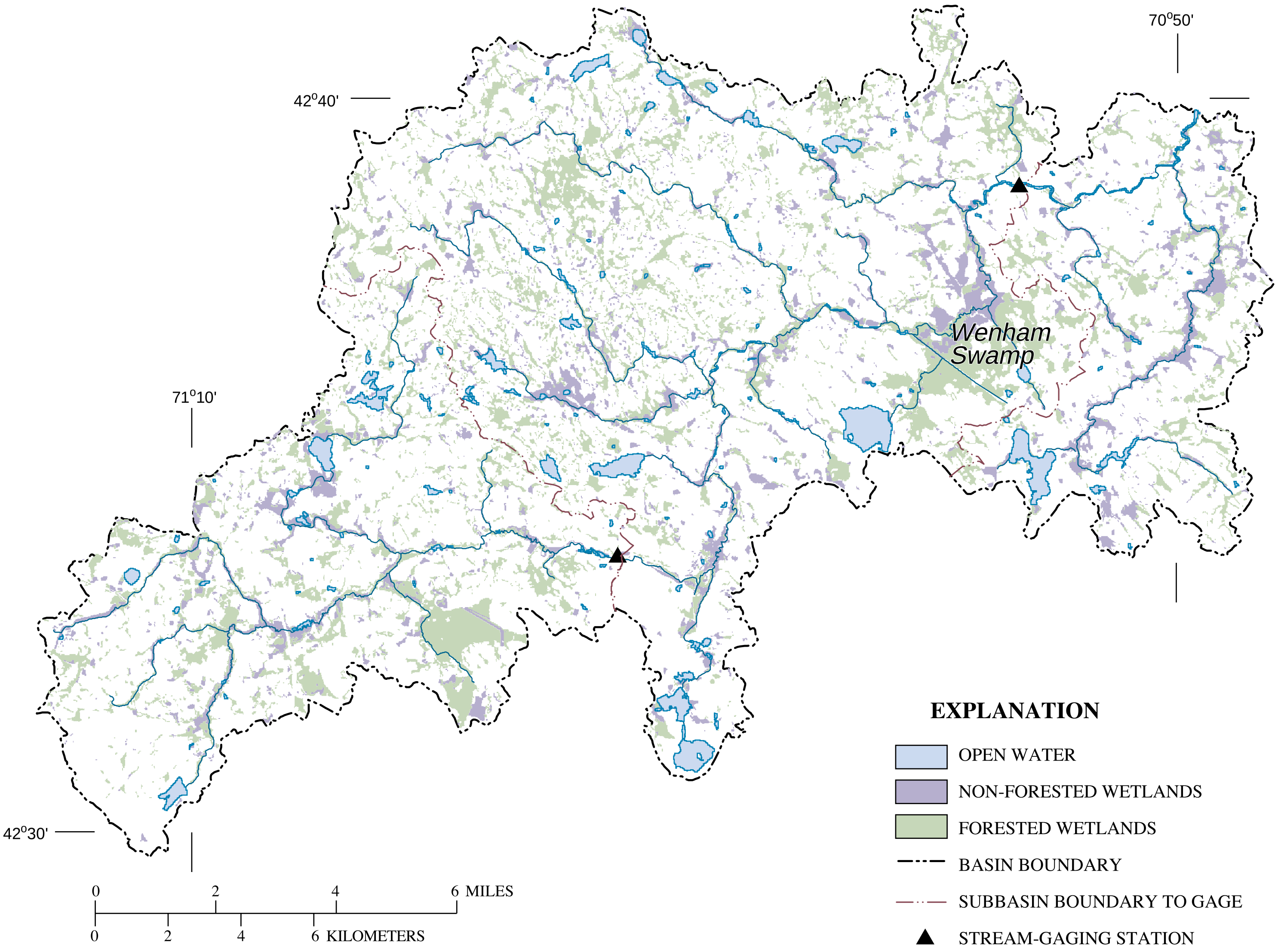


Figure 4. Wetlands in the Ipswich River Basin, Mass.

Land use: Land use in the basin is shown in figure 5. The land use as a percent of the basin area is slightly different above South Middleton station than above the Ipswich station and Sylvania Dam. Land use as a percent of the basin area above the Ipswich station and Sylvania Dam are nearly identical. Land use is predominantly residential above the South Middleton station; residential areas comprise about 38 percent of the area above the station and about 28 percent of the area below the station. Commercial areas comprise about 6 percent of the basin area above the South Middleton station and about 4 percent of the area below the station. Forests and open space comprise 34 percent of the basin area above the South Middleton station and about 44 percent of the area below the station. Open water is also somewhat less prevalent above the South Middleton station (1.7 percent) than below the station (2.5 percent).

Stream Habitat: The stream habitat along most of the Ipswich River and its major tributaries is characterized by sand-size bed material, slow-water velocities, and smooth, unbroken water surfaces. Fast, turbulent water riffle habitats are few and tend to be short. The largest naturally occurring riffles are downstream of dams. About a dozen smaller riffles are associated with structures such as highway and railroad bridges, old mills, or areas of fill. Riffles have a substantial effect on water levels in the basin because the backwater conditions above the riffle can extend hundreds to thousands of feet upstream. Riffles are also important because the aeration of water across them increases the dissolved oxygen in stream water and provides critical habitat for many aquatic species. Six critical riffle habitats were identified along the main-stem of the Ipswich River. In a related hydrologic study, habitat assessments and discharge measurements were made over a range of flows at these riffles to better understand habitat availability under various streamflow conditions (D.S. Armstrong, U.S. Geological Survey, Northborough, Mass, 1999, written commun.).

WATER WITHDRAWALS

The Ipswich River Basin supplies water to about 330,000 people (R. Tomczyk, Ipswich River Watershed Team Leader, written commun.,1999) in 21 municipalities within or partly within the basin and 2 municipalities (Salem and Lynn) entirely outside the basin (fig. 2). In addition, the towns of Essex, Gloucester, Manchester, and Rockport, which are either mostly or entirely outside the basin, have legislative rights to withdraw water from the Ipswich River, but these rights are not currently used (Massachusetts Department of Environmental Management, written commun., 1997).

The total cumulative withdrawals and the portion obtained from surface- and ground-water sources above the South Middleton station, Ipswich station, and Sylvania Dam are summarized in table 1 and shown in figure 6 along with streamflow at the stations. Ground-water withdrawals exceed surface-water withdrawals at all times above the South Middleton station because most withdrawals are from ground-water sources above this station. Below the South Middleton station, ground-water withdrawals often exceed surface-water withdrawals from June through October of each year, but surface-water withdrawals exceed ground-water withdrawals from about November through May of each year.

Municipal surface-water diversions from the Ipswich River include the city of Lynn above the South Middleton station, and the towns of Peabody, Salem, and Beverly below the South Middleton station. The State has regulated these diversions by water-use permits since the early 1900’s. In general, withdrawals are only permitted between December and May, and only when streamflow at the South Middleton station is greater than 15.5 ft^3/s, except in emergency situations. In 1998, the minimum streamflow threshold before water can be diverted from the river was changed for the Salem-Beverly supply to 43 ft^3/s at the Ipswich station (Duane LeVangie, Massachusetts Department of Environmental Protection, oral commun., 1999).

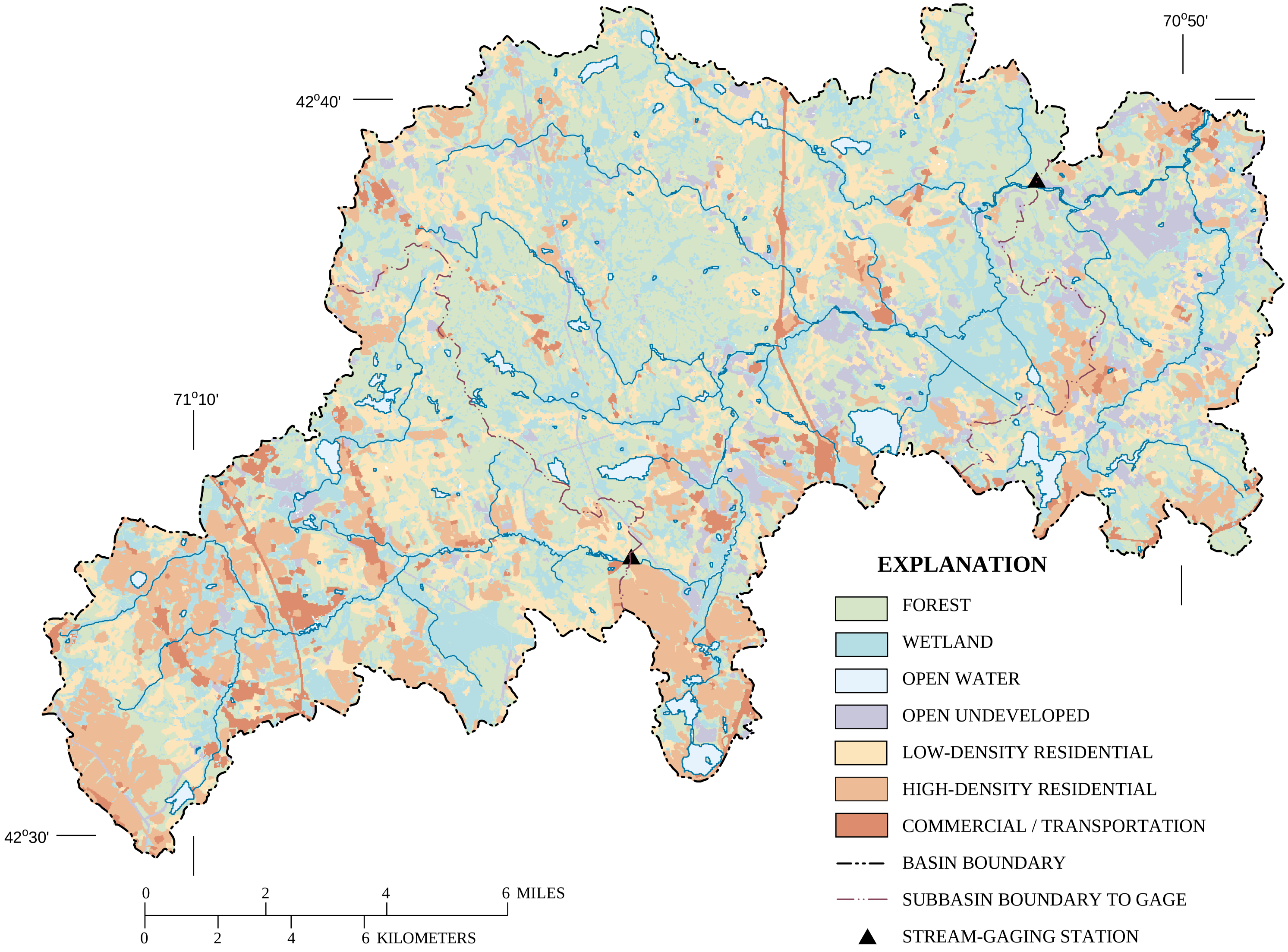


Figure 5. Generalized 1991 land use in the Ipswich River Basin, Mass.

Table 1. Monthly mean streamflow at the South Middleton and Ipswich stations, and cumulative monthly mean water withdrawals to the stations and Sylvania Dam, Ipswich River Basin, Mass. 1989–93

[Values are in cubic feet per second. STRMDEPL, program used to compute the delayed effects of ground water withdrawals on streamflow; --, indicates no data]

Month	Streamflow	Withdrawals				
		Surface water	Actual ground water	Surface water plus actual ground water	STRMDEPL	Surface water plus STRMDEPL
South Middleton station						
January	66	0	8.8	8.8	9.1	9.1
February	87	1.6	8.8	10	8.6	10
March	92	3.6	8.4	12	8.4	12
April	153	4.1	9.4	13	8.8	13
May	78	2.8	11	13	9.2	12
June	39	.52	11	12	10	10
July	7.7	.58	12	12	11	11
August	23	.50	11	11	10	11
September	13	.27	11	11	11	11
October	51	.12	9.1	9.3	10	10
November	78	.03	8.8	8.9	9.3	9.3
December	88	1.2	10	11	10	11
Mean	65	1.3	10	11	9.5	11
Ipswich station						
January	175	18	11	29	11	29
February	242	15	11	26	11	26
March	245	20	11	31	11	31
April	467	22	12	34	11	33
May	232	16	13	30	12	28
June	112	10	15	25	13	23
July	32	7.0	16	23	14	21
August	63	6.4	14	21	14	20
September	42	5.4	14	19	14	19
October	113	10	12	21	12	22
November	174	23	11	34	11	34
December	212	40	12	52	12	51
Mean	176	16	13	29	12	28
Sylvania Dam						
January	--	24	11	35	11	35
February	--	24	11	35	11	35
March	--	29	11	39	11	40
April	--	27	12	38	11	38
May	--	21	14	35	12	33
June	--	13	16	29	13	27
July	--	8	17	25	15	23
August	--	9	15	24	14	23
September	--	7	14	21	14	21
October	--	15	12	27	13	27
November	--	30	11	41	12	42
December	--	47	12	59	12	59
Mean	--	21	13	34	12	34

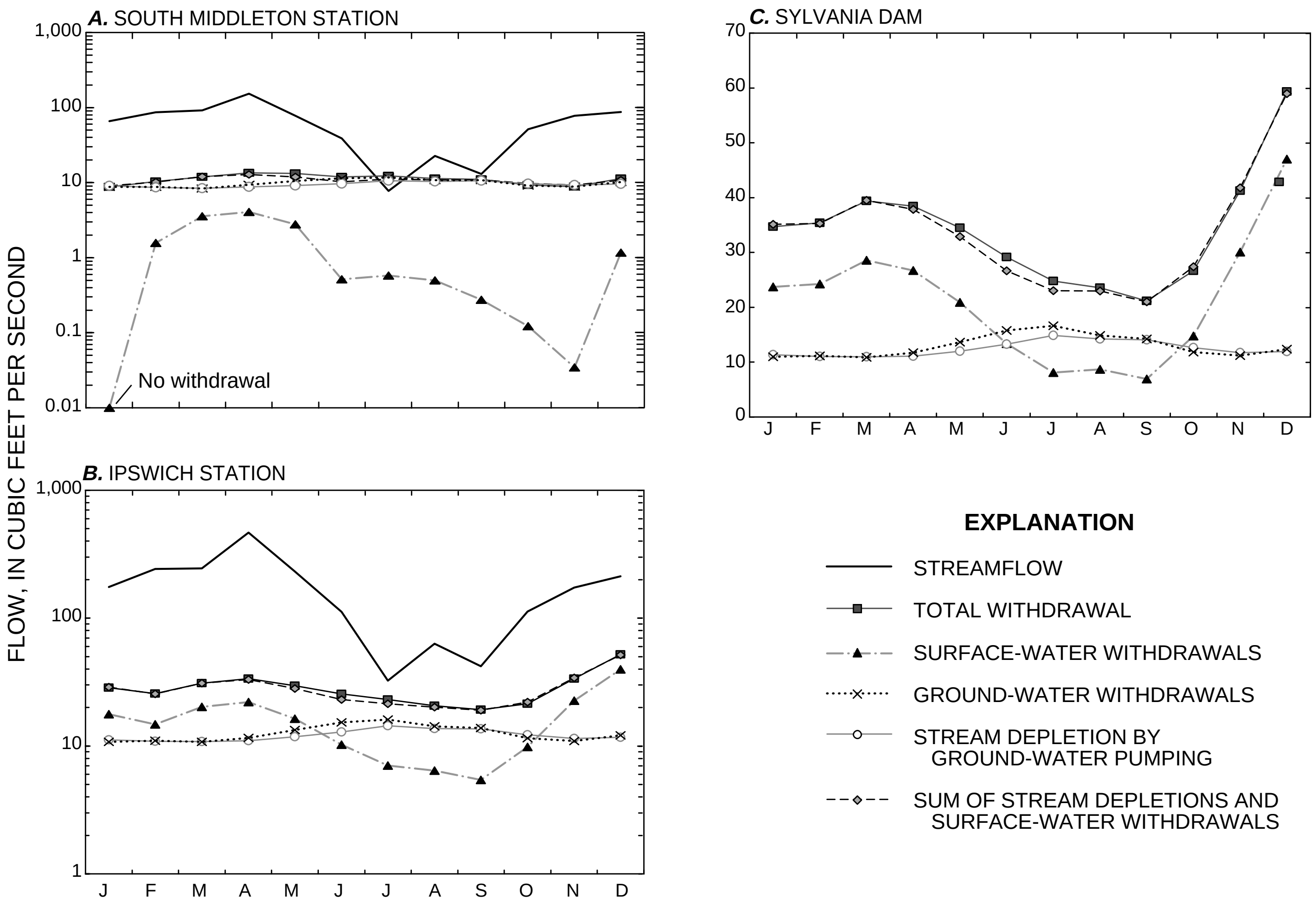


Figure 6. Monthly mean streamflows and cumulative monthly mean withdrawals at (*A*) South Middleton station, (*B*) Ipswich station, and (*C*) cumulative monthly mean withdrawals at Sylvania Dam, Mass., 1989–93. (Location is shown in fig. 2).

Surface waters can be withdrawn from reservoir storage between May and October, but these withdrawals are not included in table 1 or figure 6 to avoid double counting withdrawals from the basin. This includes transfers of water into Wenham Lake from Putnamville Reservoir and out of Wenham Lake for the Salem-Beverly supply, transfers of water out of Swan Pond and Emerson Brook Reservoir to Middleton Pond for the Danvers-Middleton supply, and transfers of water out of Winona Pond and Suntaug Lake for the Peabody supply. These rates do not include some small commercial withdrawals because data was not available, however, their total withdrawals are believed to be minor relative to the water use data summarized in the study.

The net effect of the withdrawals on the river flow at any given time depends on the timing of surface-water withdrawals, along with the delayed effects of ground-water withdrawals, which are governed by aquifer properties and the location of the well relative to the river. Therefore, depletions of streamflow caused by ground-water pumping generally are less than actual pumping rates during the spring and summer, and greater than actual pumping rates during the fall. In addition, some of the withdrawn water is returned to the basin through discharges from septic systems in areas that have municipal water supplies but do not have municipal sewer systems.

The withdrawal rates described above can be compared to the flow at the gaging stations as an indication of their relative magnitude (fig. 6); however, these flows reflect the effects of withdrawals on streamflow. The cumulative mean monthly total withdrawals above the South Middleton station exceed the mean monthly streamflow at the station during July and approach the mean monthly streamflow during

September. The cumulative mean monthly total withdrawals above the Ipswich station approach the mean monthly streamflow at the station during July. Results of model scenarios presented later in the report will provide a better indication of the effects of the withdrawals on flows in the river.

PRECIPITATION-RUNOFF MODEL

The Hydrological Simulation Program-FORTRAN (Bicknell and others, 1997), hereafter referred to as HSPF, was used to simulate runoff in response to precipitation and water withdrawals in the Ipswich River Basin. HSPF is well documented and can adequately represent the hydrology and complex water- withdrawal patterns in the basin. Computer code for HSPF and its companion programs are public domain, which can be modified when necessary to simulate unique features of individual watersheds and to add capabilities.

The steps followed to complete the Ipswich River Basin modeling study were to: (1) compile, collect, and process needed data, (2) use HSPF and associated computer software to build the model, (3) calibrate the model, (4) incorporate the model into GenScn (Kittle and others, 1998), a user-friendly decision support system, (5) examine selected water-withdrawal scenarios, and (6) document the model and results. Time series of streamflow, meteorologic, and water-withdrawal data were needed as input to the model. Hydraulic and land-surface data were needed to configure the stream reaches and land surface in the basin and to set parameters in the model.

Functional Description of the HSPF Model

HSPF is a continuous simulation model based on the principle of conservation of water mass, that is, inflow equals outflow plus or minus any change in storage. In HSPF, the land surface and the surface water bodies (lakes and streams) of the watershed are segmented into hydrologic response units (HRUs) and reaches (RCHRESs), respectively. Water budgets (inflows, outflows, and changes in storage) are calculated for each time step specified in the model for each HRU and RCHRES.

HRUs reflect areas of relatively homogeneous hydrologic response based on similar land use, soil, subsurface geology, and other factors considered important in the hydrology of the watershed. HRUs are divided into pervious area land segments (PERLNDs) and impervious area land segments (IMPLNDs).

RCHRESs are lengths of stream channels or reservoirs. The downstream end of each RCHRES is referred to as a node. Nodes are typically placed in the model to define channel segments with similar physical properties such as slopes and widths, at tributary streams, at lakes and reservoirs, at data-collection sites, and at other locations where estimates of streamflow are desired, such as upstream and downstream from municipal well fields, water diversions, or discharges of pollutants.

HSPF requires two primary input files for its operation, the User Control Input (UCI) file and the Watershed Data Management (WDM) file. The UCI file directs the process actions used by the model and sets input parameter variables. Process actions or algorithms in the model calculate the movement of water and changes in storage. The UCI file is structured in blocks that simulate different processes. The three main blocks of the UCI file simulate (1) PERLNDs, (2) IMPLNDs, and (3) RCHRESs. Within each block are modules and sub-modules, some of which are mandatory for simulations and others are optional. For example, the PWATER modules are required to simulated the hydrology of pervious areas, but the SNOW module is optional for simulating snowpack buildup and melt. A number of modules are used for administrative functions, such as controlling the operational sequence of the program and directing the model to external sources and output of time-series data.

The WDM file contains the time-series data used to simulate streamflow or output simulation time-series results. Simulations require precipitation and evapotranspiration as input time series. Meteorologic time series of air temperature, dew-point temperature, solar radiation, and wind speed are required to calculate snowpack buildup and melt. Output time series can be generated for any component in the simulation process that is defined in the Time Series Catalog section of the users manual, but time-series are mostly output for streamflow.

Water budgets calculated on PERLNDs consider infiltration and storage in the subsurface, whereas IMPLND water budgets do not. PERLND and IMPLND water-budget calculations include surface runoff, but only PERLND water budget calculations include interflow (shallow ground-water flow that responds rapidly to precipitation), baseflow (deep ground-water flow that remains relatively constant), and optionally a deep ground-water flow component that discharges outside of the basin. Process actions that control the rate of infiltration and change in subsurface storage make simulation of PERLNDs considerably more complex than the water-budget calculations for IMPLNDs. A complete description of the process actions and input model parameters are given in the ‘HSPF Users Manual’ (Bicknell and others, 1997).

Precipitation is the principal inflow to a watershed; however, inflows can also include septic effluents and other sources. Precipitation and other sources of moisture supply on impervious and pervious areas can be retained at or above the surface as interception storage and as snowpack storage, but only pervious areas retain water in the soil matrix. HSPF considers soil-water storage in two-zones: (1) the upper-zone storage, generally considered the upper-soil horizon, and (2) the lower-zone storage, a deep-soil zone that only allows outward movement of water through evapotranspiration by deep-rooted vegetation. Stream channels and lakes also have a storage component defined by their geometry.

Precipitation that is not held in storage or is lost to evapotranspiration (or optionally exits through deep ground-water) is discharged to RCHRESs as surface runoff from IMPLNDs and PERLNDs and as subsurface outflows from PERLNDs. The area of IMPLND and PERLND that drains to a RCHRES and the linkage of one RCHRES to another are specified in the SCHEMATIC block and associated MASSLINK block or NETWORK block, or both. The schematic or network blocks are used to represent the physical layout of the watershed. Relations among stage, storage, surface area, and discharge are specified for each reach in user-supplied function tables (FTABLEs). Primary inflows to a reach are (1) surface runoff from PERLNDs and IMPLNDs, (2) interflow and base flow from PERLNDs, and (3) inflow from other reaches. Inflow as direct precipitation and outflow as evapotranspiration, or inflows and outflows from other sources, such as wastewater effluent or water withdrawals, also can be simulated for RCHRESs when specified by the user.

The inflows to and outflows from a stream reach are illustrated in figure 7. Surface runoff enters the reach from impervious surfaces (SURI) and pervious surfaces (SURO). Infiltrated precipitation can flow to the reach as shallow quick responding interflow (IFWO) or a slow responding active ground water (base flow) component (AGWO). Inflow can also be from upstream reaches (IVOL). Two outflow exits (or gates) are illustrated (a reach can have up to 5 exits). The first gate (OVOL 1) is the volume time-series of water withdrawals (OUTDGT 1) for each reach read in by the EXTERNAL-SOURCE block. Specifying the first outflow gate for water withdrawals requires that these withdrawals be satisfied before water is routed through successive outflow gates. In the Ipswich River Basin model, water usually is routed downstream through the second outflow gate (OVOL 2), as illustrated, but in some instances a third outflow gate is used to route water downstream as described later in the report.

Data Base

Time-series data required for simulations and time series generated by the model are stored in the Watershed Data Management (WDM) file. The WDM data base is accessed by ANNIE, an interactive text interface to store, manage, display, transform, plot, or analyze time-series data (Flynn and others, 1995) or by GenScn, a graphical user interface that has many of the features of ANNIE but improves the ability to generate and analyze model scenarios and compare model results (Kittle and others, 1998). Data in various formats are entered into the WDM data base by use of the IOWDM program (Lumb and others, 1990).

The WDM data base is organized by data sets with a unique data set number (DSN) assigned to separate time series. Each data set also has attributes that describe the data type, time step, location, and other important features. In the Ipswich WDM file, the first 100 DSNs are used for input meteorologic time-series and observed streamflow. Data sets with numbers larger than 100 are generally organized by reach. Table 2 describes the general organization of the WDM file.

The sum of individual ground-water withdrawals plus any surface-water withdrawals provides the total water withdrawal time series for each reach (OUTDGT 1 in fig. 7). These time series were entered into the WDM file in data set numbers 101 to 166 where the last two digits correspond to the reach number. In GenScn, these time series are identified as ExDemand

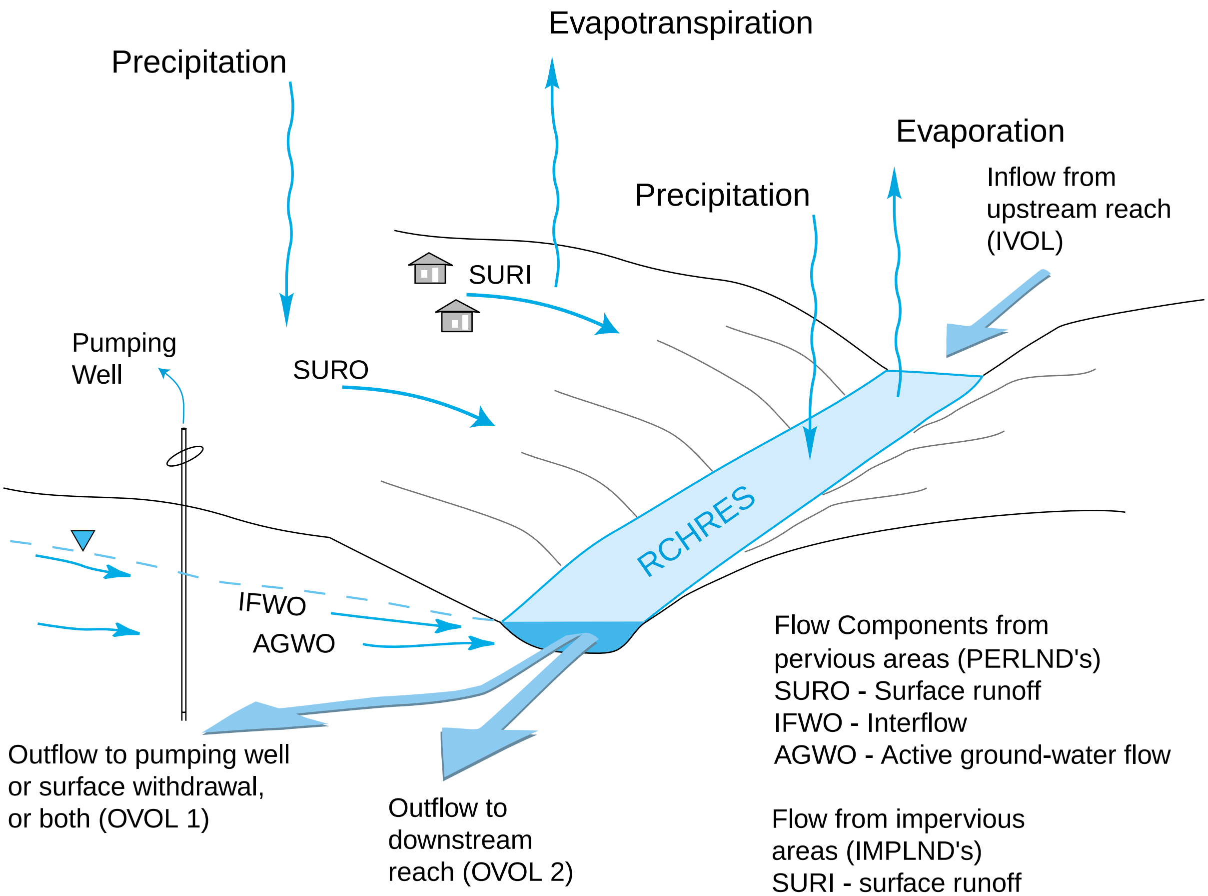


Figure 7. Schematic of inflows to and outflows from a stream reach (RCHRES) in the Hydrological Simulation Program-FORTRAN (HSPF).

in the Constituent window, OBSERVED in the Scenario window, and have a location identified with the appropriate RCHRES segment.

Streamflow depletions resulting from ground-water withdrawals were determined for wells in the basin by use of the STRMDEPL program, which is documented in Appendix A. Time series of streamflow depletions by individual wells and surface-water withdrawals are stored in the WDM file in data sets 1010 to 1679; the second and third digits correspond to the reach number and the last digit corresponds to an individual well. This scheme allows identification of up to 10 wells along a reach. In the Ipswich Basin HSPF model, only reach 8 had more than 10 wells simulated; therefore, the 11th well was numbered with the successive reach number (1090) because no withdrawals were simulated in this reach. In GenScn, the Constituent window identifies streamflow depletions by individual wells by DEPL and surface-water withdrawals by SWDL. Actual well-pumping rates are stored in the WDM file in data sets 2010 to 2679 using the same numbering scheme described above for the individual depletions. The actual pumping rates are identified in the GenScn Constituent window by PUMP. All withdrawals and streamflow depletions are identified in the GenScn Scenario window by OBSERVED.

Streamflow Data

Observed daily-flow data were obtained for the USGS gaging stations at South Middleton (1939 through 1995) and Ipswich (1931 through 1995), Mass. These stations provided the primary data used to calibrate the model. Records from the South Middleton station are generally rated fair (85 percent of the daily discharge are within 15 percent of the true discharge) and those from the Ipswich station are generally rated good (within 10 percent of the true discharge) for the

Table 2. Organization and description of Data Set Numbers (DSNs) in the Watershed Data Management (WDM) system for the Ipswich River Basin, Mass.

[STRMDEPL, stream depletion by ground-water withdrawals; HSPEXP, Hydrological Simulation Program Expert System].

DSN	Purpose
1 – 100	Observed data
101 – 167	Input total water withdrawals for a reach input to the model (OUTDGT 1)
200 – 267	Output of simulated streamflow for a reach
301 – 367	Output of total water withdrawals satisfied by streamflow for a reach
1010 – 1679	Individual surface-water withdrawal or stream depletion from ground-water withdrawal computed by STRMDEPL, where
101x – 167x	corresponds to reach number and
1xx0 – 1xx9	corresponds to individual withdrawal point (maximum 10 per reach)
2010 – 2679	Actual withdrawals for individual wells, where
201x – 267x	corresponds to reach number and
2xx0 – 2xx9	corresponds to individual withdrawal point (maximum 10 per reach)
5000 – 5100	Simulated flow components for HSPEXP
6000 –	Simulation results from different scenarios, where
60xx – 6xxx	second digit corresponds to a unique scenario and
6x01 – 6x67	last two digits corresponds to reach number

1989 to 1993 water years (Socolow and others, 1989–93). Streamflows for the South Middleton station are in DSN 19 and those for the Ipswich station are in DSN 56 in the WDM file; these DSNs correspond to the reach numbers in the model (fig. 8) in which these stations are located.

Meteorologic Data

Meteorologic data, including precipitation, air temperature, dew-point temperature, solar radiation, and wind speed for the Ipswich River Basin were provided by the Marine Biological Laboratory (MBL) in Woods Hole, Mass. These data are in hourly time steps and span the period January 1, 1961 through December 31, 1995. Hourly precipitation records were also provided by Robert Lautzenheiser (retired state climatologist, written commun., 1998) for Reading, Mass., for the period January 1, 1983 to December 31, 1998.

The MBL selected 30 National Weather Service (NWS) weather stations in and around the Ipswich River Basin to develop their data base (fig. 1). Some of the stations used are a substantial distance (as much as 45 mi) from the basin because only NWS first-order stations collect data other than precipitation and daily extreme air temperature, and those stations are sparsely distributed. Table 3 lists the stations used to develop the MBL data base, the types of data collected, their locations, and periods of record.

The MBL provided meteorologic data in a spatial grid of the Ipswich River Basin that was populated by a weighted linear spatial interpolation of hourly and daily values from the individual stations into each grid cell (Luc Claessens, Marine Biological Laboratory, 1999, written commun.). All hourly meteorologic data was in a grid matrix of 4- by 3-cells that are 38.6 mi^2 in area. Hourly precipitation and air temperature time series were developed from 9 stations with hourly data and 26 stations with daily data during 1961 to 1995. The hourly precipitation data for Reading supplied by Robert Lautzenheiser were included in the MBL database. The hourly stations were used as a basis for estimating hourly values for stations where only daily values were available using METCMP (Lumb and Kittle, 1995). The hourly values at each station were then spatially interpolated to obtain hourly values for the 12 grid cells.

Dew-point temperature, air temperature, solar radiation, and wind speed were obtained from three first-order NWS stations listed in table 3. Solar radiation was unavailable for 1991 through 1995 at these stations and was estimated from cloud cover by use of a method reported by Morton and others (1985).

The daily and hourly values of the meteorologic variables obtained from the MBL grids were averaged to obtain a single value for each variable and time step for the basin. The basin-wide average was computed because use of the grid data would have required the complete set of pervious (PERLND) and impervious (IMPLND) land units developed for the model to be duplicated in the UCI file for each grid cell. Inclusion of the additional land units would have increased tremendously the size and complexity of the UCI file and slowed processing time. The basin-wide average values were considered to be adequate for running the model because the annual spatial variation among the cells was small. Mean annual precipitation varied by 8 percent or less among the cells in the basin. This is considered a small variation in comparison to the large sampling errors associated with precipitation data. All other meteorological variables varied less than precipitation.

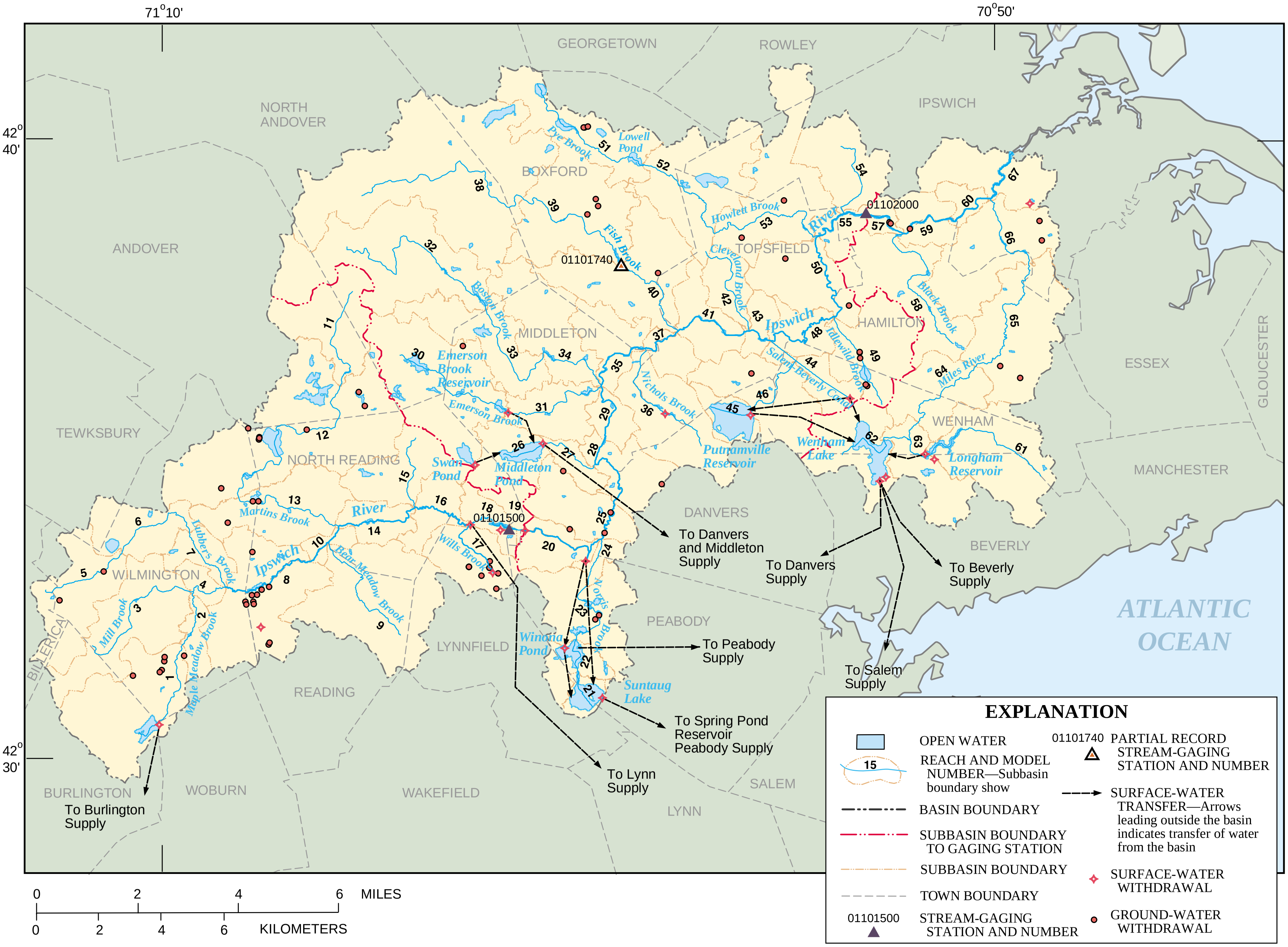


Figure 8. Model reaches, subbasin boundaries, and water withdrawal locations in the Ipswich River Basin, Mass.

Table 3. Meteorologic stations and data used to develop grid-cell data for the Ipswich River Basin, Mass.

[Locations are shown in fig. 1. NWS, National Weather Service; No., number; °, degrees; ′, minutes; ″, seconds; ● indicates available data]

NWS Station No.	Station name	Latitude	Longitude	Precipitation		Temperature			Solar radia- tion	Wind speed	Cloud cover	Period of record	
				Hourly	Daily	Mini- mum	Maxi- mum	Dew- point				Start	End
190535	Bedford, Mass.	42° 29′ 00″	71° 17′ 00″		●	●	●					1/01/61	12/31/95
190770	Boston, Mass.–Logan Airport	42° 22′ 00″	71° 02′ 00″		●	●	●					1/01/61	12/31/95
14739	Boston, Mass.–Logan Airport	42° 22′ 00″	71° 02′ 00″	●				●	●	●	●	1/01/61	12/31/95
191447	Chestnut Hill, Mass.	42° 20′ 00″	71° 09′ 00″		●	●	●					1/01/61	4/30/86
191992	Dracut, Mass.	42° 42′ 00″	71° 17′ 00″		●	●	●					1/01/71	6/15/78
193276	Groveland, Mass.	42° 45′ 00″	71° 03′ 00″		●	●	●					9/01/92	12/31/95
193276	Groveland, Mass.	42° 45′ 00″	71° 03′ 00″	●								9/01/92	12/31/95
193505	Haverhill, Mass.	42° 46′ 00″	71° 04′ 00″		●	●	●					1/01/61	12/31/95
193876	Ipswich, Mass.	42° 40′ 00″	70° 52′ 00″		●							1/01/61	12/31/95
194105	Lawrence, Mass.	42° 42′ 00″	71° 10′ 00″		●	●	●					1/01/61	12/31/95
194313	Lowell, Mass.	42° 39′ 00″	71° 22′ 00″		●	●	●					1/01/61	12/31/95
194502	Marblehead, Mass.	42° 30′ 00″	70° 52′ 00″		●	●	●					9/01/84	12/31/95
194502	Marblehead, Mass.	42° 30′ 00″	70° 52′ 00″	●								9/01/84	12/31/95
194744	Middleton, Mass.	42° 36′ 00″	71° 01′ 00″		●	●	●					1/01/61	12/31/95
195175	Natick, Mass.	42° 18′ 00″	71° 22′ 00″		●	●	●					4/01/78	12/31/95
195285	Newburyport, Mass. 3 WNW	42° 50′ 00″	70° 56′ 00″		●							1/01/61	12/31/95
196245	Peabody, Mass.	42° 32′ 00″	70° 59′ 00″		●	●	●					1/01/67	12/31/95
196783	Reading, Mass.	42° 31′ 00″	71° 08′ 00″		●	●	●					1/01/61	12/31/95
196783	Reading, Mass.	42° 31′ 00″	71° 08′ 00″	●								12/01/80	12/31/95
196977	Rockport, Mass. 1 ESE	42° 39′ 00″	70° 36′ 00″		●	●	●					1/01/61	1/16/83
196977	Rockport, Mass. 1 ESE	42° 39′ 00″	70° 36′ 00″	●								1/01/61	12/31/83
197124	Salem, Mass.–Coast Guard Station	42° 32′ 00″	70° 52′ 00″		●	●	●					1/01/61	12/31/66
198030	Spot Pond, Mass.	42° 27′ 00″	71° 05′ 00″		●							1/01/61	7/31/77
199360	Weston, Mass.	42° 23′ 00″	71° 19′ 00″		●	●	●					1/01/61	6/30/68
94746	Worcester, Mass Municipal Airport	42° 16 00″	71° 52′ 00″					●	●	●		1/01/61	12/31/95

Table 3. Meteorologic stations and data used to develop grid-cell data for the Ipswich River Basin, Mass.—*Continued*

NWS Station No.	Station name	Latitude	Longitude	Precipitation		Temperature			Solar radiation	Wind speed	Cloud cover	Period of record	
				Hourly	Daily	Minimum	Maximum	Dew-point				Start	End
14745	Concord, N.H. Municipal Airport	43° 12′ 00″	71° 31′ 00″					●	●	●		1/01/61	12/31/95
14745	Concord, N.H. Municipal Airport	43° 12′ 00″	71° 31′ 00″								●	1/01/95	12/31/95
272174	Durham, N.H.	43° 09′ 00″	70° 57′ 00″	●								1/01/61	12/31/95
272800	Epping, N.H.	43° 02′ 00″	70° 05′ 00″		●	●	●					12/01/63	12/31/95
273626	Greenland, N.H.	43° 01′ 00″	70° 50′ 00″		●	●	●					8/01/73	12/31/95
274234	Hudson, N.H.	42° 47′ 00″	71° 26′ 00″	●								1/01/61	12/31/72
275072	Manchester, N.H.	43° 00′ 00″	71° 29′ 00″		●	●	●					1/01/61	9/30/72
275211	Massabesic Lake, N.H.	42° 59′ 00″	71° 24′ 00″		●	●	●					1/01/61	12/31/95
275705	Nashua, N.H. 2	42° 47′ 00″	71° 30′ 00″	●								12/01/72	2/28/85
275712	Nashua, N.H. 2 NNW	42° 47′ 00″	71° 29′ 00″		●	●	●					1/01/61	12/31/95
275712	Nashua, N.H. 2 NNW	42° 47′ 00″	71° 29′ 00″	●								2/01/85	12/31/95
276980	Portsmouth, N.H.	43° 04′ 00″	70° 43′ 00″		●	●	●					1/01/61	5/31/73
279740	Windham, N.H. 3 NW	42° 49′ 00″	71° 20′ 00″		●	●	●					1/01/61	7/31/76

Potential evapotranspiration (PET) was calculated from daily high and low temperatures, and solar radiation by the Jensen-Haise (1963) method using METCMP (Lumb and Kittle, 1995). Near-final calibration results indicated a seasonal bias that can be attributed to the use of a constant monthly variable coefficient (CTS) in the Jensen-Haise computation. PET estimates were subsequently recalculated with a variable CTS value to correct for seasonal bias. Methods that were used to develop the CTS value are explained in the model-calibration section of the report.

Water-Withdrawal Data

Water-withdrawal information was obtained by questionnaire from water suppliers for 18 of the 22 towns in the Ipswich River Basin or obtaining water from the basin. Water suppliers were asked to provide information on their drinking-water and waste-water infrastructure and time series of withdrawal rates and waste-water discharges for the period beginning January 1, 1989, through the most-recently available data. Information was not requested from the towns of Woburn, Billerica, Rowley and Georgetown because their areas within the basin are small and they do not have municipal water supplies or their municipal water supply comes from an adjacent basin.

The information provided by each town differed considerably, and thus required various degrees of processing to format the data for input to the model. Table 4 summarizes water-use information obtained from the towns. Water-use data for Hamilton, North Reading, Peabody, and Topsfield were obtained from monthly water-use records reported to the MADEP. In addition, the MADEP provided monthly time series for seven private water users in the basin. All other water-use information was obtained directly from the water suppliers. In some instances, copies of hand-written log books provided by the water suppliers indicated periods when water meters were not in service. Recorded withdrawals for adjacent time periods were used to estimate withdrawals for the missing periods. This could result in small differences between the withdrawals reported to MADEP and the withdrawals used in the model.

Table 5 summarizes the 96 registered or permitted public and commercial water withdrawals in the basin. Several towns have large areas served by municipal water supplies, but with no municipal wastewater systems. These areas rely on onsite septic systems for waste treatment. Discussion of how these areas were treated in the model is provided in the section on ‘Hydrologic Response Units.’ The municipal water-use data and methods used to process them are described below (locations of the areas described, river reach numbers and withdrawal locations are shown in fig. 8). Generally, the town water-use data are presented in order of downstream reach number (as listed in table 5), but some towns have been grouped because of similarities in water-use patterns and methods used to process the data.

Burlington. The town of Burlington has a storage reservoir at the headwaters of Maple Meadow Brook. Water is pumped to the reservoir from outside the Ipswich Basin, stored, and released for later use outside the basin; therefore, the surface area of the reservoir was not included in the model. Water from the land area that would normally drain to the reservoir is piped under the reservoir and contributes to Maple Meadow Brook. Within the basin, the town is served by municipal water and sewer, which is discharged outside the basin.

Wilmington. The town of Wilmington obtains water from 5 wells adjacent to Maple Meadow Brook, 2 wells adjacent to Lubbers Brook, and 3 wells adjacent to Martins Brook. One of the wells was not pumped during the calibration period, but was included in the model with no withdrawals specified. The town provided combined total monthly withdrawal rates for 1969 through part of 1997 and average annual withdrawal rates for individual wells from 1991–96. Ratios of the individual average annual well withdrawals to the total average annual withdrawals for the 1991–96 period were used to apportion the total monthly withdrawals to individual well withdrawals for the 1989–90 period. The daily withdrawals were obtained by disaggregating monthly withdrawals using Wenham records as described below. The combined average withdrawal from these wells during the calibration period was 2.53 Mgal/d. Wilmington is partially served by public sewer.

Hamilton, Reading, North Reading, and Topsfield. These towns rely solely on ground water for their water supplies except North Reading, which imports up to 1.5 Mgal/d of additional water during summers from the Merrimack River Basin. Several private surface-water withdrawals from within these municipalities were also included in the model.

Table 4. Summary of municipal water-use information in the Ipswich River Basin, Mass.

[-- indicates not applicable]

Municipality	Water supply		Wastewater		Source data time step	Data in model		Remarks
	Public system	Source in basin	Public system	Discharge in basin		Begin year	End year	
Andover	Yes	No	Yes	No	--	--	--	No withdrawals from or returns to the basin
Beverly	Yes	Yes	Yes	No	Daily	1989	1998	Waste discharged to South Essex Sewage-Treatment Plant
Billerica	Yes	No	Yes	No	--	--	--	No withdrawals from or returns to the basin
Boxford	No	--	No	--	--	--	--	No public supply or sewer system
Burlington	Yes	No	Yes	No	--	--	--	No withdrawals from or returns to the basin
Danvers	Yes	Yes	Yes	No	Monthly	1987	1997	Waste discharged to South Essex Sewage-Treatment Plant
Georgetown	Yes	No	No	--	--	--	--	No withdrawals from or returns to the basin
Hamilton	Yes	Yes	No	Yes	Monthly	1989	1993	Waste all goes to septic systems
Ipswich	Yes	Yes	Yes	No	Daily	1989	1998	Ipswich wastewater is discharged to the Ipswich River below Sylvania Dam. About 50 percent of the population is unsewered.
Lynn	Yes	Yes	Yes	No	Daily	1989	1997	No land area in basin; waste discharged to Lynn Wastewater Treatment Plant
Lynnfield	Yes	Yes	No	Yes	Daily	1989	1998	Waste all goes to septic systems
Middleton	Partial	Yes	No	Yes	Monthly	1987	1997	About 60 percent of the population has public water; waste all goes to septic systems
North Andover	Yes	No	Yes	No	--	--	--	No withdrawals from or returns to the basin
North Reading	Yes	Yes	No	Yes	Monthly	1989	1993	Waste all goes to septic systems
Peabody	Yes	Yes	Yes	No	Monthly	1989	1993	Waste discharged to South Essex Sewage-Treatment Plant
Reading	Yes	Yes	Yes	No	Monthly	1987	1997	Waste discharged to Mass. Water Resources Authority
Rowley	Yes	No	No	--	--	--	--	No withdrawals from or returns to the basin
Salem	Yes	Yes	Yes	No	Daily	1989	1998	No land area in basin; waste discharged to South Essex Sewage-Treatment Plant
Tewksbury	Yes	No	Yes	No	--	--	--	No withdrawals from or returns to the basin
Topsfield	Yes	Yes	No	Yes	Monthly	1989	1993	Waste all goes to septic systems
Wenham	Yes	Yes	No	Yes	Daily	1989	1998	Waste all goes to septic systems
Wilmington	Yes	Yes	Partial	Partial	Daily	1989	1998	Wastewater from 16 percent of population goes to Mass. Water Resources Authority
Woburn	Yes	No	No	--	--	--	--	No withdrawals from or returns to the basin

Table 5. Massachusetts Department of Environmental Protection registered or permitted public and commercial water withdrawals in the Ipswich River Basin

[Reach number shown in fig. 8; Dept., Department; Mass. DEP, Massachusetts Dept. of Environmental Protection; No., number; WDM, Watershed Data Management; °, degrees; ′, minutes; ″, seconds; -- means not included or not applicable]

Reach No.	WDM data set No.	Mass. DEP source No.	Source name	Water supplier name	Included in model	Latitude	Longitude	Town	Distance from stream (feet)
1	--	3048000-02S	Mill Pond Reservoir intake	Burlington Water Dept.	No	42° 30′ 54″	71° 10′ 18″	Burlington	--
1	1012	3342000-03G	Chestnut Street well	Wilmington Water Dept.	Yes	42° 31′ 48″	71° 10′ 08″	Wilmington	560
1	1013	3342000-04G	Town Park well	Wilmington Water Dept.	Yes	42° 32′ 05″	71° 09′ 39″	Wilmington	560
1	1014	3342000-07G	Butters Row well 1	Wilmington Water Dept.	Yes	42° 31′ 58″	71° 09′ 58″	Wilmington	490
1	1015	3342000-09G	Butters Row well 2	Wilmington Water Dept.	Yes	42° 32′ 02″	71° 09′ 59″	Wilmington	280
1	1016	3342000-10G	Chestnut Street well 1A	Wilmington Water Dept.	Yes	42° 31′ 48″	71° 10′ 09″	Wilmington	560
1	--	3342001-01G	Millbrook well 1	Millbrook Country Day School, Inc.	No	42° 31′ 43″	71° 10′ 48″	Wilmington	--
5	1051	3342000-05G	Shawsheen Avenue well	Wilmington Water Dept.	Yes	42° 33′ 30″	71° 11′ 29″	Wilmington	120
5	1052	3342000-06G	Aldrich Road well	Wilmington Water Dept.	Yes	42° 33′ 01″	71° 12′ 30″	Wilmington	420
8	1080	3213000-06G	Stickney well	North Reading Water Dept.	Yes	42° 33′ 50″	71° 08′ 01″	North Reading	3,300
8	1081	3246000-02G	Revay well 2	Reading Water Dept.	Yes	42° 32′ 14″	71° 07′ 39″	Reading	5,980
8	1081	3246000-03G	Revay well 1	Reading Water Dept.	Yes	42° 32′ 16″	71° 07′ 37″	Reading	--
8	1082	3246000-04G	Well 2	Reading Water Dept.	Yes	42° 32′ 58″	71° 07′ 60″	Reading	1,340
8	1083	3246000-05G	Well 3	Reading Water Dept.	Yes	42° 32′ 56″	71° 07′ 59″	Reading	1,250
8	1084	3246000-06G	Bline well	Reading Water Dept.	Yes	42° 33′ 06″	71° 07′ 54″	Reading	490
8	1085	3246000-07G	Town Forest well	Reading Water Dept.	Yes	42° 33′ 14″	71° 07′ 38″	Reading	140
8	1086	3246000-08G	Well 82 20	Reading Water Dept.	Yes	42° 33′ 11″	71° 07′ 48″	Reading	140
8	1087	3246000-09G	Well 66 8	Reading Water Dept.	Yes	42° 33′ 05″	71° 08′ 02″	Reading	490
8	1088	3246000-10G	Well 13	Reading Water Dept.	Yes	42° 32′ 59″	71° 08′ 11″	Reading	1,110
8	1089	3246000-11G	Well 15	Reading Water Dept.	Yes	42° 32′ 56″	71° 08′ 10″	Reading	970
8	1091	31724602-01G	Well 1	Meadow Brook Golf Club	Yes	42° 32′ 34″	71° 07′ 44″	Reading	550
8	1092	31724602-01S	Surface-water withdrawal 1	Meadow Brook Golf Club	Yes	42° 32′ 32″	71° 07′ 51″	Reading	--
12	--	3009003-01G	Harold Parker well	Harold Parker State Forest	No	42° 36′ 35″	71° 05′ 31″	Andover	--
12	--	3009004-01G	Camp Evergreen well	Camp Evergreen	No	42° 36′ 20″	71° 05′ 23″	Andover	--
12	1125	3213000-04G	Central Street wellfield	North Reading Water Dept.	Yes	42° 35′ 56″	71° 06′ 44″	North Reading	100

Table 5. Massachusetts Department of Environmental Protection registered or permitted public and commercial water withdrawals in the Ipswich River Basin—*Continued*

Reach No.	WDM data set No.	Mass. DEP source No.	Source name	Water supplier name	Included in model	Latitude	Longitude	Town	Distance from stream (feet)
12	1126	3213000-05G	Route 125 well	North Reading Water Dept.	Yes	42° 35′ 58″	71° 08′ 06″	North Reading	1,550
12	1127	3213000-02G	Lakeside Boulevard well 2	North Reading Water Dept.	Yes	42° 35′ 46″	71° 07′ 51″	North Reading	140
12	1127	3213000-03G	Lakeside Boulevard well 3	North Reading Water Dept.	Yes	42° 35′ 48″	71° 07′ 50″	North Reading	140
12	1127	3213000-07G	Lakeside Boulevard well 4	North Reading Water Dept.	Yes	42° 35′ 48″	71° 07′ 50″	North Reading	140
12	1128	3342000-01G	Browns Crossing well	Wilmington Water Dept.	Yes	42° 34′ 56″	71° 08′ 44″	Wilmington	150
13	1131	3213000-01G	Railroad bed tubular wells	North Reading Water Dept.	Yes	42° 34′ 42″	71° 07′ 52″	North Reading	140
13	1132	3342000-02G	Barrows wellfield	Wilmington Water Dept.	Yes	42° 34′ 20″	71° 08′ 35″	Wilmington	100
13	1133	3342000-08G	Salem Street well	Wilmington Water Dept.	Yes	42° 34′ 42″	71° 07′ 60″	Wilmington	150
17	1171	3164000-02G	Main Street well	Lynnfield Center Water District	Yes	42° 33′ 24″	71° 02′ 41″	Lynnfield	1,060
17	1172	3164000-05G	Glen Drive well 1	Lynnfield Center Water District	Yes	42° 33′ 33″	71° 02′ 58″	Lynnfield	1,650
17	1173	3164000-06G	Glen Drive well 2	Lynnfield Center Water District	Yes	42° 33′ 33″	71° 02′ 58″	Lynnfield	1,650
17	1174	3164000-07G	Glen Drive well 3	Lynnfield Center Water District	Yes	42° 33′ 33″	71° 02′ 58″	Lynnfield	1,650
17	1175	3164000-08G	Glen Drive well 4	Lynnfield Center Water District	Yes	42° 33′ 33″	71° 02′ 58″	Lynnfield	1,650
17	1176	31716402-01G	Well 1 - Clubhouse	Sagamore Springs Golf Club, Inc.	Yes	42° 33′ 26″	71° 02′ 18″	Lynnfield	350
17	1177	31716402-02G	Well 2 - Maintenance	Sagamore Springs Golf Club, Inc.	Yes	42° 33′ 39″	71° 02′ 29″	Lynnfield	350
17	1178	31716402-03G	Well 3 - Residence	Sagamore Springs Golf Club, Inc.	Yes	42° 33′ 32″	71° 02′ 30″	Lynnfield	100
17	1179	31716402-01S	Surface-water withdrawal 1	Sagamore Springs Golf Club, Inc.	Yes	42° 33′ 30″	71° 02′ 28″	Lynnfield	--
17	1170	31716402-02S	Surface-water withdrawal 2	Sagamore Springs Golf Club, Inc.	Yes	42° 33′ 30″	71° 02′ 28″	Lynnfield	--
17	--	3164005-01G	Pocahontas well	Pocahontas Spring Water	No	42° 33′ 11″	71° 02′ 20″	Lynnfield	
18	1181	3163000-05S	Ipswich River	Lynn Water and Sewer Commission	Yes	42° 34′ 17″	71° 02′ 57″	Lynn	--
18	1182	31721303-01S	Surface-water withdrawal 1	Thomson Country Club	Yes	42° 34′ 16″	71° 02′ 09″	North Reading	--
18	1183	31721303-02S	Surface-water withdrawal 2	Thomson Country Club	Yes	42° 34′ 16″	71° 02′ 09″	North Reading	--
20	--	3184007-01G	Legion Post well	American Legion Post 227	No	42° 34′ 12″	71° 00′ 37″	Middleton	--
20	1201	3229000-03S	Ipswich River	Peabody Water Dept.	Yes	42° 33′ 39″	71° 00′ 16″	Peabody	--
21	--	3229000-02S	Suntaug Lake	Peabody Water Dept.	No	42° 31′ 17″	70° 59′ 54″	Peabody	--
22	--	3229000-04S	Winona Pond Reservoir	Peabody Water Dept.	No	42° 32′ 09″	71° 00′ 46″	Peabody	--
23	1231	3229000-01G	Pine Street well	Peabody Water Dept.	Yes	42° 32′ 38″	71° 00′ 02″	Peabody	800
23	1232	3229000-02G	Johnson Street well	Peabody Water Dept.	Yes	42° 32′ 43″	70° 59′ 57″	Peabody	100
25	1251	3071000-01G	Well 1	Danvers Water Dept.	Yes	42° 34′ 29″	70° 59′ 40″	Middleton	100
25	1252	3071000-02G	Well 2	Danvers Water Dept.	Yes	42° 34′ 08″	70° 59′ 48″	Middleton	100

Table 5. Massachusetts Department of Environmental Protection registered or permitted public and commercial water withdrawals in the Ipswich River Basin—*Continued*

Reach No.	WDM data set No.	Mass. DEP source No.	Source name	Water supplier name	Included in model	Latitude	Longitude	Town	Distance from stream (feet)
25	--	3184004-01G	Middleton Golf Course well	Middleton Golf Course, Inc.	No	42° 35′ 12″	71° 00′ 46″	Middleton	--
26	1261	3071000-01S	Middleton Pond Reservoir	Danvers Water Dept.	Yes	42° 35′ 41″	71° 01′ 15″	Middleton	--
28	--	3071002-01P	Danvers Water Dept.	Danvers State Hospital	No	42° 34′ 58″	70° 58′ 28″	Danvers	--
30	1301	3071000-02S	Swan Pond Reservoir	Danvers Water Dept.	Yes	42° 35′ 19″	71° 02′ 50″	Middleton	--
30	1302	3071000-03S	Emerson Brook Reservoir	Danvers Water Dept.	Yes	42° 36′ 12″	71° 02′ 04″	Middleton	--
30	--	3184011-01G	Candlelite well	Candlelite Motor Inn	No	42° 37′ 21″	71° 03′ 05″	Middleton	--
36	1361	--	Surface-water withdrawal 1	Tara Country Club	Yes	42° 36′ 10″	70° 58′ 24″	Danvers	--
39	--	3038009-01G	Cole School well	Harry Lee Cole School	No	42° 39′ 37″	71° 00′ 10″	Boxford	--
39	--	3038011-01G	First Church Rock well	First Church Congregation	No	42° 39′ 52″	70° 59′ 58″	Boxford	--
39	--	3038013-01G	Boxford Community Store well	Boxford Community Store, Inc.	No	42° 39′ 45″	70° 59′ 55″	Boxford	--
40	--	3038020-01G	Well 1	Andrews Farm Water Co., Inc.	No	42° 38′ 36″	70° 58′ 31″	Boxford	--
44	1441	3030001-04S	Ipswich River to Wenham Lake	Salem Beverly Water Supply Board	Yes	42° 36′ 24″	70° 54′ 05″	Wenham	--
44	1442	3030001-04S	Ipswich River to Putnamville Reservoir	Salem Beverly Water Supply Board	Yes	42° 36′ 24″	70° 54′ 05″	Wenham	--
45	1451	3030001-03S	Putnamville Reservoir to Wenham Lake	Salem Beverly Water Supply Board	Yes	42° 36′ 08″	70° 56′ 24″	Danvers	--
46	--	3298002-01G	Sleepy Hollow well	Eagle Tor Trust	No	42° 36′ 51″	70° 56′ 22″	Topsfield	--
49	1491	3119000-04G	Caisson well	Hamilton Water Dept.	Yes	42° 37′ 06″	70° 53′ 50″	Hamilton	100
49	1492	3119000-05G	Idlewild 1 well	Hamilton Water Dept.	Yes	42° 37′ 12″	70° 53′ 50″	Hamilton	300
49	1493	3119000-06G	Idlewild 2 well	Hamilton Water Dept.	Yes	42° 37′ 13″	70° 53′ 45″	Hamilton	720
49	1494	3320000-01G	Well 1	Wenham Water Dept.	Yes	42° 36′ 37″	70° 53′ 40″	Wenham	400
49	1495	3320000-02G	Well 2	Wenham Water Dept.	Yes	42° 36′ 39″	70° 53′ 41″	Wenham	300
50	1501	3119000-03G	Patton well	Hamilton Water Dept.	Yes	42° 38′ 01″	70° 54′ 04″	Hamilton	920
50	1502	3298000-02G	Perkins Row well	Topsfield Water Dept.	Yes	42° 38′ 50″	70° 55′ 33″	Topsfield	300
51	--	3038001-01G	Well 1	Four Mile Village	No	42° 41′ 07″	71° 00′ 13″	Boxford	--
51	--	3038001-02G	Well 2	Four Mile Village	No	42° 41′ 07″	71° 00′ 14″	Boxford	--
51	--	3038001-03G	Bedrock well 3	Four Mile Village	No	42° 41′ 07″	71° 00′ 08″	Boxford	--
53	1531	3298000-01G	North Street well	Topsfield Water Dept.	Yes	42° 39′ 12″	70° 56′ 34″	Topsfield	100
53	--	3298005-01G	Well 1	New Meadows Golf Club	No	42° 39′ 50″	70 °55′ 34″	Topsfield	--
57	1571	3144000-04G	Winthrop well 2	Ipswich Water Dept.	Yes	42° 39′ 26″	70° 53′ 07″	Ipswich	250
57	1571	3144000-05G	Winthrop well 3	Ipswich Water Dept.	Yes	42° 39′ 26″	70° 53′ 05″	Ipswich	380
59	1591	3144000-03G	Winthrop well 1 and tubular wells	Ipswich Water Dept.	Yes	42° 39′ 20″	70° 52′ 38″	Ipswich	70

Table 5. Massachusetts Department of Environmental Protection registered or permitted public and commercial water withdrawals in the Ipswich River Basin—*Continued*

Reach No.	WDM data set No.	Mass. DEP source No.	Source name	Water supplier name	Included in model	Latitude	Longitude	Town	Distance from stream (feet)
61	1611	3030001-02S	Longham Reservoir to Wenham Lake	Salem Beverly Water Supply Board	Yes	42° 35′ 27″	70° 52′ 17″	Wenham	--
61	1612	3030001-02S	Longham Reservoir to Miles River	Salem Beverly Water Supply Board	Yes	42° 35′ 27″	70 °52′ 17″	Wenham	--
62	1621	3030001-01S	Wenham Lake to Beverly	Salem Beverly Water Supply Board	Yes	42° 35′ 03″	70° 53′16″	Beverly/Wenham	--
62	1622	3030001-01S	Wenham Lake to Salem	Salem Beverly Water Supply Board	Yes	42° 34′ 59″	70° 53′ 24″	Beverly/Wenham	--
64	1641	31711902-01S	Surface-water withdrawal 1	Myopia Hunt Club Golf Course	Yes	42° 36′ 35″	70° 51′ 38″	Hamilton	--
65	--	3119000-01G	Bridge Street well	Hamilton Water Dept.	No	42° 36′ 57″	70 50′ 35″	Hamilton	--
65	1651	3119000-02G	School well	Hamilton Water Dept.	Yes	42° 36′ 44″	70° 50′ 07″	Hamilton	200
66	1661	3144000-06G	Essex Road well	Ipswich Water Dept.	Yes	42° 39′ 27″	70° 49′ 37″	Ipswich	150
66	1662	3144000-07G	Fellows Road well	Ipswich Water Dept.	Yes	42° 39′ 05″	70° 49′ 30″	Ipswich	350
67	--	31714401-01S	Surface-water withdrawal 1	Corliss Brothers Farm	No	42° 39′ 48″	70° 49′ 52″	Ipswich	--

During the calibration period, Hamilton obtained water from two wells along Idlewild Brook (one new well has since been installed and is included in the model, but with no withdrawals specified during the calibration period), and a well each along the Ipswich River and Miles River. The combined average annual withdrawal from these wells during the calibration period was 0.79 Mgal/d.

Reading has one of the most developed well fields along the Ipswich River —11 wells have a combined annual withdrawal of 1.96 Mgal/d. North Reading obtains water from 7 wells; 6 of these are along Martins Brook and 1 is along the Ipswich River. These wells had a combined average annual withdrawal of 0.87 Mgal/d during the calibration period. One of the wells along Martins Brook and the well along the Ipswich River were not pumped during the calibration period, but they were included in the model with no withdrawals specified during the calibration period.

Topsfield obtains water from a well along the Ipswich River and a well along Howlett Brook. These wells have a combined average annual withdrawal of 1.36 Mgal/d. Total monthly withdrawals were reported for each well.

Withdrawal rates for wells in Hamilton, North Reading, and Topsfield were obtained from the MADEP. Withdrawals in 1989 were unavailable and estimated from the average 1990–93 monthly withdrawals. Daily withdrawals were obtained by disaggregating monthly withdrawals using Wenham records as described below.

Of these four towns, only Reading has a municipal wastewater system, which discharges to the ocean through the Massachusetts Water Resources Authority system; the other three towns rely on onsite septic systems for waste disposal.

The Thomson Country Club in North Reading operates 2 surface-water withdrawals for private use that take water directly from the Ipswich River just upstream of the South Middleton station. The combined average withdrawal from the two surface-water sources was 0.023 Mgal/d during the calibration period. The withdrawals generally were taken only during April through November each year.

Lynnfield. Lynnfield obtained its entire water supply from 1 well in the Wills Brook headwaters during the calibration period. This well had an average withdrawal of 0.31 Mgal/d during the period. The town provided daily withdrawal data from the well for the period 1989–97. The town installed 4 new wells in the Wills Brook headwaters during 1997. These wells were included in the model with no withdrawals specified during the calibration period.

The Sagamore Spring Golf Club, Inc., operates 3 wells and 2 surface-water withdrawals for private use in the Wills Brook headwaters in Lynnfield. Pumping rates for these supplies were provided by the MADEP, and were included in the model. The combined average withdrawal from the three wells was 0.006 Mgal/d, and the combined average withdrawal from the two surface-water sources was 0.053 Mgal/d during the calibration period. The surface-water withdrawals generally were taken only during April through November each year. Lynnfield relies on onsite septic systems for wastewater disposal.

Lynn. Lynn (completely outside the basin) obtained water directly from the Ipswich River just above the South Middleton station during 1989 and 1993. Withdrawals averaged 3.1 Mgal/d in 1989 and 0.39 Mgal/d in 1993.

Peabody. Peabody obtains water from 2 wells along Norris Brook and directly from the Ipswich River about 1 mile downstream from the South Middleton station. Water from the Ipswich River is pumped seasonally to Suntaug Lake and from there, re-distributed to Winona Pond or other reservoirs outside of the Ipswich Basin. Under normal operation, all water from Suntaug Lake and Winona Pond is exported from the basin (Peter Smyrnios, Peabody Water Department, oral commun., 1999). Only the water withdrawn from the Ipswich River is included in the model. Direct runoff to Suntaug Lake and Winona Pond were modeled, but did not contribute to the Ipswich Basin. Municipal wastewater is discharged to the ocean.

Only one of the two wells was active during the calibration period. The monthly withdrawals from the active well were obtained from the MADEP for 1990–93. Monthly withdrawals for 1989 were estimated from the average monthly withdrawals for 1990–93 period. Daily withdrawals were estimated by transforming the withdrawal for each month into a daily value that averaged 0.07 Mgal/d during the calibration period.

Danvers and Middleton. Danvers and Middleton obtain water from two wells and three water-supply reservoirs: Swan Pond, Emerson Brook Reservoir, and Middleton Pond. Water is diverted from Swan Pond and Emerson Brook Reservoir into Middleton Pond, and from there, water is diverted into the water-supply system. Swan Pond is pumped only during October and November; at other times, the water level in the pond is maintained to help prevent dewatering of nearby residential wells. Emerson Brook Reservoir is pumped only when water is available (it usually dries in the summer) and there is storage available in Middleton Pond (Donald DeHart, Danvers Department of Public Works, written commun., 1998). Monthly water levels and curves for water level, storage volume, surface area, discharge were provided for each reservoir.

The two wells are adjacent to the Ipswich River and had a combined average withdrawal of 0.11 Mgal/d during the calibration period. Monthly withdrawals were reported for 1989 through part of 1998. Daily withdrawals were obtained by transforming monthly values into daily values. Municipal wastewater from Danvers is discharged to the ocean. Middleton is mostly unsewered and septic effluent in these areas that is not lost to evaporation is returned to the Ipswich River Basin.

Boxford. The town of Boxford has no municipal water-supply or wastewater systems. Residents rely on individual wells and onsite septic systems; thus no water-use activities were included in the model for the town.

Wenham. The town of Wenham obtains water from 2 wells adjacent to Idlewild Brook. Wenham provided total daily well withdrawals for 1989 through part of 1998. The combined daily withdrawals from these wells averaged 0.32 Mgal/d during the calibration period and are evenly divided between the two wells. Wastewater discharges to onsite septic systems.

Withdrawals from the Wenham wells were used to estimate daily withdrawals for some towns (as noted) where only monthly withdrawal rates were available. The Wenham records were considered to reflect the day-to-day water-supply demands in other towns in response to climatic conditions. Wenham records were not used to estimate daily ground-water withdrawals for Peabody, Danvers, and Middleton because their water supplies use both surface- and ground-water supplies. In systems such as these, the day-to-day fluctuations in ground-water pumping would not be the same as for a system that relies solely on ground-water supplies because short term increases in demand can be obtained from reservoir storage rather than increased well withdrawals.

Large day-to-day fluctuations in the Wenham withdrawals were probably caused by the operation of the town's water supply rather than user demands in response to climatic variations. These operational-related fluctuations were therefore removed by using a 15-day moving average, centered on the 8th day before using the record to estimate the pattern of daily demands for towns where only monthly records were available. The smoothing period was determined empirically to maintain a reasonably large variation in the daily values while eliminating the large operational fluctuations. Daily withdrawals were computed for wells with only monthly values by (1) computing monthly mean withdrawal rates from the smoothed daily values at Wenham, (2) computing the ratio between the daily withdrawals and mean monthly withdrawals for each day at Wenham, (3) computing the average daily withdrawal by month for towns where only monthly values were available, and (4) multiplying the average daily values by the daily ratios computed from Wenham data.

The variation in streamflow depletion caused by ground-water withdrawals is substantially less than actual well pumping rates because of the damping effect of aquifer storage. Figure 9 shows the combined daily pumping of the two Wenham wells for 1989, the smoothed daily pumping rate (pattern used to estimate daily pumping rates in other towns), and the calculated depletion of flow in Idlewild Brook (RCHRES no. 49, fig. 8) caused by ground-water withdrawals. The streamflow depletion is computed using the STRMDEPL program described in Appendix A.

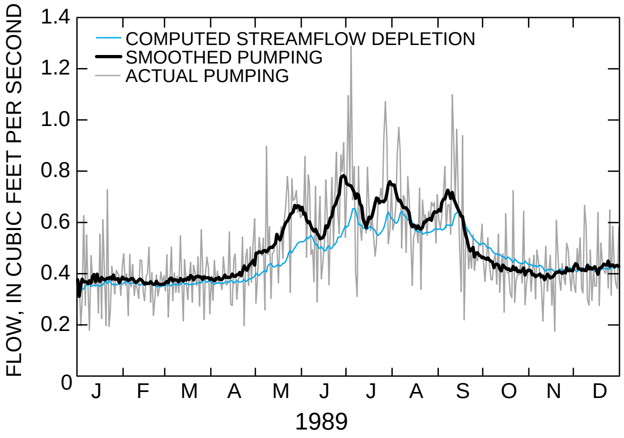


Figure 9. Combined actual and 15-day moving average daily ground-water withdrawals from two Wenham water supply wells, and the calculated streamflow depletion of flow in Idlewild Brook, Mass., 1989.

Salem and Beverly. Salem and Beverly obtain their water from the Salem-Beverly Water-Supply Board (SBWSB), which depends entirely on surface-water sources in the Ipswich River Basin. The SBWSB maintains three reservoirs in the basin: Putnamville Reservoir, Longham Reservoir, and Wenham Lake. Water is withdrawn from the Ipswich River through the 3-mile long Salem-Beverly Canal to an intake that pumps water into the Putnamville Reservoir and Wenham Lake for storage and later use. Water in Putnamville Reservoir is diverted to Wenham Lake when Wenham Lake storage runs low. Water is also diverted from Longham Reservoir, near the headwaters of the Miles River subbasin, to Wenham Lake.

The SBWSB supplied daily time series for the period 1989 through 1997 of diversions from the Ipswich River to Putnamville Reservoir and Wenham Lake, diversions from Putnamville Reservoir and Longham Reservoir to Wenham Lake, and releases from Longham Reservoir to the Miles River. The SBWSB provided monthly time series of pumping from Wenham Lake, and water levels and capacity tables for its reservoirs. During the calibration period, the SBWSB diverted an annual average of 1,787 Mgal from the Ipswich River, and 1,187 Mgal from Longham Reservoir. Wastewater for Salem and Beverly is discharged to the ocean.

Ipswich. The town of Ipswich obtains water from three wells adjacent to Ipswich River and two wells adjacent to Miles River. Monthly withdrawals were reported for 1989, and daily withdrawals were reported for 1990 through part of 1998 for each well. The town also uses water sources in the Parker River Basin, but these were not modeled. Daily withdrawals were obtained for 1989 by disaggregating monthly withdrawals using Wenham records as described above. The combined average withdrawal from Ipswich wells in the Ipswich River Basin during the calibration period was 0.21 Mgal/d. Municipal sewers serve about half the population and the treated effluent is discharged to the Ipswich River below Sylvania Dam.

Andover, Billerica, North Andover, and Tewksbury. No municipal water supplies or wastewater returns were modeled for the towns of Andover, Billerica, North Andover, and Tewksbury. These towns obtain municipal water supplies outside of the Ipswich Basin and in areas that are sewered, wastewaters are discharged outside of the basin.

Representation of the Basin

The physical and spatial representation of the basin in the model is defined by the combination of HRUs (PERLNDs and IMPLNDs), their contributing area to a reach, and the linkage of one reach to another. The process of defining HRUs, their linkage to reaches, and the linkage of reaches to each other often is referred to as the schematization or discretization of a basin. A Geographic Information System (GIS) was used to discretize the watershed. Basin boundaries for many of the reaches in the model were available from a state-wide digital data layer constructed by the USGS and MassGIS (Massachusetts Geographic Information System). Basin boundaries for reaches that were not available from this data layer were delineated from 1:25,000-scale Digital Elevation Model (DEM) data or, in some cases, they were digitized by hand from 1:25,000-scale USGS topographic maps. Other data layers used in the discretization process were obtained from MassGIS, and include 1:125,000-scale surficial geology, 1:25,000-scale land use, 1:25,000-scale hydrography, and 1:5,000-scale wetlands. These data layers, including detailed descriptions, can be obtained at MassGIS (http://www.state.ma.us/mgis/).

The spatial data were simplified and grouped to obtain categories that were considered important to the hydrology of the watershed. The surficial-geology data layer was simplified from 7 types of materials into 3 on the basis of permeability and storage characteristics: (1) sand and gravel, (2) till and bedrock, and (3) fine-grained or alluvial deposits. The land-use data layer was combined with the wetland data layer and then simplified from 62 categories to 8 land-use categories: (1) forest, (2) open irrigated, (3) open-non-irrigated, (4) open water, (5) forested wetland, (6) non-forested wetland, (7) low-density residential, (8) high-density residential, and (9) commercial. HRUs were obtained by combining the surficial geology and the simplified land-use data layers. Intersection of the combined surficial-geology and land-use data layers with the sub-basin delineations yielded the area of each HRU for each subbasin.

Hydrologic Response Units

Fourteen out of 27 possible combinations of surficial geology and land use covered areas sufficiently large to warrant unique HRUs. Combinations of surficial geology and land use with areas less than about 1 percent of the basin area were grouped into the HRU with the most similar characteristics. For instance, open-non-irrigated land accounted for about 1 percent of the watershed area; therefore, this category was combined with the open-irrigated category. From the initial 14 HRUs, four additional HRUs that represent residential areas on public water and septic systems and two HRUs that represent impervious areas were developed as described below.

Impervious Areas (IMPLNDs)

Impervious areas are any surfaces that prohibit infiltration of water into the ground, such as building roofs, paved roads, and parking lots. Water on some impervious surfaces can eventually infiltrate into the ground because these surfaces drain onto pervious surfaces that allow infiltration. In the HSPF model, IMPLNDs are used to simulate effective impervious areas, which are impervious surfaces that drain directly to streams, and thus produce only surface runoff. Non-effective impervious areas, which are impervious surfaces that drain to pervious surfaces, are incorporated into one of the disturbed PERLND types as described later. In large basins such as the Ipswich, values for imperviousness, and particularly effective imperviousness, are difficult to obtain. Initial estimates of the effective impervious area were made as a percentage of commercial land use and different classes of residential land use as indicated in table 6. High-density residential land use represents multi-family residential and single-family residential on lots with areas smaller than or equal to 0.5 acre. Low-density residential land use represents single-family homes on lots larger than 0.5 acre.

Table 6. Estimated effective impervious area by land use, Ipswich River Basin, Mass.

[MassGIS, Massachusetts Geographic Information System]

Land use classification	Area of basin as classified by MassGIS (acres)	Estimated percent of area that is effective impervious		Effective impervious area (acres)	
		Initial	Final	Initial	Final
Commercial	3,586	79	63	2,844	2,275
High-density residential	11,492	27	14	3,157	1,579
Low-density residential	14,483	5	2.5	724	362
Total	29,562			6,725	4,216

Initial estimates of effective impervious area are similar to those reported by Dinicola (1990) and Alley and Veenhuis (1983) for similar land-use types. The final effective impervious area was obtained primarily by calibration of small summer storms that generate runoff mostly from effective impervious surfaces, however, other factors including the overall responsiveness of the hydrograph to precipitation and water budgets were considered because small summer storms can also be affected by surface retention, widely distributed small flow-control structures, precipitation variability, and other factors.

Two IMPLND types were used in the model: (1) commercial, and (2) residential which represents the combined impervious area from high- and low-density residential areas. The calibrated effective impervious area was decreased from the initial estimated values by 20 percent for commercial areas and by 50 percent for residential areas. Although, about 30 percent of the basin is classified as developed, the estimated total effective impervious area as a percent of the total basin area is 6.8 at the South Middleton station, 4.6 at the Ipswich station, and 4.4 at Sylvania Dam.

Pervious Areas (PERLNDs)

Pervious areas are any surface that allows infiltration and are represented by 14 HRUs initially obtained by the intersection of data layers for surficial geology and land-use types, plus the 4 new HRUs to represent different residential areas on public water and onsite septic systems (described later). Water and wetlands (nos. 16, 17, and 18 in table 7) were not used as PERLND types in the final model, but are included in the table for reference. General descriptions and areas of each PERLND for the drainage area above the South Middleton station, Ipswich station, and the Sylvania Dam are presented in table 7. Areas of HRUs as a percentage of the drainage area to each station and the Sylvania Dam are shown in figure 10. This plot indicates that most of the HRUs are evenly distributed throughout the watershed. A small area (about 0.6 mi^2) that drains to the Ipswich station was excluded from the model because it drains directly to a supply reservoir that exports water from the basin.

Table 7. Hydrologic Response Units (HRUs) used to represent the Ipswich River Basin and their contributing areas to the South Middleton and Ipswich stations and to Sylvania Dam, Mass.

[Shaded rows indicate area incorporated into model as river reaches (RCHRES); mi^2, square mile]

HRU	Area in acres				Surficial geology	Land use
	South Middleton station	Ipswich station	Sylvania Dam	Total as a percent of basin		
PERLND 1	2,990	9,312	12,534	13	Sand and gravel	Forest
PERLND 2	377	1,762	3,554	3.7	Sand and gravel	Open
PERLND 3	675	2,391	3,879	4.1	Sand and gravel	Open, low density residential
PERLND 4	1,416	2,461	3,028	3.2	Sand and gravel	Open, low density residential on public water and onsite septic
PERLND 5	1,456	2,761	3,687	3.9	Sand and gravel	Open, high density residential
PERLND 6	1,102	1,864	2,250	2.4	Sand and gravel	Open, high density residential on public water and onsite septic
PERLND 7	626	1,125	1,280	1.3	Sand and gravel	Open, commercial
PERLND 8	4,777	20,202	22,118	23	Till	Forest
PERLND 9	328	2,170	2,658	2.8	Till	Open
PERLND 10	1,023	3,667	4,238	4.4	Till	Open, low density residential
PERLND 11	1,814	3,154	3,373	3.5	Till	Open, low density residential on public water and onsite septic
PERLND 12	989	1,991	2,290	2.4	Till	Open, high density residential
PERLND 13	1,391	2,259	2,374	2.5	Till	Open, high density residential on public water and onsite septic
PERLND 14	939	1,273	1,630	1.7	Alluvial	Forest
PERLND 15	121	171	400	.4	Alluvial	Open
16	403	1,683	2,384	2.5		Water
17	1,765	5,293	6,680	7.0		Wetland, non-forested
18	4,228	11,691	13,119	14		Wetland, forested
IMPLND 1	817	1,707	1,941	2.0		Impervious residential
IMPLND 2	1112	2,000	2,275	2.4		Impervious commercial
Total (mi^2)	44.3	124.2	149.5			

Development of PERLND Types

Twelve PERLND types were developed for open space: 3 for undeveloped open areas on different surficial deposits and 9 for open areas associated with development (table 7). Open area associated with development represents the green space between buildings and paved surfaces that likely receives runoff from adjacent impervious surfaces. These areas are considered disturbed; therefore, infiltration and soil-water storage was decreased relative to undeveloped open HRUs for similar surficial geology types. Four PERLND types were created for open residential areas to represent two different development densities over two types of surficial geology. One PERLND type was created for open commercial areas. Duplicate PERLND types are specified for each of the four open residential area PERLNDs to represent areas on public water and onsite septic systems described below. Other PERLND types include forested areas over sand and gravel, till, and alluvial deposits.

Hydrologic characteristics are generally similar for PERLNDs with similar surficial geology; however upper- and lower-zone storage and infiltration is less for disturbed open PERLNDs relative to similar undisturbed open PERLNDs. Lower-zone evapotranspiration is highest in forested PERLND types and lowest in undisturbed open PERLND types. The calibrated parameter values for each HRU are given in the UCI file listed in Appendix B.

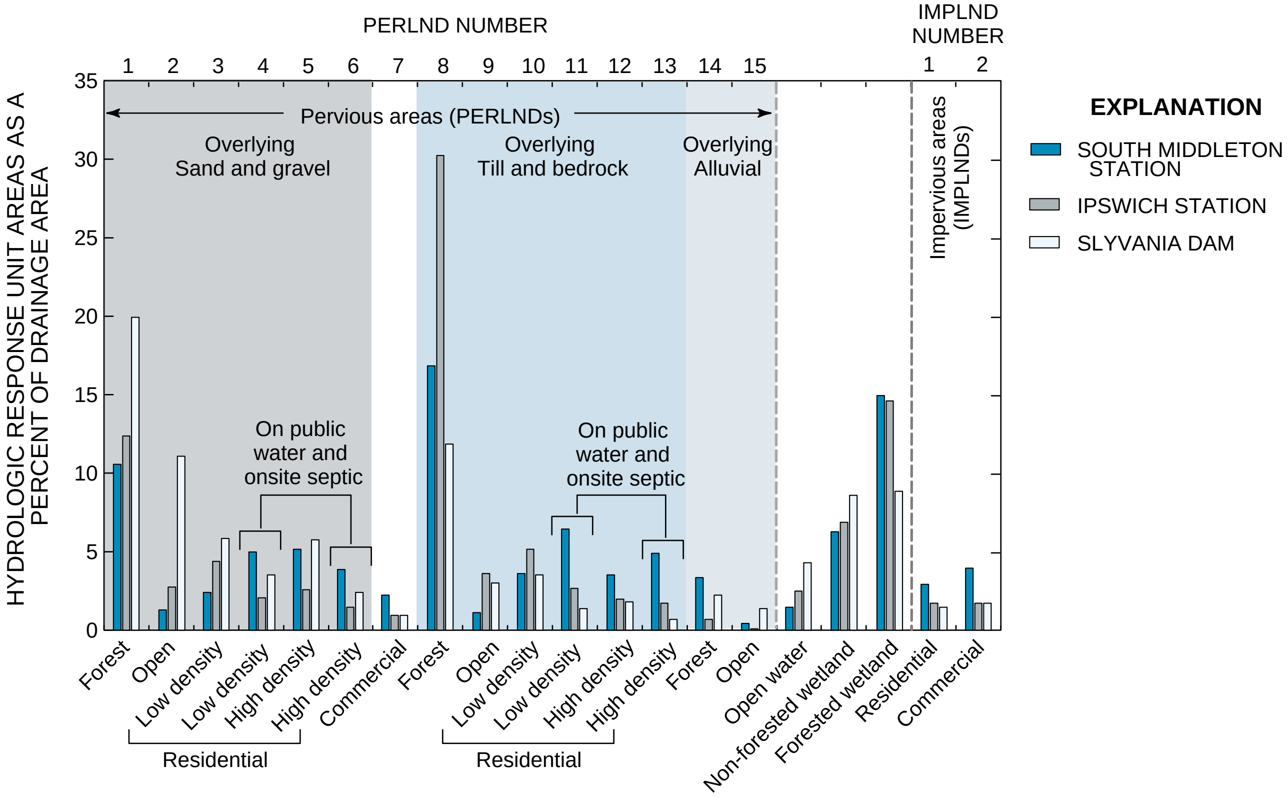


Figure 10. Areas of hydrologic response units in the Hydrological Simulation Program-FORTRAN (HSPF) model of the Ipswich River Basin, Mass. as a percentage of the drainage area above the South Middleton and Ipswich stations and above Sylvania Dam, Mass.

Residential Areas on Public Water and Onsite Septic Systems

Residential areas on public water and onsite septic systems were considered to represent a net inflow of water to the area, whereas residential areas on public water and public sewer and residential areas on private wells and onsite septic systems were considered to have no net water gain or loss. To account for residential areas on public water and septic systems, 1990 TIGER census-tract data (http://www.census.gov/) were used to determine the number of houses on public water but not public sewer. The census-tract data were used because public-utility maps were not readily available across the basin. The census-tract data indicated that about half the households in the basin are on public water but not public sewer. Several assumptions were made to relate the census-tract data with land-use information to develop HRUs served by public water but not public sewer.

The original MassGIS land-use cover had 4 categories of residential land use: (1) multi-family, (2) less than 1/4 acre, (3) 1/4 to 1/2 acre, and (4) greater than 1/2 acre. Households on public water and onsite septic systems were assumed only to be associated with residential areas of 1/4 to 1/2 acre and greater than 1/2 acre (moderate and low density residential development, respectively). Multifamily residential and high-density residential areas (lots less than 1/4 acre) were assumed to have both public water and public sewer.

Low- and moderate-density residential land-use areas were obtained for each census tract. The number of homes on public water and onsite septic systems in each census tract were apportioned to that tract’s areas of low and moderate-density residential development. It was further assumed that the average lot size for moderate-density development is 1/3 acre and for low-density development is 2/3 acre, and that houses on more than 1 acre were not classified as residential. The residential areas affected by public water and onsite septic systems were then calculated by census tract.

Subbasin areas of residential land use with public water and onsite septic systems were calculated by a weighted average of the census tract areas within each subbasin. The portion of areas on public water and onsite septic systems that overlay different types of surficial geology were calculated using the portion of area of different residential development densities over different surficial geology types in each subbasin. Minor adjustments in the calculated area were made to correct for imprecision in the method, so that the total residential area by subbasin and surficial geology remained the same as the area originally derived from the MassGIS land-use data.

Four new HRUs were added to the model to represent residential areas on public water and onsite septic systems: (1) high-density development over sand and gravel, (2) low-density development over sand and gravel, (3) high-density development over till, and (4) low-density development over till. These HRUs are identical to four corresponding residential HRUs that are not affected by public water and onsite septic systems; the difference between the two groups of HRUs is that a small quantity of water is added to the lower-soil zone as inflow from septic effluent to represent the average household water use. Low-density residential areas on public water and onsite septic systems were shifted from the area of low-density residential HRUs with similar surficial geology. Moderate-density residential areas on public water and septic were shifted from the areas of high-density residential HRUs with similar surficial geology.

The quantity of septic effluent was calculated by multiplying the average occupancy per household (average of 3 persons occupancy for homes on public water and onsite septic systems from the census-tract data) by the average water use of 79 gal/d per person (Massachusetts Department of Environmental Management, 1987a). The resulting 237 gal/d per household was distributed over the 1/3 and 2/3 acres for moderate- and low-density residential development, respectively. This value was converted to inch per hour per acre and was added to the affected HRUs – $1.09\text{x}10^{-3}$ in/hr/acre for moderate-density residential areas and $5.45\text{x}10^{-4}$ in/hr/acre for low-density residential areas. This small quantity of water was added to the applicable HRUs as inflow to the lower-zone storage (LZLI) by means of an external time-series. Applying the septic effluent to the lower-soil zone was considered the most appropriate because septic leach fields are typically installed in this part of the soil horizon. Inflow to the lower-soil zone is not available to runoff or discharge as interflow or active ground water flow. Rather, septic effluent directed into the lower-zone storage means there is less opportunity for infiltrated moisture to be held in the lower-zone storage because the added inflow from the septic effluent will keep this storage closer to its capacity then would otherwise occur. As a result, more infiltrated atmospheric moisture will reach the active ground-water storage in areas with septic effluent then in similar areas without septic effluent.

Water added to the basin in areas on public water and onsite septic systems is not linked to any particular source. Thus, the public water-supply source, whether inside or outside the basin, is inconsequential to the water added as septic effluent. For example, the town of North Reading, which is not sewered, supplements its water supply during the summer from the town of Andover system, which obtains water from the adjacent Merrimack River Basin.The septic effluent for North Reading is treated by the model as an inflow to the Ipswich Basin all year round, whether the water originated from the Merrimack Basin in the summer or from within the Ipswich Basin.

The estimated septic effluent rate is 9.6 in/yr on high-density residential areas and 4.8 in/yr on low-density residential areas; these rates represent about 20 and 10 percent of the average annual moisture-supply to these areas, respectively. Residential areas on public water and onsite septic compose an estimated 21, 13, and 12 percent of the drainage area to the South Middleton and Ipswich stations, and the Sylvania Dam, respectively. If the septic effluent were to reach the stations and Sylvania Dam this would comprise about 8 percent of the total runoff to the South Middleton station and about 4 percent each of the total runoff to the Ipswich station and to Sylvania Dam, but these values do not consider the septic effluent lost to evapotranspiration. Septic effluent is estimated to be 3 percent of the total moisture supply to the South Middleton station and about 2 percent each of the moisture supply to the Ipswich station and to Sylvania Dam.

Stream Reaches

The Ipswich River and its main tributaries were segmented into 67 reaches (fig. 8). The reach segmentation was determined based on hydrology, water use, and in some cases, habitat considerations. A list of these reaches is provided in table 8. Water from RCHRES 21 (Suntaug Lake) is diverted out of the basin for the town of Peabody water supply. This reach was included in the model, but water does not contribute to the Ipswich River, so that the model can be used for firm yield analysis of this supply in the future. RCHRES 22 (Winona Pond) was not explicitly simulated because all water is diverted into the Peabody supply. The natural drainage to the Winona Pond is diverted around the pond; therefore, the overland drainage area in RCHRES 22 was combined with RCHRES 23. Methods used to define the reach geometry that control the storage-discharge characteristics of reaches and the incorporation of wetlands as RCHRES are described below.

Hydraulic Characteristics (FTABLEs)

FTABLEs define the relations among depth, surface area, volume, and discharge of reaches used in the kinematic wave routing of flow downstream. FTABLEs are specified for the outflow gate used to route water downstream; the first outflow gate was used for reaches with no water withdrawals, and typically the second outflow gate was used for reaches with water withdrawals.

The relations in the FTABLEs depend on the hydraulic properties of the reaches. The relation between depth and discharge is usually defined by the hydraulic properties at the downstream end of the reach, but the discharge-volume relation is a function of the hydraulic properties of the entire reach. Hydraulic properties such as channel geometry, length, slope, and roughness, were determined from available data for each reach, or estimated on the basis of the properties of similar reaches. The hydraulic properties were used to solve Manning's equation for open-channel flow to develop the FTABLEs.

Reach lengths and slopes were determined from digital map layers. Node locations were digitized into a map layer. This layer was intersected with the stream map layer to determine the distances between nodes, and intersected with the DEM data to determine the elevation at each node and at the stream source in headwaters areas. Differences in elevation between nodes, or between stream sources and nodes, were divided by stream lengths to obtain reach slopes.

Channel cross-section data were obtained mostly from Federal Emergency Management Agency (FEMA) flood-prone area maps and survey data. Cross-section data were also obtained from streamflow measurements at the gaging stations and partial-record sites, site surveys, and ratings of structures provided by water suppliers. Data were available for several hundred cross sections in the basin from FEMA studies. The Channel Geometry Analysis Program (CGAP) (Regan and Schaffranek, 1985) was used to calculate the stage-storage-discharge relations from multiple cross sections and estimates of channel roughness. The stage-discharge relations obtained from CGAP commonly were adjusted on the basis of rating curves developed for the gaging stations and partial-record sites that coincided with node locations (table 8). The measurements defined the low-flow end of the relations better than the FEMA data because usually few depth readings were taken in the low-flow channel for the FEMA studies, whereas discharge measurements usually contain at least 25 such readings.

FEMA cross-sections and discharge measurements often were not available for the small tributaries and in the headwater areas of the basin. In these areas, FTABLEs were constructed for the reaches by use of the XSECT program (AquaTerra Consultants, 1998, written commun.) XSECT assumes a trapezoidal channel configuration, and solves Manning's equation based on channel slope, length, height, bottom and top width, flood-plain slope, and channel and flood-plain roughness. Channel length and slope for these reaches were determined from GIS analysis like all other cross sections. Other parameters for XSECT were determined from site inspections and by transfer of information from similar reaches where the parameters were known. XSECT also was used to develop FTABLEs for some sections of the main channel of the Ipswich River, where FEMA cross-sections were inadequately spaced to provide reasonable results with the CGAP program.

Table 8. Stream reaches (RCHRES) in the Hydrological Simulation Program-FORTRAN model of the Ipswich River Basin, Mass.

[Total drainage area includes the direct drainage area to the reach plus the drainage area above the reach. Area is in square miles; No., number; USGS, U.S. Geological Survey; --, means station number not assigned or no upstream reach;°- degrees, ′ - minutes, ″- seconds]

Reach No.	USGS station No.	Downstream node location		Reach name	Direct drainage area	Total drainage area	Upstream reach No.
		Latitude	Longitude				
1	01101300	42° 32′ 13″	71° 09′ 40″	Maple Meadow Brook at Route 38, Wilmington	4.03	4.03	--
2	--	42° 33′ 07″	71° 09′ 27″	Maple Meadow Brook above mouth, Wilmington	.66	4.69	1
3	--	42° 33′ 08″	71° 09′ 28″	Mill Brook above Maple Meadow Brook, Wilmington	3.51	3.51	--
4	--	42° 33′ 13″	71° 08′ 41″	Mill Brook above Lubbers Brook, Wilmington	.49	8.68	2,3
5	01101320	42° 33′ 50″	71° 11′ 05″	Lubbers Brook above Main Street (Route 38), Wilmington	2.83	2.83	--
6	--	42° 34′ 12″	71° 09′ 31″	Lubbers Brook above Middlesex Avenue, Wilmington	1.89	4.71	5
7	--	42° 33′ 14″	70° 08′ 41″	Lubbers Brook above mouth, Wilmington	.90	5.61	6
8	--	42° 33′ 40″	71° 05′ 40″	Ipswich River at Mill Street near Reading	4.19	18.5	4,7
9	--	42° 33′ 58″	71° 06′ 16″	Bear Meadow Brook above mouth near Reading	4.83	4.83	--
10	--	42° 34′ 15″	71° 06′ 03″	Ipswich River above Martins Brook, North Reading	.42	23.7	8,9
11	01101380	42° 36′ 42″	71° 05′ 58″	Skug River at Harold Parker Road, Andover	2.51	2.51	--
12	01101395	42° 34′ 47″	71° 08′ 22″	Martins Brook at Route 62, North Reading	7.85	10.4	11
13	01101400	42° 34′ 16″	71° 06′ 04″	Martins Brook above mouth, North Reading	2.97	13.3	12
14	--	42° 34′ 35″	71° 04′ 14″	Ipswich River above unnamed tributary, North Reading	1.02	38.1	10,13
15	01101460	42° 34′ 36″	71° 04′ 15″	Ipswich River Tributary at North Reading	2.08	2.08	--
16	--	42° 34′ 16″	71° 02′ 58″	Ipswich River above Wills Brook, North Reading	1.10	41.2	14,15
17	01101480	42° 34′ 13″	71° 02′ 57″	Wills Brook near North Reading	1.76	1.76	--
18	--	42° 34′ 11″	71° 01′ 51″	Ipswich River at South Middleton Dam, near Lynnfield	.78	43.8	16,17
19	01101500	42° 34′ 10″	71° 01′ 39″	Ipswich River at South Middleton gaging station	.61	44.4	18
20	--	42° 34′ 01″	70° 59′ 56″	Ipswich River above Norris Brook, Danvers	1.18	45.6	19
21	--	42° 31′ 33″	71° 00′ 30″	Norris Brook at Suntaug Lake Outlet, Peabody	.50	.50	--
22	--	42° 32′ 14″	71° 00′ 28″	Norris Brook at Winona Pond Outlet, Peabody	.93	1.44	21
23	01101510	42° 33′ 14″	71° 00′ 15″	Norris Brook above Russell Street, Peabody	2.66	4.10	21
24	--	42° 34′ 00″	70° 59′ 54″	Norris Brook above mouth, Danvers	.42	4.52	23
25	--	42° 34′ 40″	70° 59′ 37″	Ipswich River at Old Log Bridge Road near Middleton	1.92	52.0	20, 24
26	--	42° 35′ 40″	71° 01′ 13″	Middleton Pond Outlet, Middleton	1.53	1.53	--
27	--	42° 35′ 18″	71° 00′ 03″	Middleton Pond Brook, Middleton	.66	2.19	26
28	01101540	42° 35′ 45″	70° 59′ 49″	Ipswich River at Maple Street (Route 62), Middleton	1.64	55.8	25, 27
29	--	42° 36′ 38″	70° 59′ 53″	Ipswich River above Emerson Brook, Middleton	.74	56.6	28
30	--	42° 36′ 14″	71° 02′ 06″	Emerson Brook Reservoir, Middleton	4.71	4.71	--
31	01101550	42° 36′ 37″	70° 59′ 56″	Emerson Brook above mouth, Middleton	1.66	6.37	30
32	01101610	42° 37′ 58″	71° 02′ 35″	Boston Brook at Sharpners Pond Road near North Andover	5.59	5.59	--
33	01101650	42° 37′ 15″	71° 01′ 14″	Boston Brook at Liberty Road near Middleton	2.57	8.16	32
34	--	42° 36′ 40″	70° 59′ 55″	Boston Brook above mouth, Middleton	2.76	10.9	33
35	--	42° 37′ 17″	70° 58′ 52″	Ipswich River above Nichols Brook, Middleton	1.54	75.4	29,31,34

Table 8. Stream reaches (RCHRES) in the Hydrological Simulation Program-FORTRAN model of the Ipswich River Basin, Mass.—*Continued*

Reach No.	USGS station No.	Downstream node location		Reach name	Direct drainage area	Total drainage area	Upstream reach No.
		Latitude	Longitude				
36	--	42° 37′ 16″	70° 58′ 51″	Nichols Brook, Middleton	3.09	3.09	--
37	--	42° 37′ 35″	70° 58′ 07″	Ipswich River above Fish Brook, Topsfield	.77	79.3	35,36
38	01101720	42° 39′ 53″	71° 01′ 42″	Fish Brook near Boxford	9.86	9.86	--
39	01101740	42° 38′ 93″	70° 59′ 20″	Fish Brook at Lockwood Lane near Boxford	4.09	14.0	38
40	--	42° 37′ 36″	70° 58′ 07″	Fish Brook above mouth	3.88	17.8	39
41	--	42° 37′ 03″	70° 56′ 32″	Ipswich River at riffle site above Route 97, Topsfield	1.51	98.6	37,40
42	--	42° 37′ 37″	70° 56′ 24″	Cleveland Brook, Topsfield	1.07	1.07	--
43	--	42° 37′ 25″	70° 55′ 56″	Ipswich River above Salem–Beverly Canal, Topsfield	.64	100	41,42
44	--	42° 36′ 24″	70° 54′ 05″	Salem–Beverly Canal intake, Wenham	.85	.85	--
45	--	42° 36′ 10″	70° 56′ 24″	Putnamville Reservoir Outlet, Topsfield	.87	.87	--
46	--	42° 37′ 03″	70° 55′ 20″	Putnamville Reservoir Brook above Salem–Beverly Canal, Wenham	2.76	3.63	45
47	--	42° 37′ 24″	70° 55′ 55″	Salem–Beverly Canal outlet to Ipswich River, Topsfield	.18	4.67	44,46
48	--	42° 37′ 50″	70° 54′ 26″	Ipswich River above Idlewild Brook, Hamilton	1.03	106	43,47
49	--	42° 37′ 49″	70° 54 ′25″	Idlewild Brook, Hamilton	2.60	2.60	--
50	--	42° 39′ 12″	70° 54′ 55″	Ipswich River above Howlett Brook, Topsfield	2.35	111	48,49
51	01101840	42° 40′ 17″	70° 58′ 52″	Pye Brook at Lowe Pond Outlet, East Boxford	2.85	2.85	--
52	01101850	42° 39′17″	70 °57′ 12″	Pye Brook near Topsfield	3.80	6.65	51
53	01101900	42° 39′ 17″	70° 54′ 54″	Howlett Brook at mouth, Topsfield	4.22	10.9	52
54	01101950	42° 39′ 37″	70° 54′ 14″	Gravelly Brook, Ipswich	2.28	2.28	--
55	--	42° 39′ 34″	70° 53′ 40″	Ipswich River at Willowdale Dam, Ipswich	.73	125	50,53,54
56	01102000	42° 39′ 34″	70° 53′ 39″	Ipswich River at Ipswich gaging station	.01	125	55
57	--	42° 39′ 15″	70° 52′ 55″	Ipswich River above Black Brook, Hamilton	.42	125	56
58	--	42° 39′ 14″	70° 52′ 54″	Black Brook, Hamilton	3.19	3.19	--
59	01102008	42° 39′ 29″	70° 51′ 45″	Ipswich River at Mill Road near Ipswich	1.11	130	57,58
60	--	42° 39′ 50″	70° 50′ 49″	Ipswich River above Miles River, Ipswich	.52	130	59
61	--	42° 35′ 26″	70° 52′ 12″	Longham Reservoir Outlet, Wenham	3.58	3.58	--
62	--	42° 35′ 41″	70° 53′ 19″	Wenham Lake Outlet, Wenham	2.20	2.20	--
63	01102009	42° 36′ 01″	70° 52′ 29″	Miles River above Larch Row, Wenham	1.78	7.56	61,62
64	01102010	42° 36′ 58″	70° 51′ 09″	Miles River above Bridge Street at Hamilton	2.15	9.71	63
65	--	42° 38′ 43″	70° 49′ 54″	Miles River above Gardner Street, Hamilton	3.86	13.6	64
66	--	42° 39′ 49″	70° 50′ 47″	Miles River above mouth, Ipswich	3.49	17.1	65
67	--	42° 40′ 39″	70° 50′ 17″	Ipswich River above dam, Ipswich	2.33	149	60,66

Stage-discharge ratings were supplied for reservoirs operated by Danvers and Middleton, and by the SBWSB. These ratings were used to construct the FTABLEs for reservoir outlets. Site surveys were also used to develop FTABLEs for some structures, such as node 12 (a weir on Martins Brook) and at node 51 (the dam outlet from Lowe Pond on Pye Brook).

Wetlands

In the initial model development, wetlands were simulated as two unique PERLND types: (1) forested wetland, and (2) non-forested wetlands. Early calibration results indicated that the simulated hydrographs were much more responsive to precipitation and snowmelt than the observed flows at both stations, even after PERLND storage- and infiltration-parameter values were set beyond reasonable limits. These results indicate that the wetlands and open water, which account for about 21 percent of the total basin area, are an important storage component in the watershed. To account for this storage, wetlands and open water were treated as “virtual” RCHRESs, RCHRESs with no atmospheric water gains or losses. Virtual RCHRESs were developed for most subbasins, and represent the combined storage of all wetlands and open water in the subbasin not already considered in the reach FTABLE. All PERLNDs and IMPLNDs in the subbasin were assumed to drain into the virtual reach before draining into channel RCHRES.

Simulation of wetlands and open water as virtual RCHRESs yielded good results for flows at the South Middleton station, however, low flows at the Ipswich station were initially oversimulated. It was hypothesized that because outflows from Massachusetts's wetlands are dominated by evapotranspiration (ET) and ground-water seepage (Lent and others, 1997) more water needs to be lost through ET than could be obtained by simulating wetlands as PERLNDs and virtual RCHRES. In these simulations, ET loss is limited to precipitation falling directly on wetlands (simulated as PERLNDs) minus the water that outflows from the wetland. The available moisture for ET loss in wetlands is typically much larger than just the direct precipitation because wetlands receive both surface and subsurface lateral flows from surrounding upgradient areas. This was evident in the over-simulated flows at the Ipswich station because ET from the large, perennially wet, Wenham Swamp (fig. 4) appears to have been artificially limited by the available water.

Wetlands and open water were subsequently simulated as RCHRESs (numbered 101 to 167) with atmospheric gains and losses and inflows from adjacent overland PERLNDs and IMPLNDs. To account for the combined area of wetlands and open water, the surface area in the RCHRES FTABLE was set equal to the corresponding area of wetlands and open water previously simulated as PERLNDs (nos. 16, 17, and 18 in table 7) for that reach. Storage-discharge characteristics of the wetland RCHRES were obtained empirically by matching the simulated and observed hydrographs. Wetlands simulated as RCHRES yielded a good fit between simulated and observed flows at both stations; however, low flows at both stations were under simulated instead of over simulated as previously described. This under-simulation resulted because the model treated all water entering the wetland RCHRES as available for ET with a relatively large surface area to evaporate from. As a consequence, during periods of low precipitation and high potential ET (low flow periods), almost all the water draining to the wetland RCHRES was lost to ET. In actuality, water drains to wetlands as surface runoff, interflow, and base flow; hence ET from interflow and base flow would be limited.

Within the model, ET from RCHRES can be limited only by decreasing potential ET or decreasing the surface area in which ET is acting. A variable surface area was believed to represent actual conditions better because the free-water surface area likely decreases during periods of low flow. This approach yielded good results after an empirical adjustment was made of the FTABLE surface area for wetland RCHRES for flows below 0.5 ft^3/s.

Wetlands are an important influence on stream hydrology, as evidenced in the extensive literature on wetland functions (Lent and others, 1997; Hunt and others, 1996; Krabbenhoft and Webster, 1995; Anderson and Cheng, 1993; Mills and Zwarich, 1986). The effects of wetlands on stream hydrology in the Ipswich River Basin are evident in the different results obtained by the variety of methods used to simulate this feature, as described above. Wetlands simulated as RCHRES yielded good results, but the wetland storage-discharge characteristics, flow-path characteristics, and the interaction between ground water and surface water in these wetlands are largely unknown and should be considered in future hydrologic investigations of the Ipswich River Basin. Also, simulating wetlands as a RCHRES with a variable area introduces a structural error into the model because the drainage area that receives precipitation decreases during periods of low flow. As additional data on the hydrology of the wetlands in the basin become available, the use of a new module (HSPF version 12 beta, Aquaterra, Inc., written commun., 1999) for simulating water budgets in areas with high water tables and low gradients could be considered. Use of this module requires time-series data for ground-water levels in wetlands, which were not available for this study.

Water Withdrawals

Time series of total ground-water and surface-water withdrawals were developed for each reach where withdrawals were known to be substantial (table 5). The total water withdrawal was entered as a single data set for each affected reach in the WDM file (DSNs 101 to 167 are used to specify the total water withdrawal corresponding to RCHRESs 1 to 67, respectively). The model calibration included 23 RCHRESs (1, 5, 8, 12, 13, 17, 18, 20, 23, 26, 30, 37, 44, 45, 49, 50, 53, 59, 61, 62, 63, 64, and 66) with water withdrawals. The WDM file and model UCI files have been designed so that additional withdrawals can be added easily to other RCHRESs.

Water withdrawals are read into the model in the EXT SOURCE block (external source) of the UCI file and are the time-dependent volume demands passed to the first outflow gate in a RCHRES. These withdrawals must be satisfied before water can exit from the next outflow gate, which, in most cases, is the water routed to the downstream reach. Water in reaches with no water withdrawals exits through a single outflow gate. Several reaches (RCHRESs 30, 44, and 61) used three outflow gates. In RCHRES 30 separate outflow gates were specified for withdrawals from: (1) Swan Pond, (2) Emerson Brook Reservoir, and (3) downstream routing.

Flows in the Salem-Beverly Canal (RCHRES 44, fig. 8) can reverse if withdrawals from the Salem–Beverly Water-Supply Board (SBWSB) are high enough. When the SBWSB is not pumping or if the pump rate is less than the flow of water into the canal from its 4.7 mi^2 drainage area (subbasins for RCHRESs 44, 45, 46, and 47), water flows into the Ipswich River at the upstream end of RCHRES 48. When the SBWSB is pumping and the flow into the canal from its drainage area is less than the withdrawal rate, water will flow into the canal from the Ipswich River. Water withdrawn from the Ipswich River is taken from the downstream end of RCHRES 43 (upstream end of RCHRES 48). SBWSB demands are further complicated because water is diverted to both Wenham Lake (RCHRES 62) and Putnamville Reservoir (RCHRES 45).

HSPF cannot simulate flow reversals; therefore the representation of the SBWSB withdrawals was simplified in the model by taking the entire withdrawal directly from the Ipswich River at RCHRES 43 and routing flows from the drainage area to the canal into the Ipswich River at RCHRES 48. The net flow in the Ipswich at RCHRES 48 is the same as if the SBWSB withdrawals were taken from the Ipswich River only when withdrawals exceeded supply from the canal contributing area. Simulated flows at RCHRES 43 on the Ipswich River can differ from the actual flows, however, because diversions do not account for the water from the 4.7 mi^2 drainage area of RCHRESs 44, 45, 46, and 47. Three outflow gates were specified for RCHRES 43: (1) withdrawals diverted to Wenham Lake, (2) withdrawals diverted to Putnamville Reservoir, and (3) downstream routing.

Three outflow gates were also specified for the Longham Reservoir (RCHRES 61): (1) withdrawals diverted to Wenham Lake, (2) time series for outflow over the spillway into Miles River (RCHRES 63), and

(3) an FTABLE that specifies the volume-discharge characteristics of the reservoir and spillway. The third outflow gate is needed for this reach to route flow downstream for long-term simulations when time-series of discharge over the spillway is unavailable. The time series of the reported discharge to Miles River are used when available because the spillway can be manually adjusted by three flashboards.

Streamflow Depletion by Ground-Water Withdrawals

The effects of ground-water withdrawals on streamflow are calculated for each well with the program STRMDEPL described in Appendix A. STRMDEPL produces a time series of the total streamflow depletion in response to pumping, which consists of captured discharge or induced infiltration, or both. The time-varying streamflow depletion is calculated on the basis of the daily pumping rate, distance of the well from the stream, aquifer properties, and the hydraulic connection of the stream and the aquifer. Because STRMDEPL provides a direct measure of the effects of ground water withdrawals on streamflow, ground-water withdrawals are taken directly from reaches, which provide the spatial reference for the well or well field in the basin.

STRMDEPL variables for all the pumped wells in the Ipswich Basin were assigned a diffusivity (DIFFUS) of 10,000 ft^2/d (based on aquifer properties reported by Baker and others,1964, and Samuel and others,1966) and a streambank material (IBANK) of zero to indicate no semi-impervious material is present. Other STRMDEPL variables depended on the distance of the well from the stream (given in table 4) and the initial pump rate. The pumping rates for individual wells are available in the WDM file (DSNs 2010 through 2679).

Ground-water flow to a well is affected by many factors, including (1) transmissivity and storage properties of the aquifer, (2) types and relative position of boundary conditions, (3) withdrawal rates, and (4) transient conditions such as a change in recharge (Theis, 1940). Detailed analyses of factors that affect flow to wells have been described by many authors and have been summarized by Reilly and Pollock (1993) and Franke and others (1998).

Although flow to a pumped well occurs in three dimensions, a simplified cross-section schematic of ground-water flow in a homogeneous aquifer to a stream illustrates the effects of pumping on streamflow (fig. 11). The ground-water flow system before development, in which the stream gains flow from ground-water discharge sustaining base flow in the stream, is shown in figure 11*A*.

The hypothetical effects of a pumped well are shown in figure 11*B* for the case of an initial water-table surface similar to the undeveloped aquifer in figure 11*A*. A cone of depression forms around the pumped well; flow is diverted toward the well (forming a contributing area) resulting in a flow divide between the well and the stream. In this case, flow in the stream is decreased by the amount of ground-water flow diverted toward the well (captured base-flow). The size of the contributing area is affected by the factors mentioned previously, but can also include the influence of other ground-water withdrawals.

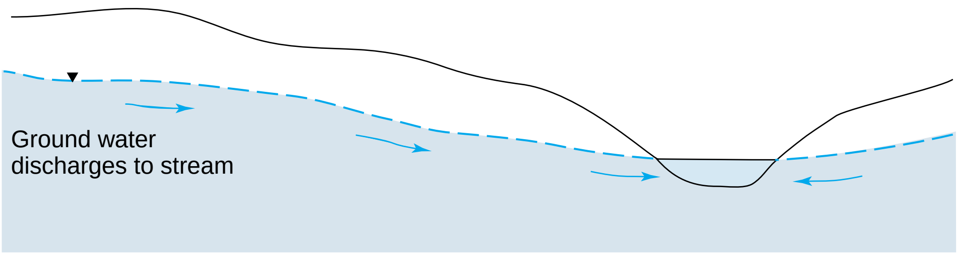
The ground-water flow paths when the contributing area extends below a wet stream channel and the head in the aquifer is below the head in the stream are shown in figure 11*C*. The downward gradient between the stream and the aquifer induces infiltration of stream water into the aquifer. If the captured baseflow (fig. 11*B*) and induced infiltration (fig. 11*C*) are in equilibrium with withdrawals, the water table surface will remain unchanged.

When ground-water withdrawals exceed captured baseflow and induced infiltration, water is removed from ground-water storage, as shown in figure 11*D*. The water-table surface continuously lowers while the well is being pumped and is considered a transient or unsteady-state condition that typically occurs only during extended dry periods in the Ipswich River Basin. Changes in ground-water storage that result from withdrawals in excess captured base-flow and induced infiltration require special consideration in the Ipswich Basin HSPF model to preserve a mass balance of water.

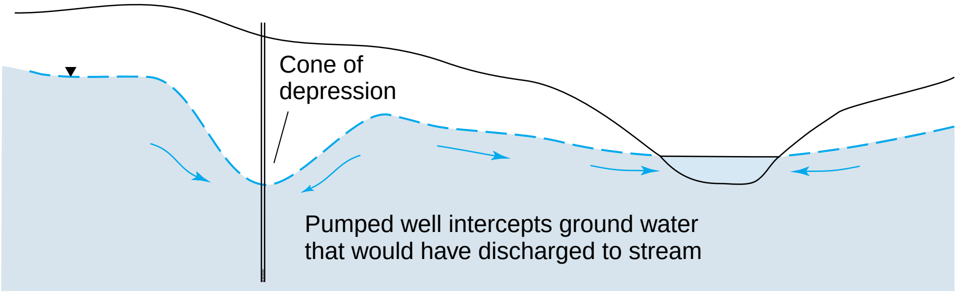
Water Withdrawals in Excess of Streamflow

During extended periods of dry weather, ground-water withdrawals can exceed streamflow in a river reach. A comparison of actual withdrawals and the withdrawals satisfied by streamflow in the HSPF simulations in reaches above the South Middleton station indicates that this condition occurs mostly in reaches 1 and 17 and mostly between June and September of each year. These are headwater reaches with multiple pumped wells. Water withdrawals commonly exceed streamflow in these reaches by 50 percent or more for periods of several days or more during late summer.

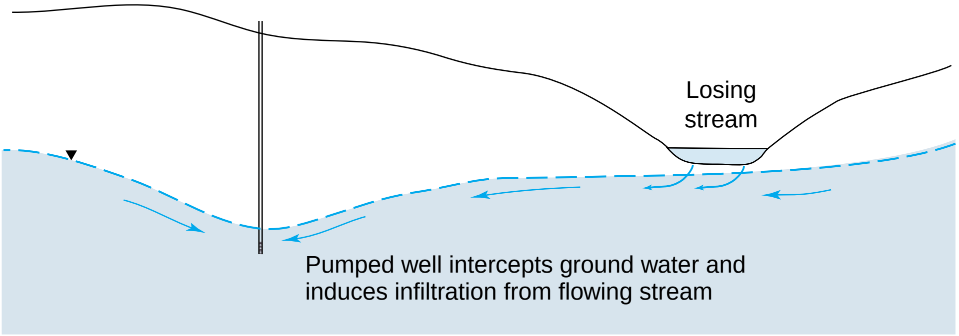
A. Ground-water flow paths under undeveloped conditions



B. Ground-water flow paths with a pumped well



C. Ground-water flow paths to a pumped well (low-water table condition) that intercepts ground water and induces infiltration from the steam



D. Ground-water flow to a pumped well that intercepts ground water and depletes ground-water storage (low recharge and dry stream condition)

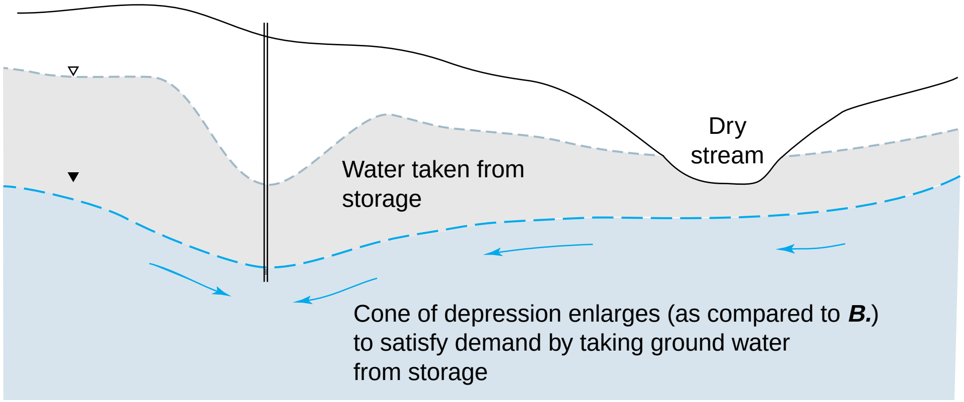


Figure 11. Ground-water flow paths illustrating captured recharge and induced infiltration in a hypothetical aquifer: (*A*) undeveloped aquifer, (*B*) pumped well with a high water table, (*C*) pumped well with a low-water table surface, and (*D*) changing storage when withdrawals exceed captured recharge and induced infiltration.

In other reaches, water withdrawals seldom exceed the streamflow. For example, water withdrawals in reach 8 are about twice those in reach 1, but the cumulative withdrawals in the reach rarely exceeded streamflow in the reach during the calibration period, except in the summer of 1993. The reason for this difference is that the drainage area for reach 8 is about 4.5 times that of reach 1 and the runoff from this drainage area is normally sufficient to satisfy withdrawals in this reach. Table 9 summarizes the average difference between the actual withdrawals and the withdrawals satisfied by streamflow in the HSPF simulations for the 1989–93 model calibration period. Table 9 also summarizes the number of days during which the withdrawals exceeded streamflow during this period.

When water withdrawals exceed the flow in the reach, an error was introduced in the hydrologic budget in the model with the original implementation of the STRMDEPL program. The error in the hydrologic budget in the HSPF simulations as a result of the deficit between actual withdrawals and the withdrawals satisfied by streamflow is generally minor, but can be appreciable during periods of low flow in some reaches. The error caused by the deficit between actual withdrawals and satisfied withdrawals will be exacerbated during periods of extended drought and cause deficits in reaches further downstream as flows decrease.

In nature, when ground-water withdrawals exceed streamflow, the excess demand is satisfied from ground-water storage, as previously described. Neither the HSPF model, or the STRMDEPL program, accounts for changes in ground-water storage that result from withdrawals in excess of streamflow. A ‘Special Action’ was developed in the Ipswich River Basin HSPF model to correct for this inadequacy.

Special Actions can be introduced into the HSPF model to increase its power and flexibility. The special action (herein referred to as SA) developed as part of this study accounts for a running deficit between the actual withdrawals and the withdrawals satisfied by streamflow in the simulation. The SA then replenishes this deficit when streamflow exceeds demands, thereby maintaining the hydrologic mass balance of the system over the simulation time period. In effect, replenishing the deficit by the SA is analogous to recharging the diminished ground water storage shown in figure 11*D*.

The SA tracks deficits for each reach with ground-water withdrawals. The following user-defined variable quantities (UVQUAN’s) are used where:

nn is the reach number;

def_{nn} is the current deficit in the reach;

$cdem_{nn}$ is the current time interval demand (withdrawal specified in the input time series);

$pdem_{nn}$ is the previous time interval demand (withdrawal specified for the previous interval);

$with_{nn}$ is the simulated withdrawal that was satisfied by streamflow for the previous interval; and

$deffrc$ is the fraction of deficit that must be satisfied before streamflow can pass through a reach.

The variables def_{nn} and $deffrc$ require a target address (UVNAMEs) for reference in action lines. The UVNAMEs $\mathrm{DEF}_{\mathrm{nn}}$ and DEFFRC correspond to the quantities def_{nn} and $deffrc$, respectively.

Table 9. Deficit between actual water withdrawals and the withdrawal satisfied by streamflow in the Hydrological Simulation Program-FORTRAN (HSPF) for Ipswich River reaches above the South Middleton station, Mass.,1989–93

[**Percent:** Percent difference between the actual water withdrawal and the satisfied withdrawal by streamflow. **Days:** Number of days when withdrawals exceeded streamflow. No., number; ft^3/s, cubic foot per second]

Reach No.	1989		1990		1991		1992		1993		Average withdrawal (ft^3/s)
	Percent	Days	Percent	Days	Percent	Days	Percent	Days	Percent	Days	
1	11	43	8.3	26	17	56	4.5	28	31	88	2.0
5	0	0	0	0	0	0	0	0	0	0	.1
8	.3	4	1.2	7	.5	5	0	1	15	52	3.8
12	0	0	0	0	.1	1	0	0	13	48	2.1
13	.5	6	.5	5	3.3	18	0	0	29	72	1.5
17	18	54	15	36	21	53	7.8	34	50	101	.7
18	.5	1	0	0	1.2	3	1.0	2	.7	2	.2

DEFFRC represents the hydraulic connection between the stream and the aquifer (often referred to as leakance) by designating the fraction of the deficit satisfied before streamflow can pass downstream. In the Ipswich River Basin, DEFFRC was set to 1.0 for all reaches (the entire deficit must be replenished before any water is routed downstream) because the stream and the aquifer are believed to be well connected. In systems with a poor hydraulic connection, DEFFRC values less than 1.0 could be used, thus allowing some flow to pass downstream before the deficit is satisfied.

A GENER operation is associated with each reach for which a deficit is computed. The value in each GENER corresponds to the deficit in the reach plus the current withdrawal in the reach. The deficit (def_{nn}) is incremented each time step by adding the previous time interval's actual demand ($pdem_{nn}$) minus the previous interval's satisfied withdrawal ($with_{nn}$). If the deficit is greater than zero, the Operation Status Vector (OSV) variable K in the GENER operation is set equal to the deficit times the fraction allowed to pass through a reach (*deffrc*). The current demand ($cdem_{nn}$) is then added to the value of K. If there is no deficit, K is set equal to zero. The NETWORK block passes the GENER K values to the time-series specified for the first outflow gate (OUTDGT 1) in reaches that have water withdrawals.

Initial simulations with the SA indicated model run times on a 400mHz Pentium II processor in excess of 2 hours as compared to run times of about 3 minutes with no SA when the model was run within GenScn. The SA causes a dramatic increase in run time because the model is required to work up and down the operation sequence to compute variables used in the SA. Subsequently, the SA was modified to decrease the main swapping by a factor of 24 by setting $\mathrm{pdem}_{\mathrm{nn}}$ equal to the demand 25 hours ago and $with_{\mathrm{nn}}$ equal to the actual withdrawal 24 hours ago. These values are then used to update the current deficit (def_{nn}) as above, but with values that have a 24-hour lag time. The revised SA no longer uses the variable $cdem_{nn}$, but rather reads the current outflow demand directly from the WDM file (targeted to the first outflow gate-OUTDGT 1). The GENER K value is passed to OUTDGT 1 as above to produce the current outflow demand plus any deficit.

Figure 12 shows the actual withdrawal and the withdrawal satisfied by streamflow in the HSPF simulation in reach 1 for June through August 1991. In July, the withdrawal begins to exceed streamflow, and thus the withdrawal is only partly satisfied. During several periods the streamflow meets withdrawals, but streamflow does not exceed withdrawals until the end of August. At this time, the deficit between actual withdrawal and the withdrawal that is satisfied by streamflow in the simulation is replenished over a 6-day period.

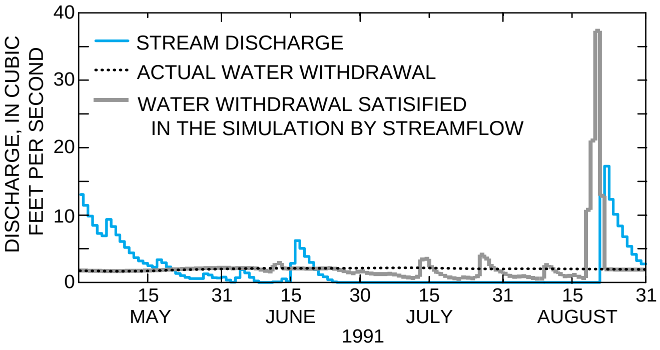


Figure 12. Actual water withdrawals and the withdrawals satisfied by streamflow in the Hydrological Simulation Program-FORTRAN (HSPF) in reach 1 of the Ipswich River Basin, Mass. for the period June 1, 1991 through August 31, 1991.

Model Calibration

The Ipswich River Basin model was calibrated for the period January 1, 1989 to December 31, 1993 using an hourly time step. The 1989–93 period was used for calibration because water withdrawals could be obtained or estimated for the major water-supply demands on the system during that time, and because land-use data for 1991 were used to define the PERLNDs. The water-withdrawal data were needed to calibrate the model, and were not available for all water suppliers prior to 1989, at which time the suppliers were required to report their monthly water use to the State. Water-use data were available for years more recent than 1993, but because land use has changed rapidly in the basin since 1991, a calibration period centered on 1991 was believed to best represent the basin.

By calibrating to a period when water withdrawals were quantified, the effects of these withdrawals could be included in the simulation so that values of hydrologic parameters would not be skewed. In effect, this normalizes the simulated hydrograph so that the values of hydrologic parameters are calibrated to unaffected flows and hence reflect the natural hydrologic response of the watershed. If the water withdrawals had been ignored in the calibration, then the hydrologic parameter values would have been skewed to include the effect of these withdrawals on flows.

Model parameter values were calculated from available spatial data to the extent possible. For example, the average slopes of the PERLNDs were calculated from the digital elevation data. Most parameter values could not be measured directly, however, and were derived by means of an iterative calibration process. HSPF modeling reports for the nearby Charles River watershed by Socolofsky (1997) and Munson (1998) provide initial values for some parameters that could not be measured. An iterative process (calibration) was then used to adjust the initial values to minimize the difference between simulated and observed flows.

Flows at the South Middleton station and the Ipswich station, which correspond to RCHRESs 19 and 56 (fig. 8), provided the principal data for calibration. The model was calibrated in accordance with guidelines by Donigian and others (1984) and Lumb and others (1994a). This generally entailed adjusting the parameter values to improve the model fit for annual and seasonal budgets, then adjusting values to improve the model fit for daily flows while maintaining the annual and seasonal budgets. Storm flow and snowmelt were not given detailed consideration because of the study time constraints and the primary purpose of the model for simulating low-flow periods.

Precipitation data at Reading, Mass. and the averaged data from the 12-grid cell data provided by MBL (herein referred to as the centroid) were used for calibration because it was uncertain which data best represented precipitation in the basin. Model-fit statistics are summarized in table 10 and generally were similar for simulations made with precipitation from each source. The quality of the model fit was examined by: (1) the coefficient of determination (r^2) of the linear regression between simulated and

Table 10. Summary of annual, monthly, and daily model-fit statistics at South Middleton and Ipswich stations for Hydrological Simulation Program-FORTRAN (HSPF) simulations made with centroid and Reading precipitation data, Ipswich River Basin, Mass., 1989–93

[ft^3/s, cubic feet per second; >, less than; %, percent]

Model-fit statistic	Annual		Monthly		Daily	
	Centroid	Reading	Centroid	Reading	Centroid	Reading
South Middleton station						
Number of years, months, or days	5	5	60	60	1,826	1,826
Coefficient of determination (r^2)	.85	.99	.96	.95	.92	.92
Coefficient of model-fit efficiency	.72	.98	.92	.90	.85	.84
Standard error (ft^3/s)	3.5	.8	2.0	2.2	.6	1.1
Root mean square error (percent)	9.1	3.1	42	37	94	100
Percent time simulated value <10%	80	100	37	32	23	24
Percent time simulated value <25%	100	100	65	63	51	49
Median percent error	2.4	2.4	-.1	8.2	-.4	5.6
Minimum percent error	-17	-1.7	-42	-41	-82	-89
Maximum percent error	7.4	5.2	185	122	1,588	2,122
Ipswich station						
Number of years, months, or days	5	5	60	60	1,826	1,826
Coefficient of determination (r^2)	.92	.97	.98	.95	.94	.89
Coefficient of model-fit efficiency	.82	.92	.95	.90	.88	.79
Standard error (ft^3/s)	6.6	4.7	4.3	6.6	1.6	1.8
RMSE (percent)	7.5	5.4	32	27	51	54
Percent time simulated value <10%	80	100	38	43	24	26
Percent time simulated value <25%	100	100	68	72	56	58
Median percent error	-.4	1.6	-4.4	1.0	-4.2	1.8
Minimum percent error	-12	-8.3	-41	-48	-88	-86
Maximum percent error	4.9	4.4	115	106	369	628

observed discharge; (2) the coefficient of model-fit efficiency, which measures the proportion of variance in the observed discharge explained by the simulated discharge (Nash and Sutcliffe, 1970). The coefficient of determination (r^2) and the coefficient of model-fit efficiency are similar because both provide a measure of the variation in the simulated value explained by the observed value. The coefficient of model-fit efficiency, however, provides a more rigorous evaluation of the fit quality than does the r^2 because the model-fit efficiency measures the magnitude of the differences between simulated and observed values, whereas the r^2 measures the difference between mean values (Duncker and Melching, 1998). In cases in which the observed values and model residuals are normally distributed, the value of the r^2 and the model-fit efficiency should be equal. The difference between simulated and observed discharges were also reported as the (1) standard error, in cubic feet per second; (2) root mean square error, in percent; (3) percent of time differences were within 10 percent, and (4) percent of time differences were within 25 percent; (5) median percent error, (6) minimum percent error, and (7) maximum percent error.

Table 11. Observed and simulated annual discharge at South Middleton and Ipswich stations for Hydrological Simulation Program-FORTRAN (HSPF) simulations made with centroid and Reading precipitation data, Ipswich River Basin, Mass., 1989–93

[Discharge values in cubic foot per second. Precipitation values in inches]

Year	Observed discharge	Centroid			Reading		
		Simulated discharge	Percent difference	Precipitation	Simulated discharge	Percent difference	Precipitation
South Middleton station							
1989	47	48	2.4	44.2	48	2.4	44.7
1990	83	69	-17	49.3	85	1.5	54.3
1991	59	63	6.4	47.6	58	-1.7	44.8
1992	57	54	-6.1	43.8	59	3.2	46.0
1993	76	81	7.4	44.9	80	5.2	44.7
Mean	64	63	-2.1	46.9	66	2.2	45.9
Ipswich station							
1989	126	133	4.9	44.2	133	5.0	44.7
1990	212	186	-12	49.3	229	6.9	54.3
1991	164	163	-.4	47.6	151	-8.3	44.8
1992	158	143	-9.5	43.8	157	-.8	46.0
1993	214	223	3.9	44.9	219	1.6	44.7
Mean	175	170	-3.1	46.9	178	1.1	45.9

Mean Annual Discharge

Observed and simulated mean annual discharge at the South Middleton and Ipswich stations for simulations made with centroid and Reading precipitation data for the 1989–93 calibration period are summarized in table 11. Mean annual discharge at the South Middleton station are undersimulated on average by 2.1 percent for simulations made with centroid precipitation data and oversimulated by 2.2 percent for simulations made with Reading precipitation data. Mean annual discharge at the Ipswich station are undersimulated on average by 3.1 percent for simulations made with centroid precipitation data and oversimulated on average by about 1.1 percent for simulations made with Reading precipitation data. Donigian and others (1984) suggest that simulated total water budgets within 10 percent of the observed represent a very good model fit.

Simulated versus observed mean annual discharge is shown in figure 13. The linear regression line (fig. 13) closely matches the line of equality and the coefficient of model-fit efficiency indicates that the model explained 92 percent, or more, of the variation in the mean annual discharge for simulations made with the Reading precipitation data at both sites. The coefficient of model-fit efficiency indicates that the model explained 72 percent, or more, of the variation in the mean annual discharge for simulations made with the centroid precipitation data at both sites. The overall model-fit statistics (table 10) and regression fit (fig. 13) are somewhat better for simulations with the Reading precipitation than with the centroid precipitation at both stations, largely because of the simulations with the centroid data are undersimulated by more than 10 percent at both stations in 1990 (table 11). The total annual precipitation in 1990 with the centroid data is

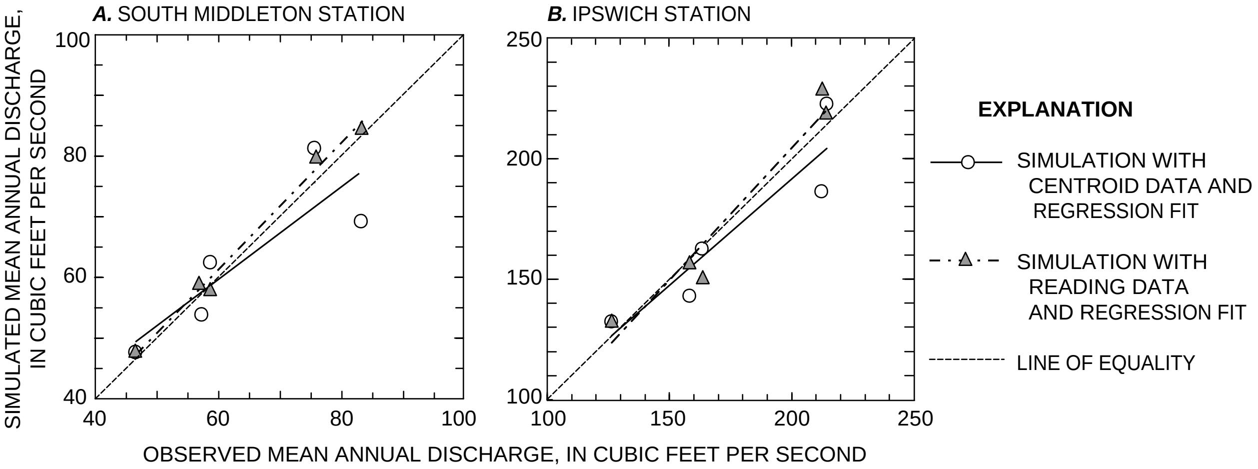


Figure 13. Relation of simulated mean annual discharge to observed for simulations made with centroid and Reading precipitation data for the Ipswich River, Mass., at (*A*) South Middleton station, and (*B*) Ipswich station, 1989–93.

about 10 percent less than the Reading data, thus the centroid data appears to under-represent precipitation in the basin during this year.

Monthly Mean Discharge and Seasonal Water Budgets

Observed monthly mean discharges ranged from lows of 1.0 and 8.1 ft^3/s (August 1993) to highs of 343 and 1,070 ft^3/s (April 1993) at the South Middleton and Ipswich stations, respectively. Simulated discharge for the same periods ranged from lows of 1.0 and 5.0 ft^3/s to highs of 347 and 974 ft^3/s at the South Middleton and Ipswich stations, respectively, for simulations made with the centroid precipitation data. Simulated monthly mean discharges for the same periods made with the Reading precipitation data ranged from lows of 1.3 and 5.9 ft^3/s to highs of 297 and 833 ft^3/s at the South Middleton and Ipswich stations, respectively. The coefficient of model-fit efficiency indicates that at a minimum the model explained 90 percent of the variation in the observed monthly flows at both stations when the flows are simulated with either set of precipitation data. Regression lines indicate little bias in the simulated monthly mean discharge (fig. 14); however, the regression fit is slightly better for simulations made with the centroid precipitation data than for simulations made with the Reading precipitation data because the regression line is leveraged by an outlier (high runoff in April 1993) that was better simulated with the centroid data than the Reading data.

A seasonal bias was observed during calibration of flows at both the South Middleton and Ipswich stations (fig. 15 dashed line). This appears to reflect the seasonal bias reported in the Jensen-Haise PET computations by Winter and others (1995), who compared 11 methods for calculating free-surface evaporation for a small lake in Minnesota. They report that the Jensen-Haise method, and other equations with a solar radiation component, overestimate evaporation during May through July and underestimate evaporation in September in comparison to values computed from an energy budget. Winter and others (1995) also reported a large scatter in the Jensen-Haise PET computed values for August. Leavesley and others (1983) report that the Jensen-Haise and Hamond methods tend to underestimate PET during the winter period. PET values computed by equations that are based on solar radiation data tend to exhibit a seasonal bias because they do not account for latent heat in the water body; this results in overestimated PET values during the spring and early summer period and underestimated PET values during the early fall through early winter period. The Ipswich River Basin model simulated discharges made with unadjusted Jensen-Haise PET values reflect this bias by undersimulating discharge in the spring and early summer and oversimulating discharge in the fall and winter.

Initial Jenkins-Haise PET values were adjusted empirically during the calibration by modifying the monthly variable coefficient (CTS) to minimize seasonal bias (fig. 15 solid line). These changes in the CTS

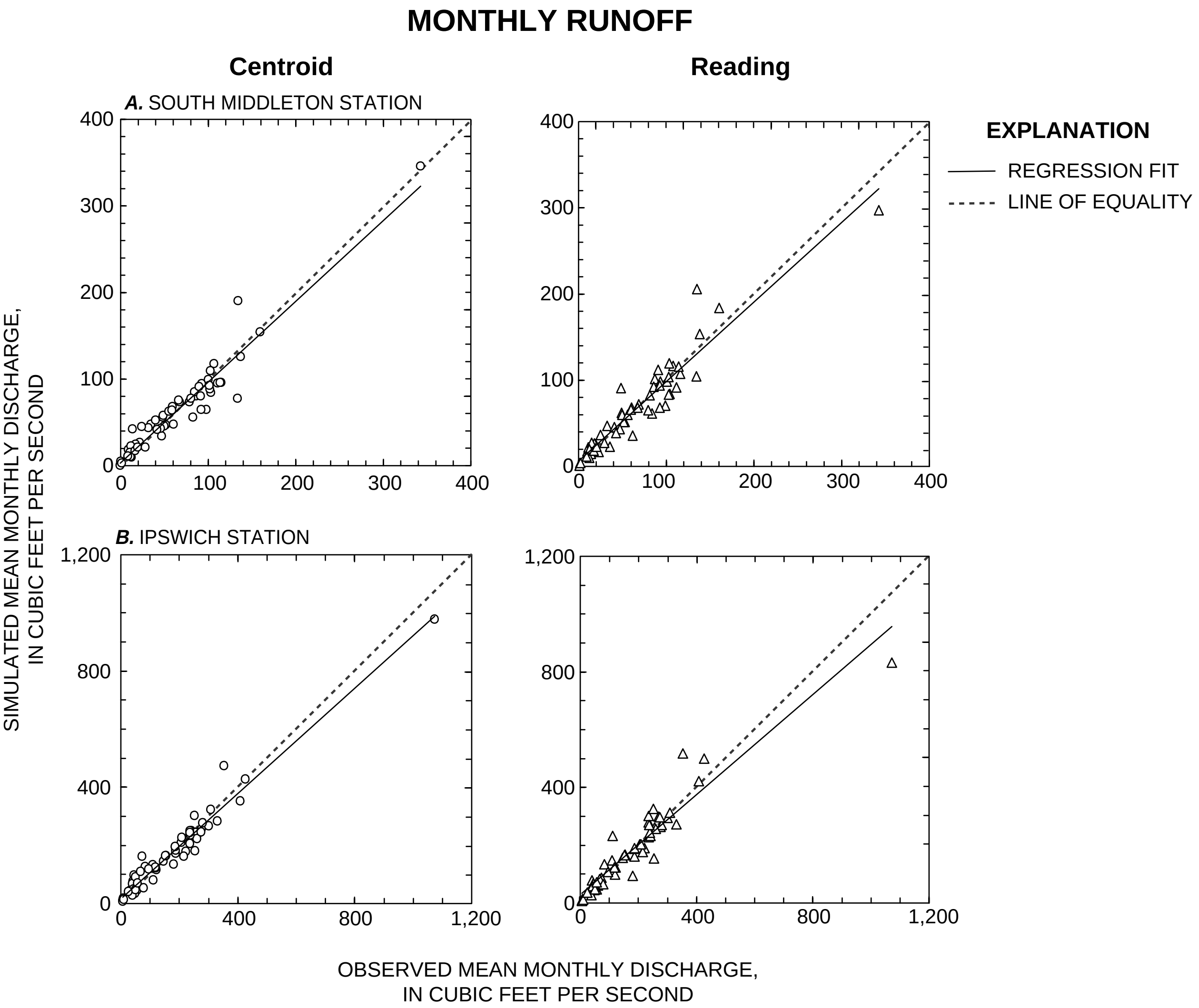


Figure 14. Relation of simulated monthly discharge to observed for simulations made with centroid and Reading precipitation data for the Ipswich River, Mass. at (*A*) South Middleton station, and (*B*) Ipswich station, 1989–93.

values are within guidelines described in METCMP (Lumb and Kittle, 1995). Figure 15 indicates that most of the seasonal bias at both stations was removed by adjusting the PET data. The percent mean monthly discharge error departs from the zero line for several periods, but these departures are largely due to outliers. The coefficient of model-fit efficiency indicates that at a minimum the model explained 75 percent of the seasonal flow variability for simulations made with the centroid precipitation data. The coefficient of model-fit efficiency values for monthly seasonal discharges were generally less for simulations made with Reading precipitation data than for simulations made with centroid data (table 12). Typically, a seasonal model-fit efficiency with a low value for simulations made with one precipitation source had a substantially higher model-fit efficiency for the same season for simulations made with the other precipitation source.

Daily Flow

Observed daily mean discharges for the calibration period ranged from 0.3 ft^3/s (August 29, 1993) to 670 ft^3/s (April 2, 1993) at the South Middleton station, and from 2.5 ft^3/s (September 4, 1993) to 2,490 ft^3/s

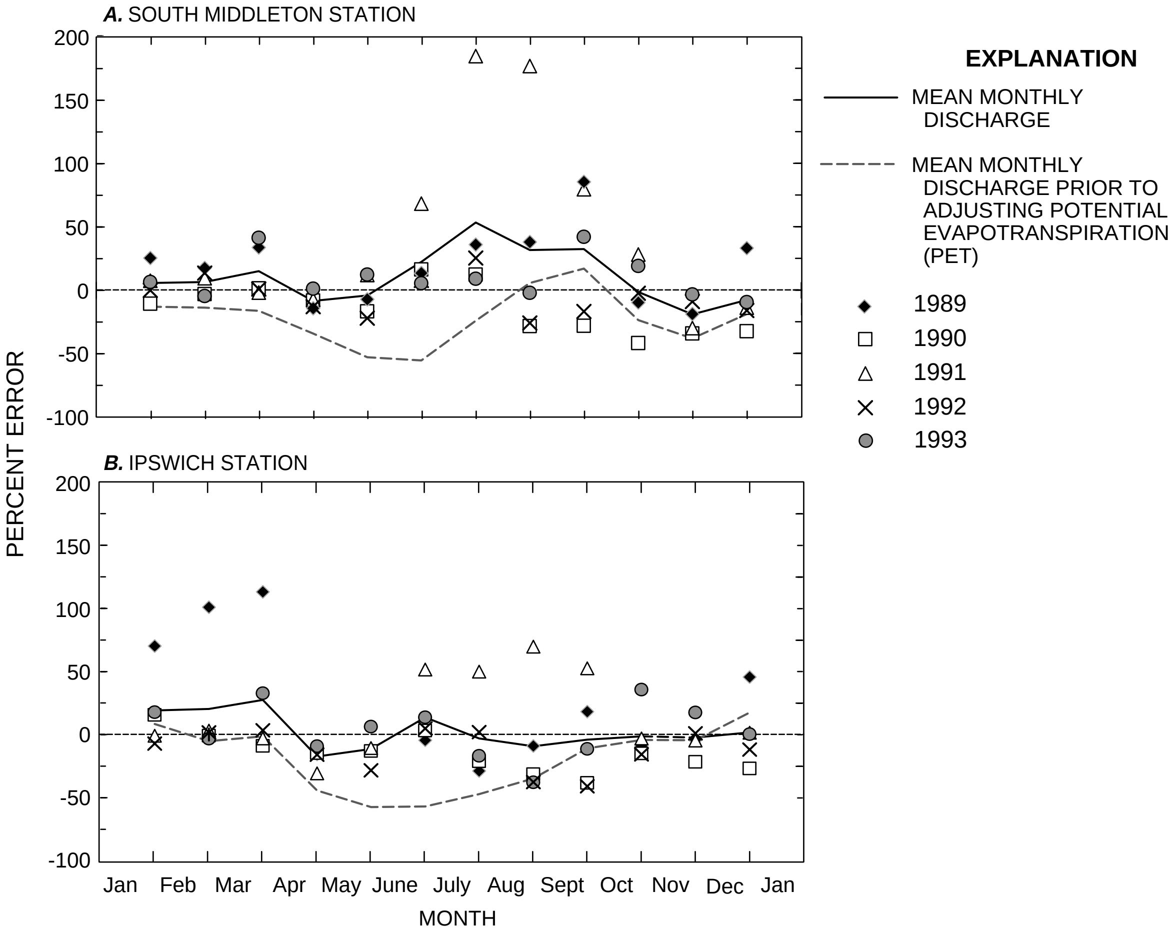


Figure 15. Percent error between simulated flow made with the centroid precipitation data and observed flows for the Ipswich River, Mass., at the (*A*) South Middleton and (*B*) Ipswich stations by month, before and after adjusting evapotranspiration rates for seasonal bias, 1989–93.

(April 2, 1993) at the Ipswich station (fig. 16). Simulated daily mean discharges for the same period made with the centroid precipitation data ranged from 0.3 ft^3/s to 657 ft^3/s at the South Middleton station, and from 2.8 ft^3/s to 1,710 ft^3/s at the Ipswich station. Simulated discharges made with the Reading precipitation data ranged from 0.3 ft^3/ to 580 ft^3/s at South Middleton station and from 3.5 ft^3/s to 1,500 ft^3/s at the Ipswich station. The coefficient of model-fit efficiency indicated that at a minimum, the model explained 85 percent of the variation in the observed daily mean discharge at both stations for simulations made with the centroid precipitation data. The coefficient of model-fit efficiency was slightly less for simulations made with the Reading precipitation data (table 10).

In general, the simulated hydrographs at the South Middleton and Ipswich stations parallel the observed hydrographs over a wide range of flow conditions and seasons (figure 17*A* and 17*B*) for simulations made with the centroid precipitation data. The hydrographs for simulations made with the Reading precipitation data were similar to those for simulations made with the centroid precipitation data and, therefore, were not included in figure 17. The simulated spring hydrograph recession generally matches the observed hydrograph recession; this match indicates that storage in the Ipswich River Basin, and physical properties that affect storage, are reasonably represented in the model.

Table 12. Summary of seasonal model-fit statistics at South Middleton and Ipswich stations for Hydrological Simulation Program-FORTRAN (HSPF) simulations made with centroid and Reading precipitation data, Ipswich River Basin, Mass., 1989–93

[ft^3/s, cubic foot per second; >, less than; %, percent]

Model-fit statistic	Winter		Spring		Summer		Fall	
	Centroid	Reading	Centroid	Reading	Centroid	Reading	Centroid	Reading
South Middleton station								
Number of months	15	15	15	15	15	15	15	15
Coefficient of determination (r^2)	.96	.96	.97	.93	.90	.94	.93	.98
Coefficient of model-fit efficiency	.91	.89	.94	.86	.76	.52	.75	.88
Standard error (ft^3/s)	2.9	3.1	4.7	7.0	2.3	2.7	5.0	3.4
Root mean square error (percent)	11	21	19	25	79	67	43	36
Percent time simulated value <10%	47	47	47	40	20	7	27	33
Percent time simulated value <25%	80	80	87	80	47	27	47	67
Median percent error	-.1	4.7	-1.6	-.1	14	39	-8.9	-2.0
Minimum percent error	-32	-26	-21	-42	-28	-6	-41	-28
Maximum percent error	33	43	41	52	179	122	86	45
Ipswich station								
Number of months	15	15	15	15	15	15	15	15
Coefficient of determination (r^2)	.96	.96	.97	.92	.94	.90	.97	.98
Coefficient of model-fit efficiency	.92	.87	.93	.84	.88	.58	.93	.95
Standard error (ft^3/s)	7.4	8.1	15	24	4.6	8.0	5.3	4.4
Root mean square error (percent)	39	35	38	26	36	37	27	19
Percent time simulated value <10%	53	47	33	40	33	40	33	47
Percent time simulated value <25%	73	67	73	73	53	60	73	87
Median percent error	1.5	7.7	-11	-3.0	-4.4	6.4	-4.8	-1.5
Minimum percent error	-27	-42	-31	-48	-38	-27	-41	-37
Maximum percent error	101	73	113	46	70	106	53	34

Differences between simulated and observed flows are shown in figure 18 as a function of time and in figure 19 as a function of discharge. These figures were developed from results of simulations made with the centroid precipitation data. Figure 18 indicates that the largest errors (at both the South Middleton and Ipswich stations) are during the winter period, probably because of differences between actual and simulated snowpack buildup and melt. This is underscored by the errors shown as a function of the magnitude of flow (fig. 19), which indicates that the largest errors are during the highest flows. The annual peak discharge is often during the spring and usually includes snowmelt runoff. A comparison of the simulated and observed hydrographs at the Ipswich station, and the simulated snowpack water (fig. 20) during the peak of record for the calibration period (early April 1993) suggests that water was retained in the snowpack longer and then released more rapidly than simulated; this increased the simulated discharge earlier than observed which resulted in a smaller simulated peak discharge than observed.

Flow Duration

Flow-duration curves show the percentage of time a specified discharge is equaled or exceeded, and reflect the combined effects of climate, topography, and hydrogeologic conditions on the distribution of flow magnitude through time (Searcy, 1959). A comparison of flow-duration curves computed from observed mean daily discharges at the South Middleton and Ipswich stations for the 1989-93 calibration period with those

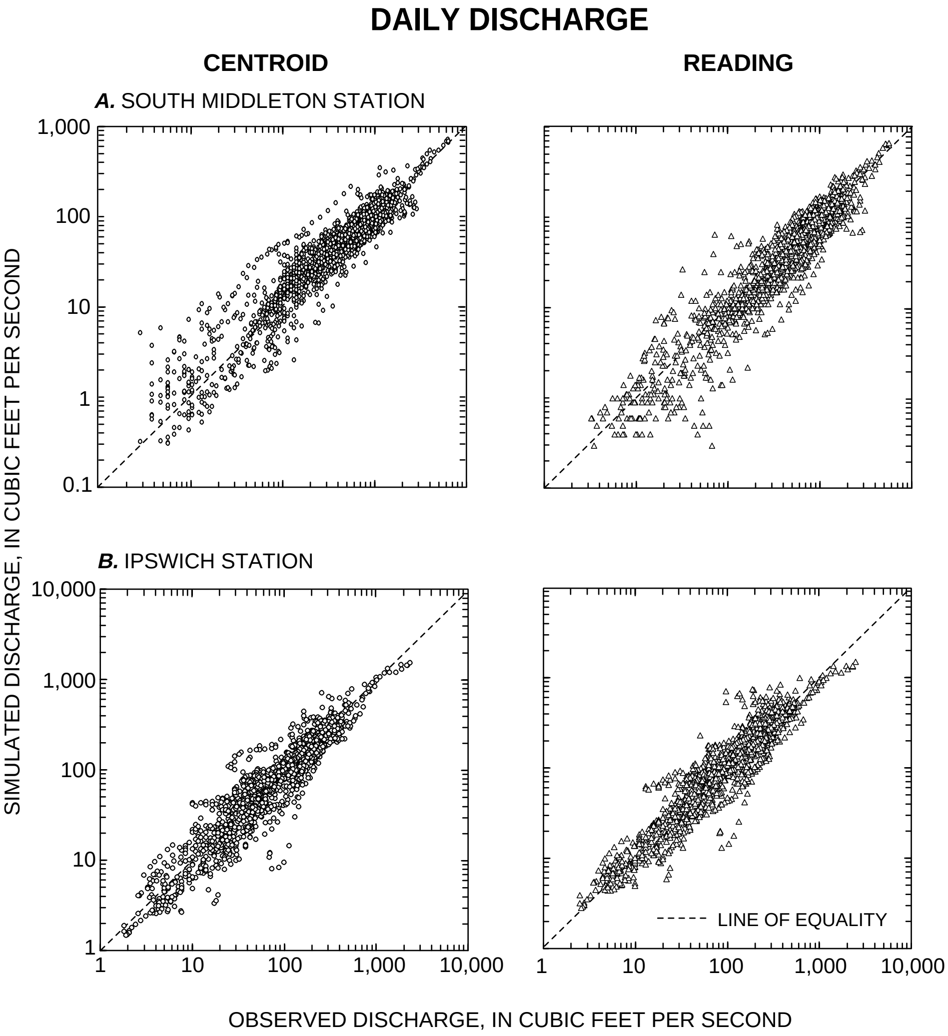


Figure 16. Relation of simulated daily mean discharge to observed for simulations made with centroid and Reading precipitation data for the (*A*) South Middleton, and (*B*) Ipswich stations, Ipswich River, Mass., 1989–93.

from simulated mean daily discharges made with either set of precipitation data indicates a similar magnitude and frequency of daily flows (fig. 21). The flow frequency curve of simulated daily discharges deviates from the curve of the observed discharges for flows greater than 1,500 ft^3/s (0.5 percent probability of being equaled or exceeded) at the Ipswich station for simulations made with either precipitation data; this reflects the difference in the timing of snowmelt runoff as previously mentioned.

Low Flows

Simulated and observed flows that have exceedence probabilities of 98 percent and 90 percent or more at the South Middleton and Ipswich stations were compared. These are flows less than about 0.7 and 6 ft^3/s for flows with a 98-percent exceedence probability, and 7 and 22 ft^3/s at the 90-percent exceedence probability at the South Middleton and Ipswich stations, respectively (flow duration curves, fig. 21). The computed error statistics between simulated and observed flows within the 98- and 90-percent

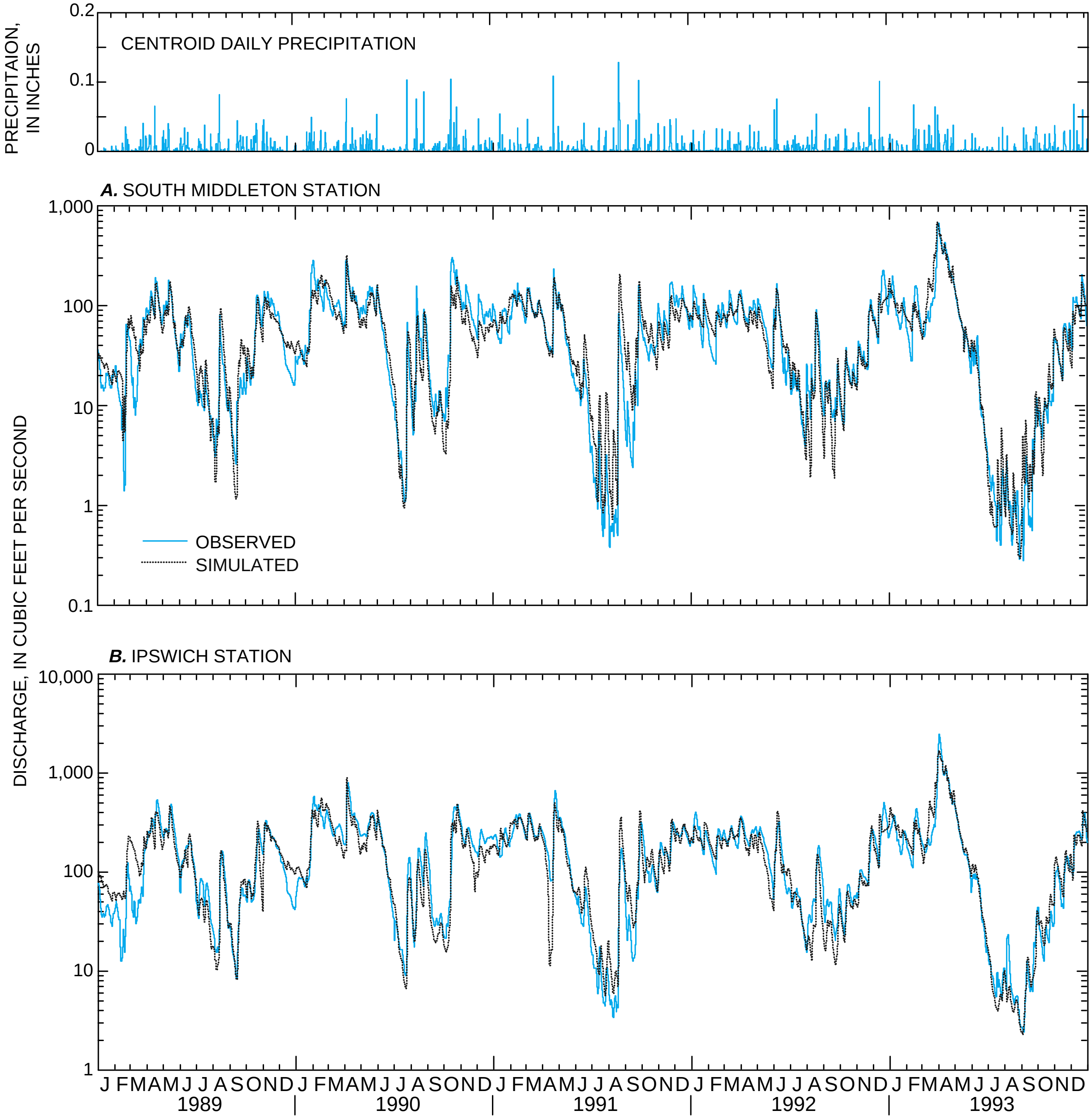


Figure 17. Simulated and observed daily-mean-discharge hydrographs for simulations made with centroid precipitation data at the (*A*) South Middleton, and (*B*) Ipswich stations, Ipswich River, Mass., 1989–93.

probability range are given in table 13 for simulations made with the centroid and Reading precipitation data. Note that some values, such as the root mean square error, are reported in cubic feet per second instead of percent as reported previously. Model-fit statistics reported as a percent can be a poor indicator of the quality of the fit because a small absolute difference can be a large difference when expressed as a percentage of the low-flow value. In general, the model fit for simulations made with precipitation data from the centroid are comparable to simulations made with the Reading precipitation data.

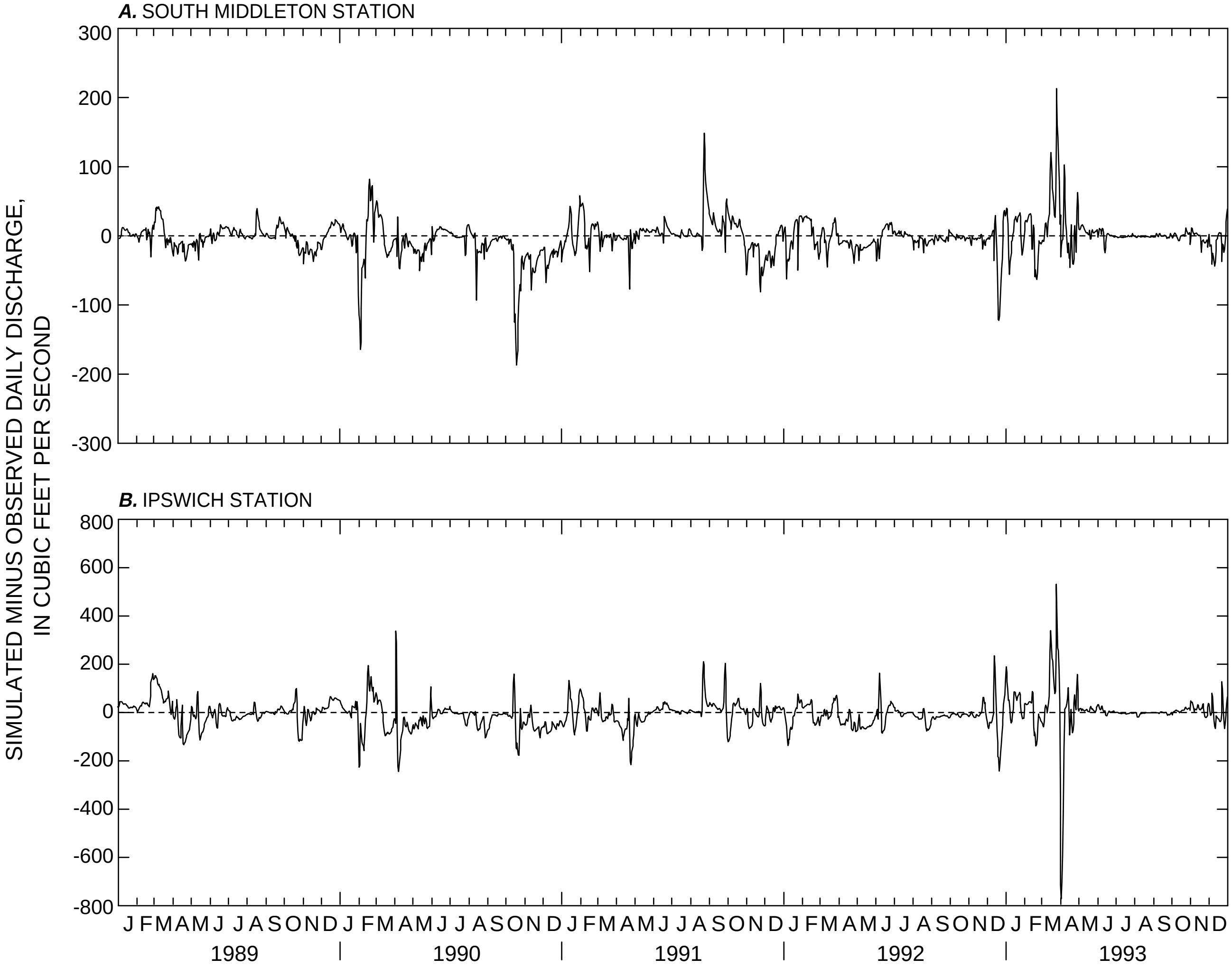


Figure 18. Difference between simulated and observed daily mean discharges as a function of time at the (*A*) South Middleton, and (*B*) Ipswich stations, Ipswich River Mass., 1989–93.

The coefficients of determination and model-fit efficiency have decreased considerably from the model fit for all daily flows. This decrease is largely because of the scatter between simulated and observed discharges at this range in flow, particularly at the South Middleton station (fig. 16). Table 13 indicates that the model fit improves considerably for flows at the 90-percent exceedence probability compared to those at the 98-percent exceedence probability. The model fit for simulated low flows is also somewhat better at the Ipswich station than at the South Middleton station. In general, the standard error and root mean square errors are small and within plus or minus the flow magnitude at the given exceedence probability at both sites.

For the 1989–93 period, the median observed flow at or below the 98-percent exceedence probability was 0.6 ft^3/s at the South Middleton station and 5.4 ft^3/sec at the Ipswich station; the median observed flow at or below the 90-percent exceedence probability was 1.8 ft^3/s at the South Middleton station and 11 ft^3/s at the Ipswich station. For the same period that the observed flows were at or below the 98-percent exceedence probability, the median simulated flow made with either set of precipitation data was 1.0 ft^3/s at the South Middleton station and 5.4 ft^3/s at the Ipswich station. For the same period that the observed flows were at or below the 90-percent exceedence probability, the median simulated flow made with either precipitation data was 2.5 ft^3/s at the South

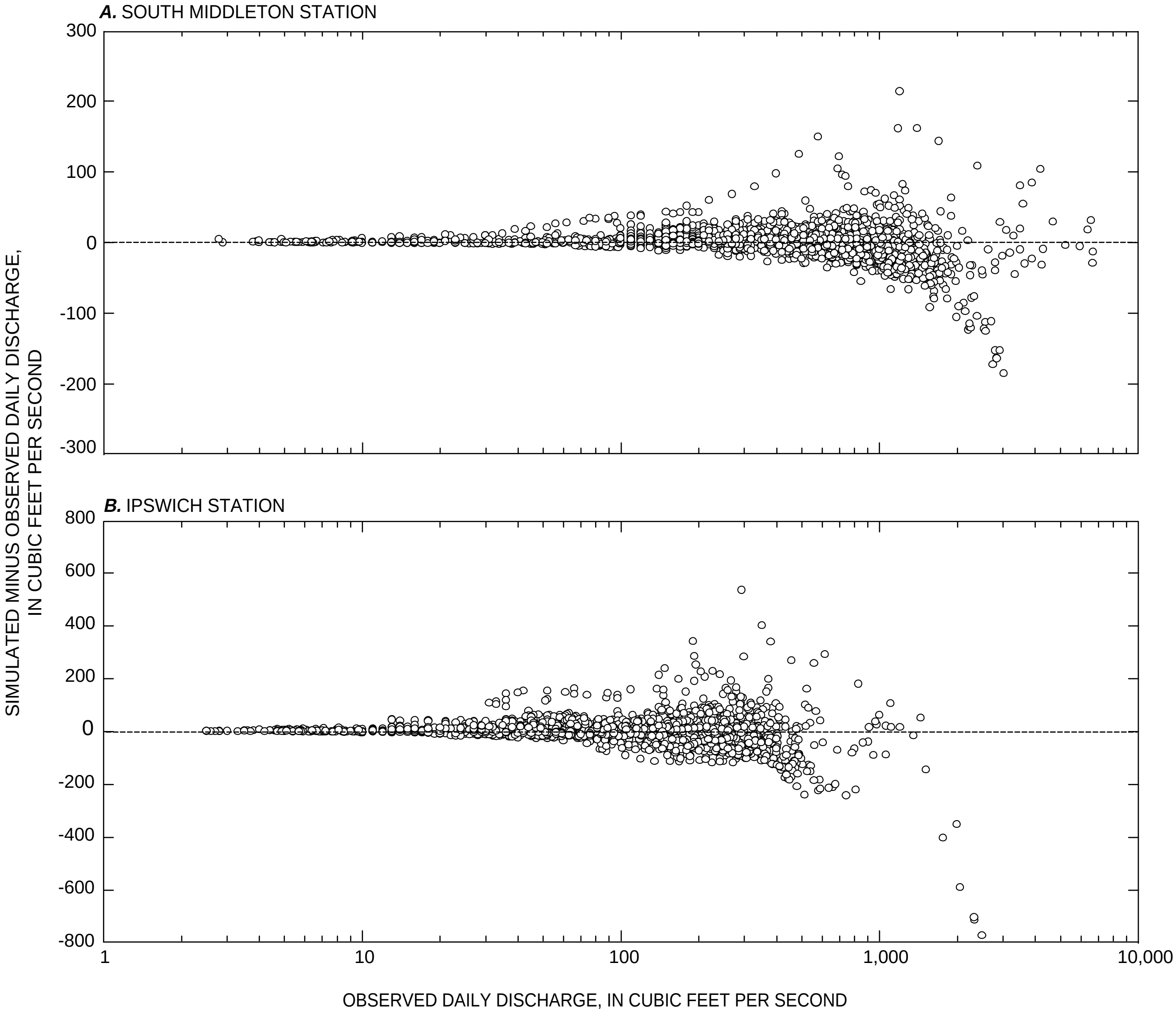


Figure 19. Difference between simulated and observed daily mean discharges as a function of observed discharge at the (*A*) South Middleton, and (*B*) Ipswich stations, Ipswich River, Mass., 1989–93.

Middleton station and 11 ft^3/s at the Ipswich station. At the South Middleton station, the median simulated flow during the time the observed flows were at or below the 90- and 98-percent exceedence probabilities were about 50 percent larger than the observed median flows. At the Ipswich station, the median simulated flows during the time the observed flows were at or below the 90- and 98-percent exceedence probabilities were the same as the observed median discharges.

Miscellaneous Discharge Measurements

Miscellaneous discharge measurements have been made at a number of locations in the Ipswich River Basin for the river habitat assessment study (David Armstrong, USGS, person. commun., 1999). Discharge measurements were made at only Fish Brook at Lockwood Lane near Boxford (fig. 8, 01101740), which is represented by reach number 39, during the calibration period. Fish Brook near Boxford

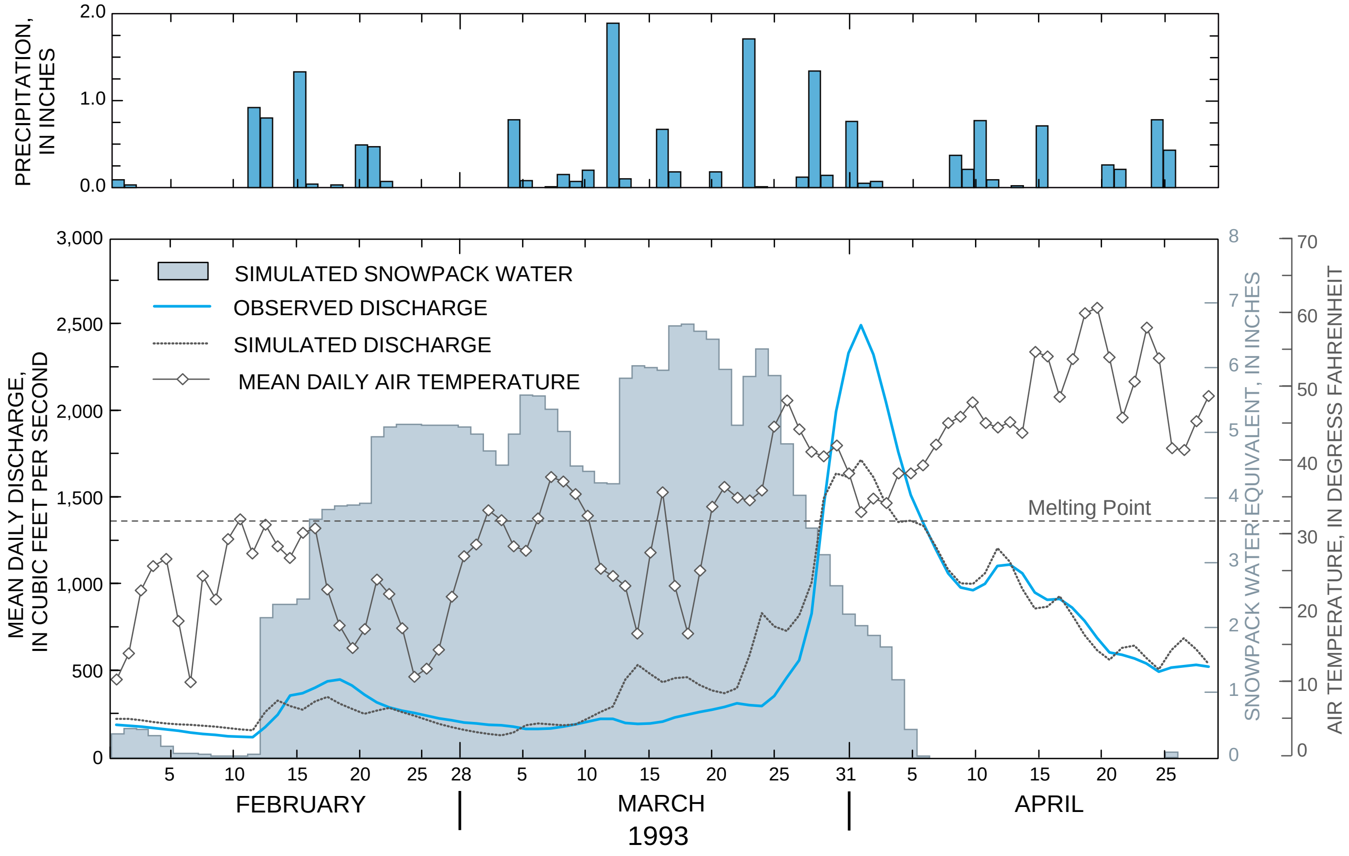


Figure 20. Observed and simulated daily mean discharge at the Ipswich station for simulations made with the centroid precipitation, air temperature, and simulated snowpack water for the Ipswich River Basin, Mass., February through April 1993.

drains a 15.5 mi^2 area that is 40 percent forest and 23 percent wetland. Three discharge measurements were made at this site in July 1993. Figure 22 indicates that the simulated discharges are slightly greater than measured discharges; however, the simulations appear reasonable given the fact that no direct calibration was performed for this location. Simulated flows made with either set of precipitation data appear to closely match the measured flows at the stations during this time.

Summary of the Differences Between Simulations with Reading and Centroid Precipitation Data

A number of factors affect the match between the simulated and observed discharge, especially the representativeness of precipitation data over the basin. Although results for simulations made separately with the Reading and centroid precipitation data are similar, simulations made with one data set improved some measures of the model fit, but caused others to worsen.

In general, simulations made with the Reading data appear to represent the precipitation in the upper part of the basin (to the South Middleton station) better than the simulations made with the centroid data. Conversely, simulations made with the centroid data appear to represent precipitation in the lower basin (to the Ipswich station) better than simulations made with the Reading data. These differences in the model fit that result from use of different precipitation data sets are expected because of the spatial position of the source data in the basin (fig. 1). The small gains in the goodness of the model fit probably do not warrant using separate precipitation data for different parts of the basin because this would double the number of HRUs and there are no long-term differences between these data.

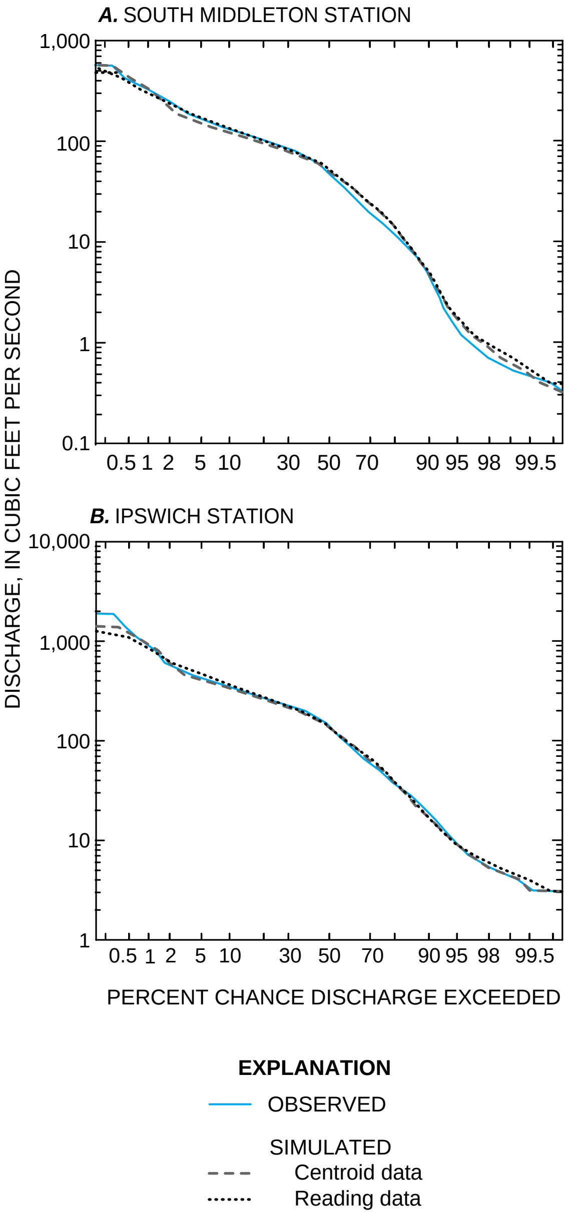


Figure 21. Flow-duration curves for observed and simulated daily mean discharges for simulations made with the centroid and Reading precipitation data for the (*A*) South Middleton, and (*B*) Ipswich stations, Ipswich River, Mass., 1989–93.

Simulation results made with the two precipitation data sets do not clearly indicate that one precipitation station better represents precipitation over the entire basin than the other. Daily flows simulated with the centroid precipitation data were slightly “better” overall than daily flows simulated with the Reading precipitation data and, therefore, were used for all scenario simulations.

Sensitivity Analysis

A sensitivity analysis provides an indication of the effects of changes in the parameter values representing watershed properties on the response of the model-simulated values. An iterative process, whereby the value of a given parameter is varied while all other parameters are held constant, indicates the degree to which that parameter can affect simulation results. The sensitivity analysis applied constant changes in parameter values equally over seasons and among the hydrologic response units. A discussion of the flow components and evapotranspiration losses simulated by the Ipswich River Basin model for each of the hydrological response units is given below. The relative differences between HRUs provide an understanding of the model response (sensitivity) to changes in parameter values.

Response of Pervious (PERLNDs) and Impervious (IMPLNDs) Land Segments

The hydrologic response of pervious and impervious land segments are important to understand the effect that HRUs have on the model results. Examination of flow components and evapotranspiration losses for each HRU indicate the predominant sources and losses of water in the model and which model parameters will be most influential in the simulation process. Flow components and evapotranspiration losses for PERLNDs and IMPLNDs are plotted in figure 23 for (1) the mean annual water budget during 1989–93, (2) a wet month (April 1993), and (3) a dry month (August 1993). Flow components (discharge to streams in the Ipswich River Basin model) are shown as bars above the zero line and evapotranspiration losses are shown as bars below the zero line.

Surface runoff from an IMPLND is equal to the moisture supply minus a small evaporation loss from interception storage. Although the total runoff per unit area from an IMPLND is larger than a PERLND (which has evapotranspiration losses from subsurface storages), the timing and magnitude of runoff from an IMPLND is not moderated by subsurface storage, as is flow from a PERLND. Thus, IMPLNDs produce larger storm flows and smaller low flows then a PERLND.

Table 13. Summary of low-flow model-fit statistics at the South Middelton and Ipswich stations for Hydrological Simulation Program-FORTRAN (HSPF) simulations made with centroid and Reading precipitation data, Ipswich River Basin, Mass., 1989–93

[ft^3/s, cubic foot per second; <, less than; %, percent]

Model-fit statistic	98-Percent exceedence probability[1]		90-Percent exceedence probability[2]	
	Centroid	Reading	Centroid	Reading
South Middleton station				
Number of days	41	41	229	229
Coefficient of determination (r^2)	-.11	-.10	.54	.58
Coefficient of model-fit efficiency	-169	-323	-5.4	-3.1
Standard error (ft^3/s)	.20	1.7	4.5	3.6
Root mean square error (ft^3/s)	1.5	2.1	4.9	4.0
Percent time simulated value <10%	5	7	9	10
Percent time simulated value <25%	10	10	21	23
Median error (ft^3/s)	.50	.5	.4	.5
Minimum error (ft^3/s)	-.3	-.3	-5.0	-4.9
Maximum error (ft^3/s)	5.2	6.4	28	25
Ipswich station				
Number of days	75	75	222	222
Coefficient of determination (r^2)	.42	.61	.60	.60
Coefficient of model-fit efficiency	-4.9	-2.2	-2.0	-2.8
Standard error (ft^3/s)	3.0	.70	9.4	.11
Root mean square error (ft^3/s)	3.3	2.4	9.9	11
Percent time simulated value <10%	21	27	18	21
Percent time simulated value <25%	52	49	43	49
Median error (ft^3/s)	.1	1.1	-1.0	1.0
Minimum error (ft^3/s)	-2.9	-2.1	-17	-16
Maximum error (ft^3/s)	11.	8.3	45	55

[1] Discharges less then or equal to: 0.7 ft^3/s at the South Middleton station, 6.0 ft^3/s at the Ipswich station.

[2] Discharges less then or equal to: 7.0 ft^3/s at the South Middleton station, 22 ft^3/s at the Ipswich station.

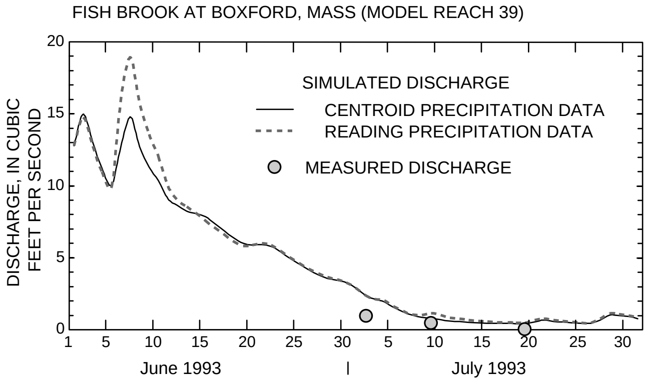


Figure 22. Discharge simulated with centroid and Reading precipitation data and instantaneous discharge measurements made at Fish Brook near Boxford, Mass., July 1993.

No surface runoff (as a percent of the mean annual runoff or during a wet or dry month) was indicated from PERLNDs representing sand and gravel (nos. 1 through 6). Mean annual surface runoff as a percent of total runoff from PERLNDs representing till (nos. 8 through 13) ranged from 1.5 to 5.9 percent and was greatest in high-density residential areas (nos. 11 and 13). Surface runoff represented less than 1 percent of the total runoff from PERLNDs representing alluvium (nos. 14 and 15) and commercial areas (no. 7). Surface runoff represented 4 percent or less of the total runoff during the wet month (April 1993) for PERLNDs representing till (nos. 8 through 13) and commercial areas (no. 7) and no surface runoff is indicated for any PERLND during the dry month (August 1993).

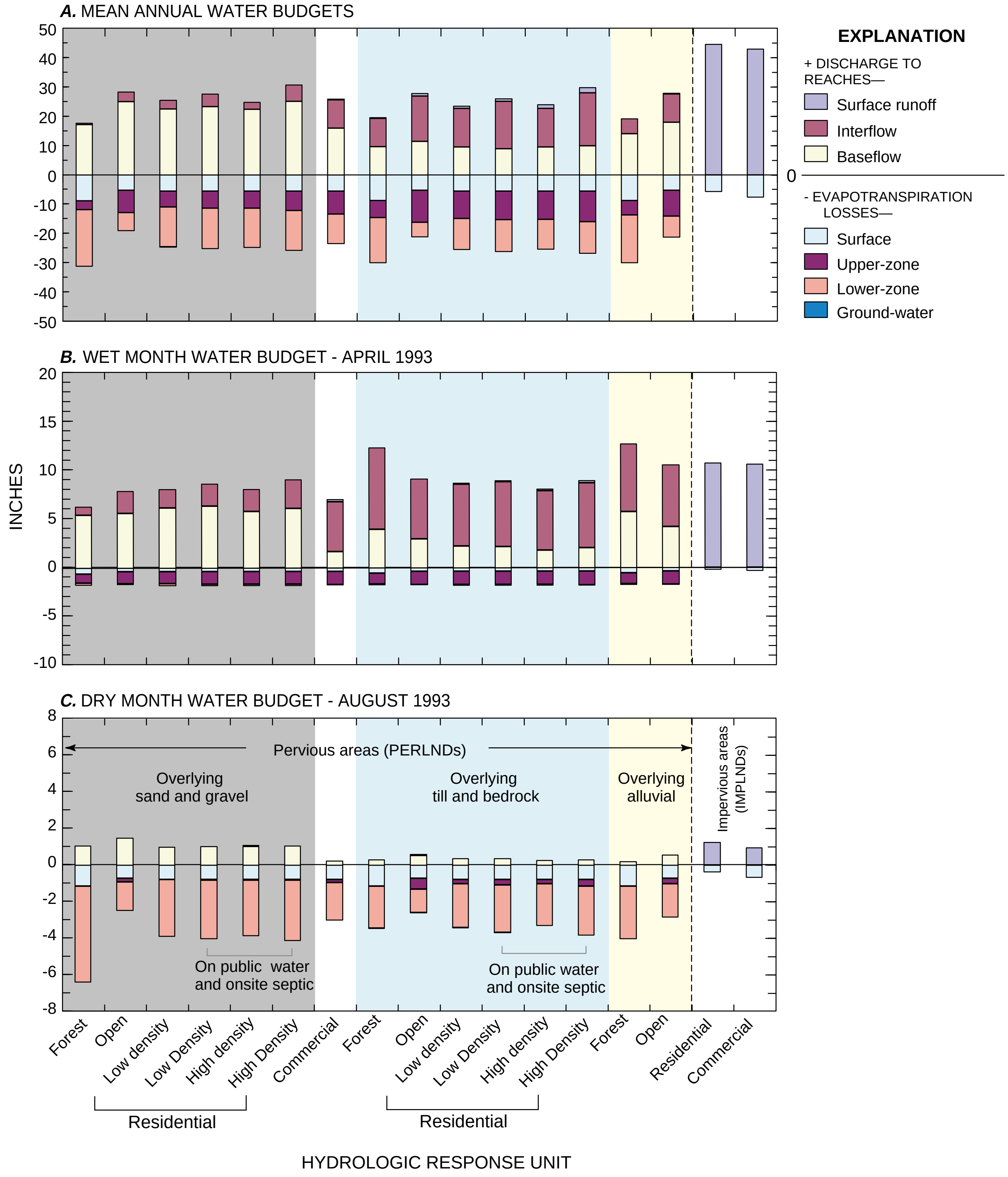


Figure 23. Runoff as surface-flow, interflow, and base-flow, and evapotranspiration losses from surface storage, upper-zone storage, lower-zone storage, and ground-water storage from each hydrologic response unit for: (*A*) mean annual water budget, (*B*) wet-month water budget for April 1993, and (*C*) dry-month water budget for August 1993, Ipswich River Basin, Mass.

Mean annual interflow as a percent of total runoff ranged from 2 to 11 percent in PERLNDs representing sand and gravel (nos. 1 through 6), 46 to 58 percent in PERLNDs representing till (nos. 8 through 13), and 25 to 34 percent in PERLNDs representing alluvium (nos. 14 and 15). Interflow was generally smallest in PERLNDs representing forest (nos. 1, 8, and 14). During the wet month (April 1993), interflow as a percent of total runoff ranged from 14 to 33 percent in PERLNDs representing sand and gravel, 68 to 76 percent in PERLNDs representing till, and 55 to 60 percent in PERLNDs representing alluvium. It should be noted that some differences in runoff during this period result from uneven moisture supply distribution from snowpack water carried over from the previous month. During the dry month (August 1993), interflow as a percent of total runoff was less than 1 percent in PERLNDs representing sand and gravel, 2.6 to 6.3 percent in PERLNDs representing till, and 0 to 2.2 percent in PERLNDs representing alluvium.

Mean annual baseflow as a percent of total runoff ranged from 89 to 98 percent in PERLNDs representing sand and gravel (nos. 1 through 6), 36 to 52 percent in PERLNDs representing till (nos. 8 through 13), and 65 to 74 percent in PERLNDs representing alluvium (nos. 14 and 15). During the wet month (April 1993), baseflow as a percent of total runoff ranged from 67 to 86 percent in PERLNDs representing sand and gravel, 21 to 32 percent in PERLNDs representing till, and 40 to 45 percent in PERLNDs representing alluvium. During the dry month (August 1993), baseflow represented nearly the entire runoff from all PERLNDs.

Mean annual evapotranspiration (ET) losses are relatively evenly distributed among PERLNDs. ET losses from the surface, and upper- and lower-zone storage represent about 24, 30, and 45 percent of the total mean annual ET loss, respectively. Active ground water ET is less than 1 percent of the total annual ET from any PERLND. During the wet month (April 1993), ET losses are primarily from upper-zone storage (averages 68 percent of the total ET loss) and surface ET (averages 25 percent of the total ET loss). During the dry month (August 1993), ET losses are primarily from the lower-zone storage (averages 70 percent of the total ET) and surface ET (averages 24 percent of the total ET).

Several general findings can be drawn from this comparison. Surface runoff is generated primarily by IMPLNDs and to a small extent by PERLNDs simulating areas of till (nos. 8 through 13). Surface runoff from these till PERLNDs generally occurs during periods of heavy precipitation or snowmelt, or both, during the winter and spring, when evapotranspiration losses are small and subsurface storage is at or near saturation. Surface runoff generally represents a small component of the hydrologic budget; thus, parameters that affect surface runoff have little effect on the uncertainty of the model predictions.

Interflow is a major runoff component from areas overlying till and this component becomes a larger portion of the total runoff during wet months. Model parameters that affect interflow will have a greater effect in PERLNDs representing till (nos. 8 through 13) than in other PERLNDs and interflow model parameters will have a larger effect on runoff during wet months than dry months. Baseflow is a major runoff component from areas of sand and gravel and is the dominant runoff component during dry months for all PERLNDs. Model parameters that affect baseflow will have a greater effect on PERLNDs representing sand and gravel (nos. 1 through 6) than in other PERLNDs, and baseflow model parameters will be the dominant model parameters during periods of low flow.

ET losses are primarily from upper-zone storage during the non-growing (cooler) months and from lower-zone storage during the growing season. Model parameters that affect the amount of upper-zone storage and the rate of ET loss from the upper zone will have a greater effect in the cooler months than during the growing season. Conversely, model parameters that affect the amount of lower-zone storage and the rate of ET loss from the lower zone will have a greater effect in the growing season than in the non-growing season.

Parameter Values

Model sensitivity to eleven PERLND parameters, and storage associated with wetland reaches, (tables 14 and 15) were examined by sequentially doubling and then halving the calibrated parameter or storage values and measuring the effect of these changes on the simulated (1) total runoff volume, (2) high- and low-flow distribution, (3) seasonal and summer runoff, (4) peak stormflow, and (5) proportion of interflow and surface runoff. These flow characteristics were examined using HSPEXP (Lumb and others, 1994a); however, the inflow from septic effluent was redirected as lateral surface inflow (LSURLI) due to limitations of HSPF version 11. The special action (SA) component of the Ipswich River Basin model, which accounts for deficits between water withdrawals and the withdrawal that was satisfied by streamflow, was not used for these simulations. Tests indicated that flow characteristics generated at the South Middleton and Ipswich stations did not appreciably change when the SA was included in the simulations used for sensitivity testing.

Several parameters (IRC, LZETP, and AGWRC) could not be doubled because they would exceed the model’s maximum allowed value; for these parameters the upper values were set at the maximum allowed value or by half the difference between the base value and the maximum allowed value, depending on which value best reflected the change in the value relative to other PERLNDs. The effect of altering the calibrated values is expressed in table 14 as the relative sensitivity (RS), in percent, and in table 15 as the absolute error (AE) relative to the observed value. The sensitivity values are calculated from a single flow characteristic value generated by the HSPEXP for the entire calibration period. The relative sensitivity (*RS*) is computed using the following equation:

$$RS = \left(\frac{V_b - V_a}{V_b + V_a}\right) \Big/ \left(\frac{P_b - P_a}{P_b + p_a}\right) \times 100 \quad , \qquad (1)$$

where

V is the value of the flow characteristic (inches),
P is the parameter value;
$_b$ is the calibrated value, and
$_a$ is the altered sensitivity value.

The absolute error is calculated by the following equation:

$$AE = \left(\frac{V_o - V_s}{V_o}\right) \times 100 \quad , \qquad (2)$$

where

V_O is the value of the observed flow characteristic (inches); and
V_S is the value of the simulated flow characteristic (inches).

The AGWRC variable, the rate that water is released from active ground-water storage, is close to its maximum permitted value. As a result, even a small change in the flow characteristic from an increase in AGWRC (table 14) produces a large change in the *RS* value because the denominator in the *RS* equation is small. IRC, the interflow recession constant, is also highly sensitive to increases in its value for similar reasons.

In general, the relative sensitivity analysis indicates that the most influential model parameters are those that affect ground water (AGWRC and KVARY) and to a lesser extent, parameters that affect interflow (INTFLW and IRC). In addition, model simulation results are sensitive to changes in parameters that influence the amount of precipitation that eventually discharges from ground water or interflow (INFILT, LZSN, UZSN). As indicated previously, ground-water discharge to stream reaches is the dominant flow component in the Ipswich River Basin, followed by interflow. Hence, uncertainties in the parameters that affect ground water will have the largest influence in model performance, followed by uncertainties in interflow parameters. In general, model results are insensitive to wetland storage, possibly because the calibrated storage is set sufficiently high that changes in storage volumes within the range tested do not produce much change in the flow characteristics examined.

The absolute error in the flow characteristics (table 15) indicates that some perturbations improved the model fit, compared to the base calibration. Changes in parameter values that decrease error for some flow characteristics, however, also increased error for other flow characteristics. In addition, decreases in runoff error at one station typically results in increased runoff error at the other station. In general, the calibrated parameter values appear to yield the best overall model fit, that is, the least overall runoff error.

Table 14. Relative sensitivity of simulated flow characteristics to HSPF model parameter or storage change, Ipswich River Basin, Mass., 1989–93

[HSPF, Hydrological Simulation Program-FORTRAN. Values represent the relative change in the flow characteristic in percent. 2x indicates the calibrated value doubled except when limited by the permitted value range, 0.5x indicates the calibrated value was halved. 10-percent flow indicates the flow that is equaled or exceeded 10 percent of the time (high flow). 50-percent flow indicates the flow that is equaled or exceeded 50 percent of the time (low flow). Storm statistics determined from an average of 10 storms: 4/2/1990, 7/23/1990, 10/10/1990, 4/20/1991, 8/17/1991, 9/22/1991, 11/20/1991, 3/10/1992, 9/25/1992, 12/10/1993. **Model parameters:** INFILT, Infiltration rate of soil; LZSN, Lower zone nominal storage; UZSN, Upper zone nominal storage. INTFLW, Interflow parameter; IRC, interflow recession constant; LZETP, Lower zone evapotranspiration; INTCEP, Interception storage; NSUR, Roughness of surface plain; LSUR, Length of surface plain; KVARY, ground water behavior constant; AGWRC, Active ground water recession constant; FVOL, reach storage.]

Model parameter	Change	Relative sensitivity (percent)											
		Total volume	10-percent flow	50-percent flow	Evapotranspiration	Storm volume	Peak flow	Base flow	Interflow	Surface runoff	Volume		
											Summer	Winter	Summer storm
South Middleton station													
INFILT	2x	1.9	-3.4	18	-2.6	-1.5	-27	1.6	-58	-9.3	10	0.10	-2.9
	.5x	-.11	5.8	-13	1.5	4.5	0	0	44	20	-8.2	1.8	5.6
LZSN	2x	-6.2	-6.0	-6.3	40	-5.6	-27	0	-31	-1.9	-8.5	-5.6	-5.8
	.5x	5.2	4.2	7.8	-4.8	4.9	0	0	26	1.2	11	3.6	5.6
UZSN	2x	-9.7	-10	-12	-7.2	-33	-60	1.6	-19	70	-22	-7.8	-93
	.5x	5.2	.25	13	-19	-17	-27	1.6	31	72	10	3.1	-61
INTFLW	2x	.02	-.86	.63	-.08	-6.1	-27	0	8.2	-9.9	0	-.10	-2.9
	.5x	.03	2.2	-2.2	.15	13	0	0	-19	24	-.29	.46	8.3
IRC	2x	-8.8	-91	119	0	11	0	17	.66	0	93	-32	-64
	.5x	.73	13	-15	0	23	23	0	2.0	0	-.43	2.8	33
LZETP	2x	-16	-7.6	-29	16	-11	0	0	-15	18	-7.3	-23	19
	.5x	23	17	33	-29	36	23	0	45	8.1	19	26	39
INTCEP	2x	-2.5	-.40	-8.5	3.0	-2.5	-27	0	1.3	0	-9.3	-.92	-2.9
	.5x	1.5	.35	5.1	-1.9	1.5	0	0	.65	-.09	5.6	.76	0
NSUR	2x	-.03	-.25	.09	.02	-1.5	-27	0	2.9	-3.1	-.14	.05	0
	.5x	.06	.40	-1.0	-.02	1.5	.05	0	-.54	3.0	0	.10	0
LSUR	2x	-.03	-.25	.09	.02	-1.5	-27	0	2.9	-3.1	-.14	.05	0
	.5x	.06	.40	-9.8	-.02	1.5	0	0	-.5	5.9	0	.10	0
KVARY	2x	1.8	6.1	-8.1	0	-3.0	-27	0	1.2	0	-9.0	6.2	-5.8
	.5x	-1.7	-5.4	7.2	0	2.5	0	0	1.2	0	7.8	-5.0	5.6
AGWRC	2x	-425	-699	387	0	331	0	0	132	0	685	-927	617
	.5x	6.5	29	-43	-.03	22	23	-4.8	1.2	0	-6.3	19	50
Wetland	2x	-.08	.45	-1.6	0	6.4	0	0	1.2	0	2.1	-.72	16
FVOL	.5x	.03	.30	.36	0	-6.7	-27	1.6	1.2	0	-2.5	1.1	-21

Table 14. Relative sensitivity of simulated flow characteristics to HSPF model parameter or storage change, Ipswich River Basin, Mass., 1989–93—*Continued*

Model parameter	Change	Relative sensitivity (percent)											
		Total volume	10-percent flow	50-percent flow	Evapotranspiration	Storm volume	Peak flow	Base flow	Interflow	Surface runoff	Volume		
											Summer	Winter	Summer storm
Ipswich station													
INFILT	2x	1.6	-3.7	11	-2.3	-.60	-33	0	-59	-12	11	-.47	5.7
	.5x	.18	6.2	-12	1.0	3.5	0	0	44	26	-9.5	2.1	-5.9
LZSN	2x	-15	-14	-11	3.7	0	0	0	-40	-6.3	-10	-17	16
	.5x	-3.6	-16	22	-8.6	13	0	0	-22	-18	23	-11	40
UZSN	2x	-6.1	-5.9	-6.3	5.0	-5.5	0	0	-31	-2.9	-8.1	-5.6	-5.9
	.5x	5.1	4.24	8.1	-4.7	5.9	0	0	25	1.6	10	3.4	5.7
INTFLW	2x	-2.6	-.58	-8.6	2.9	-3.6	0	0	.41	.13	-10	-1.0	-12
	.5x	1.7	.37	5.3	-2.0	2.4	0	0	0	0	6.3	.78	5.7
IRC	2x	-10	-100	111	0	39	0	0	-4.6	0	123	-35	0
	.5x	.94	14	-14	0	21	27	0	1.6	0	-1.5	3.4	40
LZETP	2x	-17	-8.5	-28	16	-24	-40	0	-20	15	-7.3	-23	0
	.5x	23	17	34	-29	42	27	0	45	9.6	19	26	60
INTCEP	2x	-2.6	-.58	-8.6	2.9	-3.6	0	0	.41	.13	-10	-1.0	-12
	.5x	1.7	.37	5.3	-2.0	2.4	0	0	.35	0	6.3	.78	5.7
NSUR	2x	-.02	-.32	.19	0	-1.8	0	0	2.3	-4.0	-.16	0	-5.9
	.5x	.06	.37	-.39	-.15	1.8	0	0	-.95	4.1	-.16	.05	0
LSUR	2x	-.02	-.32	.19	0	-1.8	0	0	2.3	-4.0	-.16	0	-5.9
	.5x	.06	.37	-.39	-.15	1.8	0	0	-.95	4.3	-.16	.05	0
KVARY	2x	1.7	6.1	-9.0	0	-5.5	0	0	.70	0	-11	6.2	-25
	.5x	-1.6	-5.5	7.8	0	4.7	0	0	.70	0	8.5	-4.9	16
AGWRC	2x	-423	-726	464	0	587	0	0	78	0	703	-898	1,818
	.5x	6.1	28	-44	-.15	9.8	27	-3.2	.70	0	-17	21	26
Wetland FVOL	2x	.29	.26	1.2	0	3.0	0	0	.70	0	2.2	-.16	11
	.5x	-.39	.05	-2.2	0	-3.0	0	0	.70	0	-2.8	.16	-18

Table 15. Sensitivity of runoff characteristics as the percent error from the observed value to selected model PERLND parameters and wetland storage values in the HSPF Ipswich River Basin model, Mass., 1989–93

HSPF, Hydrological Simulation Program-FORTRAN. 2x indicates the calibrated value doubled except when limited by the permitted value range, 0.5x indicates the calibrated value was halved. 10-percent flow indicates the flow that is equaled or exceeded 10 percent of the time (high flow). 50-percent flow indicates the flow that is equaled or exceeded 50 percent of the time (low flow). Storm statistics determined from an average of 10 storms: 4/2/1990, 7/23/1990, 10/10/1990, 4/20/1991, 8/17/1991, 9/22/1991, 11/20/1991, 3/10/1992, 9/25/1992, 12/10/1993. **Model parameters:** INFILT, Infiltration rate of soil; LZSN, Lower zone nominal storage; UZSN, Upper zone nominal storage; INTFLW, Interflow parameter; IRC, interflow recession constant; LZETP, Lower zone evapotranspiration; INTCEP, Interception storage; NSUR, Roughness of surface plain; LSUR, Length of surface plain; KVARY, ground water behavior constant; AGWRC, Active ground water recession constant; FVOL, reach storage.]

Model parameter	Change	Runoff error (percent difference from observed value)										Percent of total runoff	
									Volume				
		Total volume	10-percent flow	50-percent flow	Evapo-transpiration	Storm volume	Peak flow	Base flow	Summer	Winter	Summer storm	Interflow	Surface runoff
South Middleton station													
Base calibration		-1.7	-5.5	22	-19	-14	11	0	18	-2.9	83	25	16
INFILT	2x	-.5	-7.6	37	-20	-15	-7.4	1.1	27	-2.9	79	17	15
	0.5x	-1.8	-1.8	11	-18	-11	11	0	12	-1.8	90	34	19
LZSN	2x	-5.7	-9.2	17	5.9	-17	-7.4	0	12	-6.5	76	21	16
	.5x	1.8	-2.8	28	-22	-11	11	0	27	-.56	90	30	16
UZSN	2x	-7.8	-12	12	-23	-31	-26	1.1	1.9	-7.9	-3	22	26
	.5x	1.8	-5.4	33	-28	-23	-7.4	1.1	27	-.93	21	31	27
INTFLW	2x	-1.7	-6.1	22	-19	-17	-7.4	0	18	-3.0	79	27	15
	.5x	-1.7	-4.1	20	-19	-5.8	11	0	18	-2.6	93	22	19
IRC	2x	-2.2	-11	31	-19	-13	11	1.1	25	-4.8	76	25	16
	.5x	-1.2	3.0	10	-19	.3	30	0	18	-1.1	128	26	16
LZETP	2x	-10	-9.4	3.2	-11	-19	11	0	14	-14.8	103	23	18
	.5x	14	5.7	52	-33	9.5	30	0	34	15.4	138	34	17
INTCEP	2x	-3	-5.8	15	-17	-15	-7.4	0	11	-3.5	79	25	16
	.5x	-.7	-5.3	26	-20	-13	11	0	23	-2.4	83	25	16
NSUR	2x	-1.7	-5.7	22	-19	-15	-7.4	0	18	-2.9	83	26	16
	.5x	-1.6	-5.3	21	-19	-13	11	0	18	-2.9	83	25	17
LSUR	2x	-1.7	-5.7	22	-19	-15	-7.4	0	18	-2.9	83	26	16
	.5x	-1.6	-5.3	14	-19	-13	11	0	18	-2.9	83	25	17
KVARY	2x	-.5	-1.6	15	-19	-16	-7.4	0	12	1.2	76	25	16
	.5x	-2.8	-8.8	28	-19	-12	11	0	25	-6.1	90	25	16
AGWRC	2x	-4.2	-9.4	25	-19	-12	11	0	23	-8.2	90	25	16
	.5x	2.7	15	-8.6	-19	0	30	-3.2	14	10.4	155	25	16
Wetland	2x	-1.7	-5.2	20	-19	-10	11	0	20	-3.4	103	25	16
FVOL	.5x	-1.7	-5.3	22	-19	-18	-7.4	1.1	16	-2.2	59	25	16

Table 15. Sensitivity of runoff characteristics as the percent error from the observed value to selected model PERLND parameters and wetland storage values, in the HSPF Ipswich River Basin model, Mass., 1989–93—*Continued*

Model parameter	Change	Runoff error (percent difference from observed value)										Percent of total runoff	
		Total volume	10-percent flow	50-percent flow	Evapotranspiration	Storm volume	Peak flow	Base flow	Volume				
									Summer	Winter	Summer storm	Interflow	Surface runoff
Ipswich station													
Base calibration		-3.3	-4.9	5.6	-24	34	69	0	-2.1	2.0	70	26	11
INFILT	2x	-2.3	-7.1	14	-25	33	35	0	5.2	1.7	76	17	11
	.5x	-3.2	-.83	-2.6	-24	37	69	0	-8.1	3.4	63	34	14
LZSN	2x	-13	-13	-2.0	-22	34	69	0	-8.6	-9.0	90	20	11
	.5x	-5.6	-14	22	-29	45	69	0	14	-5.5	122	22	10
UZSN	2x	-7.2	-8.5	1.3	-22	29	69	0	-7.3	-1.7	63	21	11
	.5x	.08	-2.1	11.4	-27	39	69	0	4.9	4.3	76	30	12
INTFLW	2x	-3.3	-5.5	6.2	-24	27	35	0	-2.1	1.9	63	27	11
	.5x	-3.3	-3.3	4.1	-24	44	69	0	-2.3	2.3	83	23	14
IRC	2x	-3.9	-10	13	-24	37	69	0	5.4	-.11	70	25	11
	.5x	-2.7	4.5	-3.7	-24	54	102	0	-3.1	4.3	122	26	11
LZETP	2x	-11.8	-9.3	-9.6	-17	17	35	0	-6.0	-10	70	23	12
	.5x	12.7	6.3	32.2	-38	77	102	0	11	21	155	35	12
INTCEP	2x	-5.0	-5.2	-.27	-23	30	69	0	-8.4	1.3	57	26	11
	.5x	-2.2	-4.6	9.4	-25	36	69	0	2.1	2.5	76	26	11
NSUR	2x	-3.3	-5.1	5.8	-24	32	69	0	-2.2	2.0	63	26	11
	.5x	-3.2	-4.6	5.4	-24	35	69	0	-2.2	2.0	70	25	12
LSUR	2x	-3.3	-5.1	5.8	-24	32	69	0	-2.2	2.0	63	26	11
	.5x	-3.2	-4.6	5.4	-24	35	69	0	-2.2	2.0	70	25	12
KVARY	2x	-2.2	-.90	-.54	-24	29	69	0	-9.2	6.3	44	26	11
	.5x	-4.3	-8.3	11	-24	38	69	0	3.6	-1.3	90	26	11
AGWRC	2x	-5.7	-8.9	8.6	-24	38	-83	0	2.1	-3.4	90	26	11
	.5x	.72	15	-21	-24	43	102	-2.1	-13	17	103	26	11
Wetland	2x	-3.1	-4.7	6.5	-24	36	69	0	-.6	1.9	83	26	11
FVOL	.5x	-3.5	-4.8	4.1	-24	31	69	0	-3.9	2.1	50	11	11

Model Limitations

Mathematical models that are used to represent complex natural systems are simplified by necessity, both in terms of the processes simulated and the physical representation of the system. Hence, there are inherent limitations to the types of questions that can be appropriately addressed by the model. The Ipswich River Basin precipitation-runoff model was conceptualized and calibrated to evaluate the effects of water withdrawals from relatively shallow ground water and surface sources on streamflow. The model can be used to evaluate many water-resource management questions by providing information about the effects of alternative management scenarios, or by generating data that would be difficult to obtain otherwise. The model may not be an appropriate tool to evaluate some management questions, however, and the simulation results could be incorrect or misleading, which could lead to poor management decisions. Therefore, the use of the model and results of simulations should always be weighed in the context of the inherent limitations of the model.

For example, the use of this model may not be appropriate to evaluate the effects on streamflow of wells tapping fractured bedrock, because ground water in fractured bedrock can have a widely variable area of recharge and natural discharge. One of the underlying assumptions in the streamflow depletion program (STRMDEPL) developed for this study is that the pumped well is completed in a uniform aquifer with a fully-penetrating stream. The accuracy of streamflow depletion calculated by STRMDEPL depends closely on how well the actual aquifer conditions fit the underlying assumptions. Without detailed geohydrologic investigations of bedrock aquifer conditions, application of the STRMDEPL program to determine any streamflow depletions caused by bedrock wells would have a high degree of uncertainty.

Another consideration in evaluating model simulation results is the degree to which the model was calibrated. A good fit was obtained between simulated and observed flows over a wide range of conditions for the Ipswich River at the South Middleton and Ipswich stations; however, most reaches were ungaged and the model could not be calibrated for stream reaches below the Ipswich station. Furthermore, the calibration reflects the combined effects of various hydrologic response units (PERLNDs and IMPLNDs) and reach characteristics. Hydrologic judgment was used to represent the response of different PERLNDs and IMPLNDs, but no information was available to explicitly calibrate the unique HRUs. Therefore, simulation results from ungaged areas or changes in flow produced by the variation of the properties of HRUs are uncertain, and the results should be viewed as evidence of a relative change instead of an absolute change. Stage, storage, and discharge characteristics of reaches (including wetlands) are determined from measured channel geometry to the extent possible, but many factors, such as channel roughness and the large number of changes in channel geometry along a stream reach, could not be measured within the scope of this project. The stage, storage, and, discharge characteristics of a stream reach affect the flow routing in the model and the stream stage at a given discharge.

APPLICATION OF THE MODEL: EFFECTS OF WATER WITHDRAWALS ON STREAMFLOW

The Ipswich River Basin model was developed as a tool to evaluate the response of streamflow to various water withdrawal scenarios. Results of the simulation of these scenarios, along with those of any future scenarios that might be tested, will help water-resource planners develop management strategies to satisfy water supply needs while simultaneously maintaining flows to protect the river ecosystem. Six hypothetical scenarios identified by the Ipswich River Task Force Science and Data Committee as important to understanding the effects of water withdrawals were simulated:

1. Stopping all withdrawals during the 1989–93 calibration period,
2. Only ground-water withdrawals for the calibration period,
3. Only surface-water withdrawals for the calibration period,
4. Simulate long-term (1961–95) streamflows with 1991 land-use conditions as developed in the calibrated model, and stopping all withdrawals,
5. Simulate long-term streamflow conditions by reverting developed HRUs to undeveloped HRUs and stopping all withdrawals, and
6. Simulate long-term streamflows in response to average 1989–93 water withdrawals.

A new model run file (*uci*) and unique scenario identification was created for each scenario. Simulation results for each scenario were targeted to a unique data set in the WDM file so that the scenarios could be compared. Table 16 summarizes the scenarios, model run files, and output data sets.

All scenarios required modification of the base model run file (ips.uci) to change withdrawal rates in the external source block (EXT SOURCES) and to output streamflow to unique DSNs in the external target (EXT TARGET) block. The GLOBAL block was also modified in the last three scenarios to change the simulation period. Scenario 5 converted all developed HRUs (PERLNDs 3 through 7 and 10 through 13, and IMPLND 1 and 2) to forested HRUs (PERLNDs 1 and 8) with similar surficial geology by changing the drainage areas from developed HRUs to undeveloped HRUs in the SCHEMATIC block. This scenario approximates the natural flow of the river by stopping withdrawals and reverting land use to undeveloped conditions. Scenario 6 required streamflow depletion from ground-water and surface-water withdrawals over the 1961–95 period; however, these data were generally unavailable except for the calibration period (table 4). Water withdrawals were estimated for periods of missing data for each reach by averaging daily withdrawals for each month that data were available and generating a similar daily withdrawal for each month for periods of no record.

Table 16. Alternative water withdrawal and land-use scenarios simulated for the Ipswich River Basin, Mass.

Scenario	Model run file	Scenario identification	Output data set numbers
1. Stop all withdrawals	No_demd.uci	No_demd	6001 to 6066
2. Ground-water withdrawals only	No_GWdem.uci	No_GWdem	6101 to 6166
3. Surface-water withdrawals only	No_SWdem.uci	No_SWdem	6201 to 6266
4. Long-term with no water-supply demands	LT-NoDem.uci	LT-NoDem	6301 to 6366
5. Long-term undeveloped land use and no water demands	LT-Undev.uci	LT-Undev	6401 to 6466
6. Long-term with 1989–93 average water withdrawals	LT-Demd.uci	LT-Demd	6501 to 6566

Simulation results for the scenarios provide relative differences between streamflows under different water withdrawals and land uses. Results are best compared in groups of scenarios with similar time spans so that the differences between model runs represent differences between scenarios and not the differences between climatic conditions. The first three scenarios span the 1989–93 period used to calibrate the model; water withdrawals during this period are mostly from reported records. The last three scenarios span the 1961–95 period; water withdrawals (when included in the simulation) are mostly estimated from the reported withdrawals for the 1989–93 period and do not reflect changing water use over this period. The reported ground-water withdrawals were relatively constant from year to year for similar months. The reported surface withdrawals are often dependent on streamflow, and thus, are subject to wider variations in monthly values.

Calibration-Period Simulations

Flow-duration curves for simulations of the 1989–93 period are shown in figure 24 for the base simulation and for scenarios with (1) no withdrawals, (2) only surface-water withdrawals, and (3) only ground-water withdrawals. Flow-duration curves are nearly identical for the base simulation and simulations with only ground-water withdrawals at both the South Middleton and Ipswich stations. Flow-duration curves are also nearly identical for simulations with no withdrawals and simulations with only surface-water withdrawals at both the South Middleton and Ipswich stations. The two sets of curves differ by about an order of magnitude at the 99.8 percent exceedence probability at both sites. This indicates that surface-water withdrawals have little effect on the duration and frequency of low flows and that the ground-water withdrawals have a large effect on the magnitude, duration, and frequency of low flows. The relative difference between curves is somewhat larger at the South Middleton station than at the Ipswich station because of the relatively greater rate of ground-water withdrawal with respect to streamflow above the South Middleton station than above the Ipswich

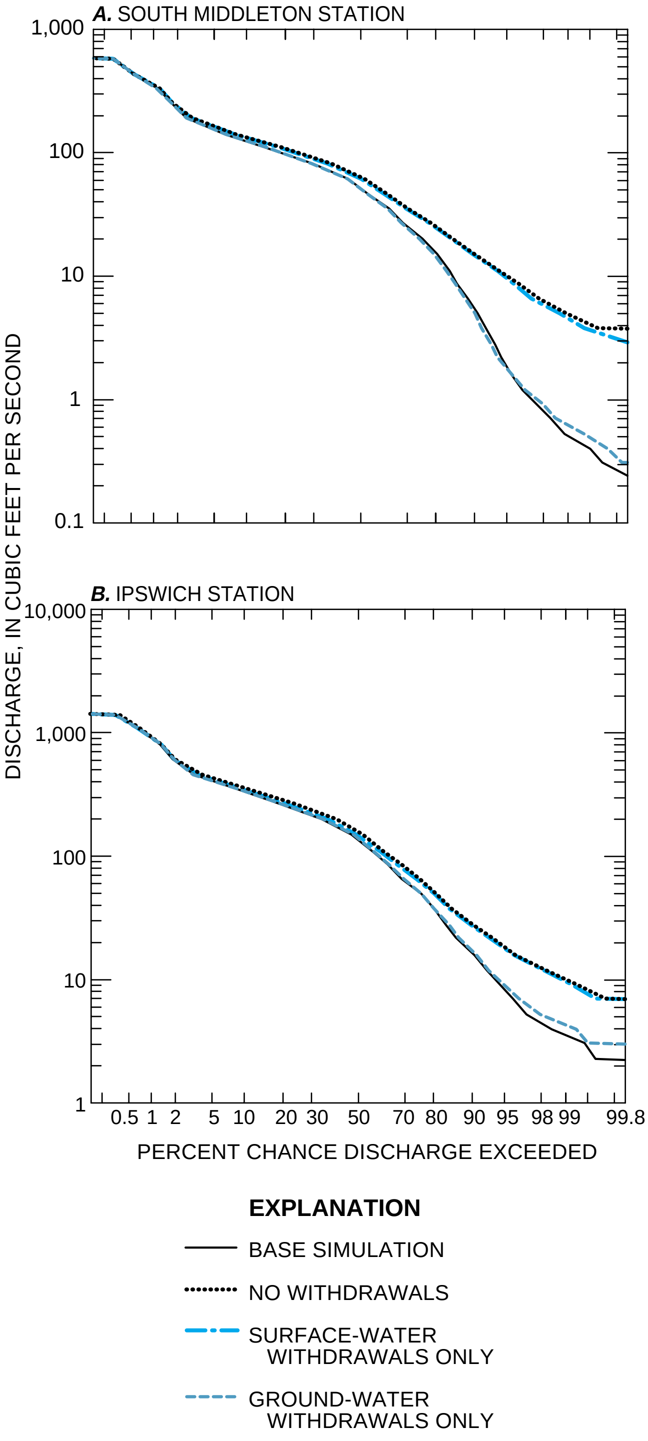


Figure 24. Flow-duration curves developed from simulated daily flows for current conditions (base simulation) and three scenarios—no withdrawals, only surface-water withdrawals, and only ground-water withdrawals—for the Ipswich River at the (*A*) South Middleton and (*B*) Ipswich stations, Mass., 1989–93.

station. The differences between curves diminish as the exceedence probability decreases; little difference between curves is indicated below the 50 percent exceedence probability at both sites. This indicates that water withdrawals have little effect on high and medium flows at either station.

Hydrographs of simulated daily flows further illustrate the effect of ground-water withdrawals on low flows (fig. 25). During most of the year hydrographs for the various scenarios are nearly identical; during periods of low flow (especially during the summers of 1991 and 1993), however, the hydrograph with no withdrawals and the hydrograph with only surface-water withdrawals are sustained at a higher discharge than the hydrographs for the base simulation or that with only ground-water withdrawals.

Long-Term Simulations

Long-term simulations (1961–95) indicate that the differences in streamflow between scenarios with no withdrawals and those with average water withdrawals (fig. 26) are similar to the differences in streamflow for the 1989–93 simulations for similar types of scenarios. The flow-duration curve for undeveloped land use with no withdrawals is similar to the flow-duration curve with no withdrawals with 1991 land-use conditions (fig. 24). Small differences can be noted in the flow-duration curves between simulations with undeveloped land use with no withdrawals and simulations with no withdrawals with 1991 land-use conditions for medium- to low-flow conditions at the South Middleton station and medium- to high-flow conditions at the Ipswich station. The differences in duration curves for low-flow conditions at the South Middleton station reflect the greater infiltration and increased base flow under undeveloped conditions than developed conditions, whereas the lack of difference at the Ipswich station (which has less developed land use than above the South Middleton station) reflect greater lower zone evapotranspiration between forested and open land which offsets any gains in base flow.

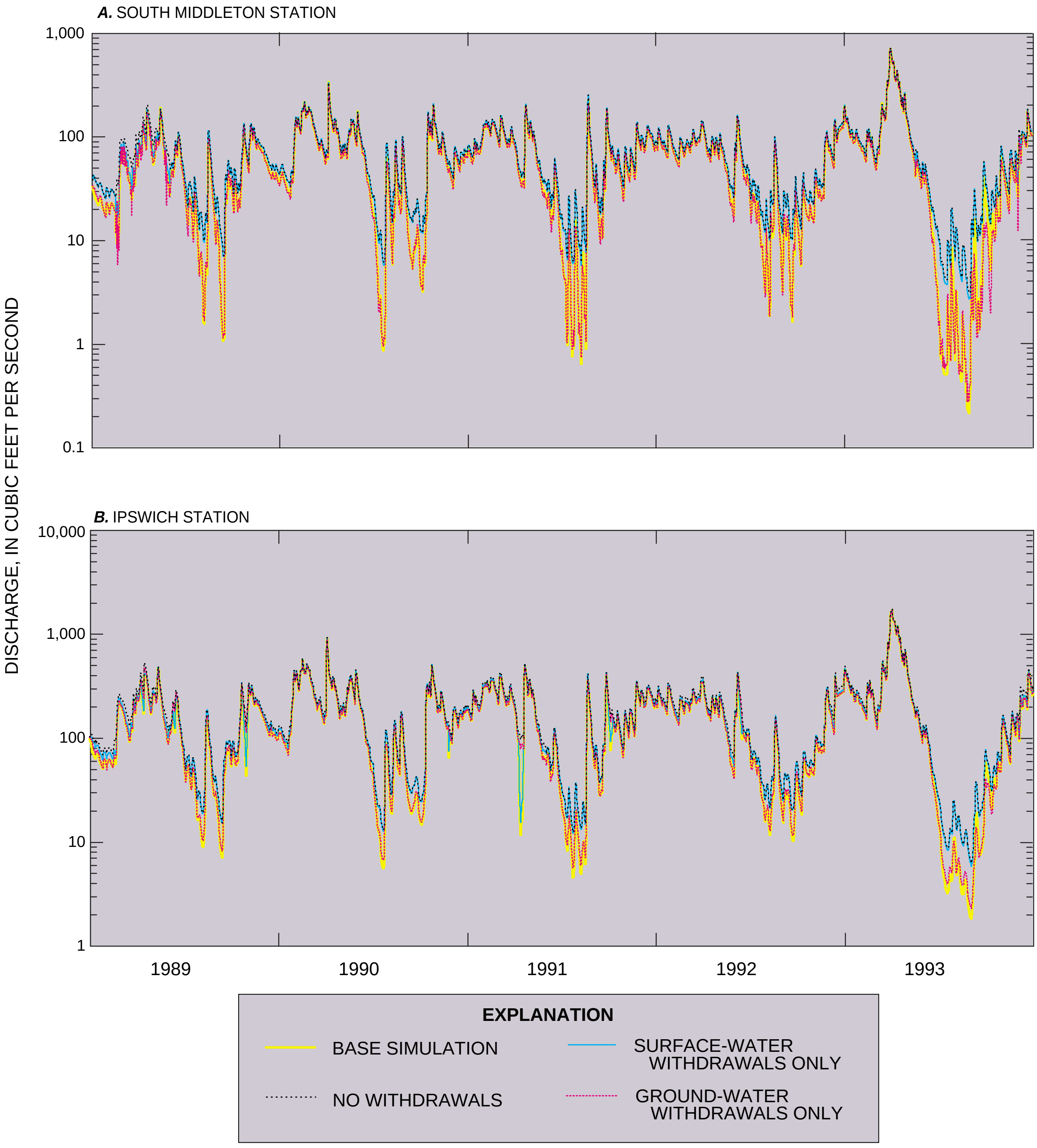


Figure 25. Discharge for current conditions (base simulation) and three scenarios—no withdrawals, only surface-water withdrawals, and only ground-water withdrawals—for the Ipswich River at the (*A*) South Middleton and (*B*) Ipswich stations, Mass., 1989–93.

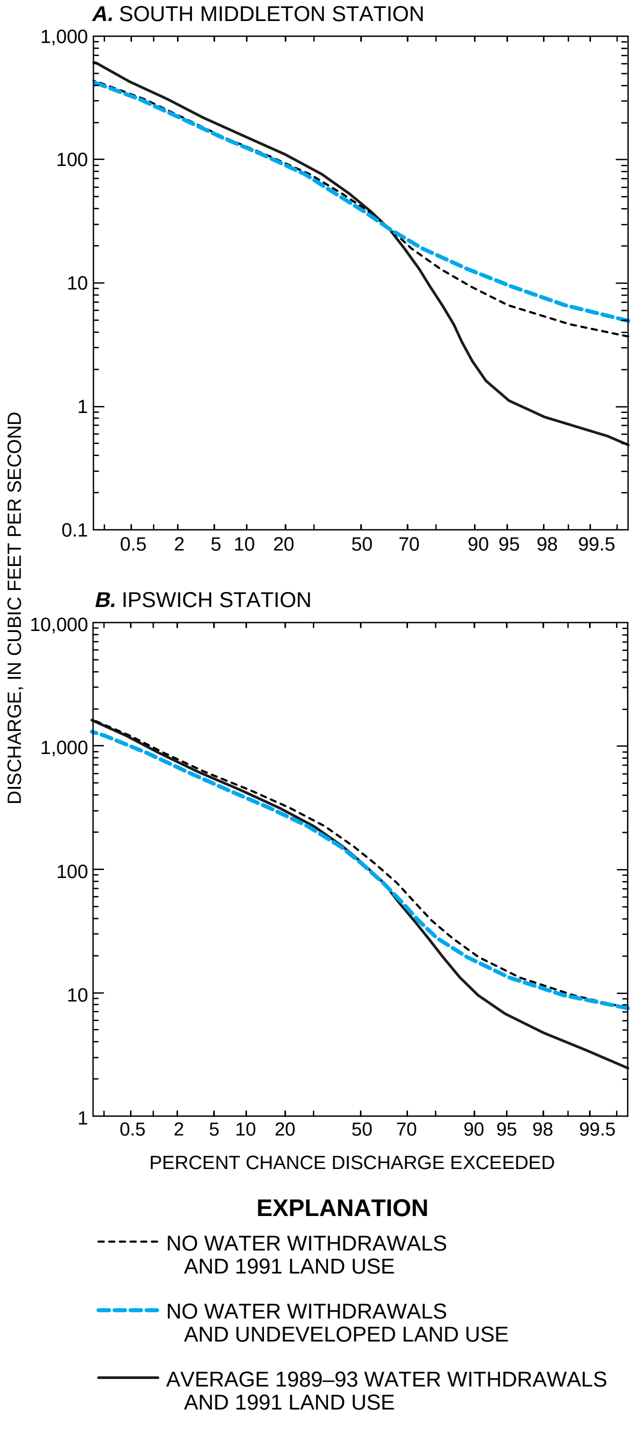


Figure 26. Flow-duration curves for average water withdrawals with 1991 land-use conditions, no withdrawals with 1991 land-use conditions, and no withdrawals with undeveloped land-use conditions, for the Ipswich River at the (*A*) South Middleton, and (*B*) Ipswich stations, Mass., for long-term simulations (1961–95).

Long-term simulations enabled the computation of low-flow-frequency probabilities by fitting annual series of low flows to the log-Pearson Type III distribution. Low-flow frequency probabilities were computed from annual series of minimum 1-day, 7-day, and 30-day mean flows for each of the long-term simulation scenarios using SWSTAT, a program designed to compute surface-water statistics (Lumb and others, 1994b). The low-flow frequency curves computed from the simulated daily discharges for each of the long-term scenarios are shown for each period of minimum flow in figure 27.

The 1-day low-flow probability curve indicates the minimum daily discharge that is likely to occur in the specified recurrence interval (bottom x-axis), which is the reciprocal of the probability of non-exceedence (top x-axis). For instance, streamflow at the South Middleton station for simulations with no water withdrawals and 1991 land use indicate that the minimum daily flow with a recurrence probability of 50 years is 2.9 ft^3/s. Flows might not fall below 2.9 ft^3/s in a given 50-year period or could fall below this level more than once in a 50-year period; over a long period of time, however, this minimum daily flow would be expected to occur, on average, once in 50 years if no water withdrawals were being made.

Minimum daily flows for simulations with no withdrawals with 1991 land-use conditions and no withdrawals with undeveloped land-use conditions were comparable. At the South Middleton station, flows ranged from 2.7 and 3.5 ft^3/s at the 100-year recurrence interval to 9.9 and 15 ft^3/s at about the 1-year recurrence interval for simulations with (1) no withdrawals with 1991 land-use conditions and (2) no withdrawals with undeveloped land-use conditions, respectively. At the Ipswich station, flows ranged from 5.8 and 5.5 ft^3/s at the 100-year recurrence interval to 23 and 21 ft^3/s at about the 1-year recurrence interval for simulations with (1) no withdrawals with 1991 land-use conditions and (2) no withdrawals with undeveloped land-use conditions, respectively. Simulations with no withdrawals with 1991 land-use conditions and those with undeveloped land-use conditions indicate that undeveloped land-use conditions resulted in increased discharge above South Middleton station, but slightly decreased discharge at the Ipswich station.

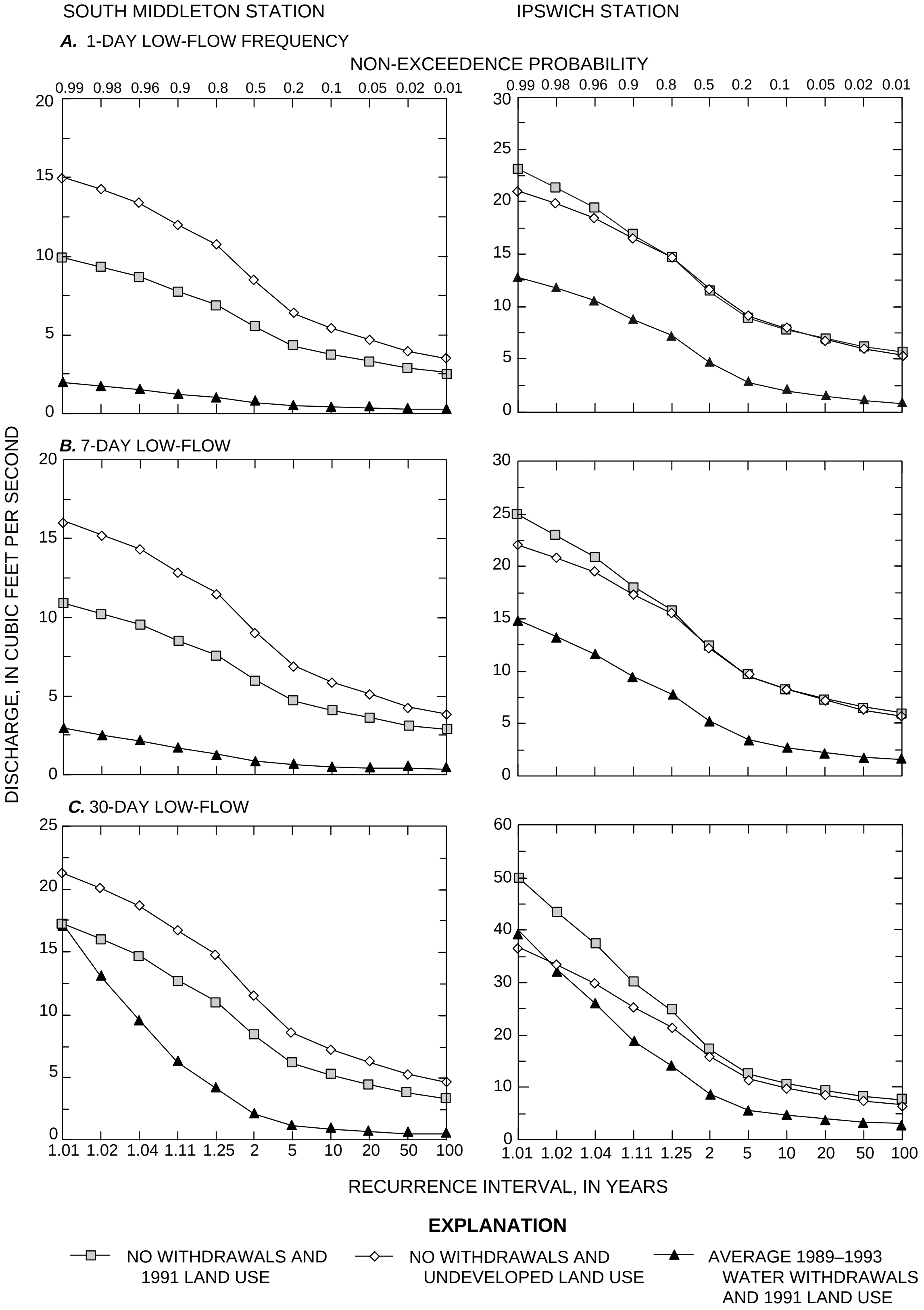


Figure 27. Log-Pearson Type III low-flow exceedence probabilities and recurrence intervals for (*A*) 1-day, (*B*) 7-day, and (*C*) 30-day annual minimum mean streamflows based on long-term (1961–95) simulations of average water withdrawals, no withdrawals with 1991 land-use conditions, and no withdrawals with undeveloped land-use conditions, for the Ipswich River at the South Middleton and Ipswich gaging stations, Mass.

This indicates that the imperviousness above the South Middleton station under the 1991 land-use condition was sufficient to inhibit infiltration and, thereby, decrease baseflow. This is underscored by the fact that under relatively less developed conditions at the Ipswich station, the undeveloped condition resulted in lower flow through evapotranspiration than the developed condition.

Minimum daily flows for simulations with average 1989–93 withdrawals were considerably less than the minimum daily flows for simulations with no withdrawals for either land-use condition. At the South Middleton station, flows with water withdrawals ranged from 0.32 ft^3/s at the 100-year recurrence interval to 2.0 ft^3/s at about the 1-year recurrence interval. At the Ipswich station, flows with water withdrawals ranged from 0.84 ft^3/s at the 100-year recurrence interval to 13 ft^3/s at about the 1-year recurrence interval.

The 7-day low-flow frequency represents the minimum flows over a continuous 7-day period. The 7-day low-flow probabilities are similar to, but slightly greater than, the 1-day low-flow probabilities. At the South Middleton station, flows ranged from 2.9 and 3.8 ft^3/s at the 100-year recurrence interval to 11 and 16 ft^3/s at about the 1-year recurrence interval for simulations with (1) no withdrawals with 1991 land use conditions, and (2) no withdrawals with undeveloped land conditions, respectively. At the Ipswich station, flows ranged from 6.0 and 5.7 ft^3/s at the 100-year recurrence interval to 25 and 22 ft^3/s at about the 1-year recurrence interval for simulations with (1) no withdrawals with 1991 land-use conditions and (2) no withdrawals with undeveloped land conditions, respectively. Minimum 7-day flows for simulations with water withdrawals ranged from 0.38 ft^3/s at the 100-year recurrence interval to 3.0 ft^3/s at about the 1-year recurrence interval at the South Middleton station, and from 1.5 ft^3/s at the 100-year recurrence interval to 15 ft^3/sec at about the 1-year recurrence interval at the Ipswich station.

The 7-day, 10-year, low-flow (7Q10), which represents the probable minimum flow over a 7-day period that will occur on average once in 10 years, is a widely used regulatory statistic. At the South Middleton station, the 7Q10 flows were 4.1 ft^3/s, 5.9 ft^3/s, and 0.54 ft^3/s for simulations with (1) no withdrawals with 1991 land-use conditions, (2) no withdrawals with undeveloped land-use conditions, and (3) average water withdrawals with 1991 land-use conditions, respectively. At the Ipswich station, the 7Q10 flows were 8.3 ft^3/s, 8.2 ft^3/s, and 2.7 ft^3/s for simulations with (1) no withdrawals with 1991 land use conditions, (2) no withdrawals with undeveloped land conditions, and (3) average water withdrawals with 1991 land-use conditions, respectively.

The 30-day low-flow frequency represents the minimum annual flow over a continuous 30-day period. The 30-day low-flow probabilities are similar, but larger, than flows at the 1- and 7-day low-flow probabilities. At the South Middleton station, flows ranged from 3.4 ft^3/s and 4.7 ft^3/s at the 100-year recurrence interval to 17 ft^3/s and 21 ft^3/s at about the 1-year recurrence interval for simulations with (1) no withdrawals with 1991 land-use conditions and (2) no withdrawals with undeveloped land conditions, respectively. At the Ipswich station, flows ranged from 7.6 ft^3/s and 6.6 ft^3/s at the 100-year recurrence interval to 50 ft^3/s and 37 ft^3/s at about the 1-year recurrence interval for simulations with (1) no withdrawals with 1991 land use conditions and (2) no withdrawals with undeveloped land conditions, respectively. Minimum 30-day flows for simulations with water withdrawals ranged from 0.52 ft^3/s at the 100-year recurrence interval to 17 ft^3/s at the 1-year recurrence at the South Middleton station, and from 3.1 ft^3/s at the 100-year recurrence interval to 40 ft^3/s at the 1-year recurrence interval at the Ipswich station.

Low flows for simulations with no water withdrawals and undeveloped land use tend to decrease relative to simulations with no water withdrawals and 1991 land-use conditions for return intervals of about 2 years or less for all duration periods, and especially for the 30-day low-flow period. At the Ipswich station, the 30-day low flow for no withdrawals with undeveloped conditions was less than the 30-day low flow with average water withdrawals as the return period approached 1 year. This suggests that the evaporation losses, which are greater in forested PERLNDs than in other PERLND types, become increasingly important in establishing the long-duration (e.g., 30-day interval) low-flow characteristic for short return intervals.

Because the amount of effective impervious area in the basin is uncertain, another simulation was made (LT-imp.uci) for the 1961–95 period with average 1989–93 withdrawals, but with the effective impervious area set equal to the initial estimated values of effective imperviousness shown in table 6. This simulation required shifting area from disturbed open PERLNDs into the corresponding IMPLNDs and represents about a 50 percent increase in the effective impervious area in the Ipswich River Basin model. Results of this simulation can be used to assess the hydrologic effects of changes in effective impervious area and can provide a reasonable upper limit to the relative hydrologic change from a undeveloped to an developed land-use condition.

Flow duration curves for simulated daily flows made with increased effective impervious area are nearly identical to the flow duration curves for simulated daily flows with the calibrated effective impervious area at both the South Middleton and Ipswich stations. Small changes in the computed log-Pearson low-flow-frequency probabilities were noted, however, between simulated flows made with the different effective impervious areas. Simulation results with the larger effective impervious area indicated that the minimum annual daily flow decreased by about 7 percent over the entire range of recurrence intervals compared to the minimum annual daily flow for simulations made with the calibrated effective impervious area at the South Middleton station. At the Ipswich station, the minimum annual daily flow decreased by about 6 percent for return periods that approached 1-year, but increased by about 5 percent for return periods of 5 or more years. Thus, the difference in the 1-day low flow between simulations made with undeveloped land-use conditions and developed land-use conditions would generally be larger, particularly at the South Middleton station (more developed) when the effective imperviousness is increased to a reasonable upper limit.

Simulations made with increased impervious area indicated that the 30-day low flow increased by 1.3 percent for a 100-year recurrence interval to 13 percent for about a 1-year recurrence interval at the South Middleton station compared to flows simulated with the calibrated impervious area; a similar, but smaller increase was noted at the Ipswich station. This increase in the 30-day low flow reflects the increased runoff from storms that likely occur during a 30-day period, but as previously noted, the flow between storms will generally be less as a result of increased imperviousness. In general, the differences between flow characteristics for simulations made with the calibrated effective impervious area and the initial effective impervious area are small at the stream-gaging stations, but changes in the effective imperviousness will have a greater impact in subbasins that are more developed than in subbasins with less development, which is evident from the relatively large change in flow characteristics at the South Middleton station compared to those at the Ipswich station.

SUMMARY

The Ipswich River Basin supplies water to about 330,000 residents in 23 municipalities in or near the basin. Urbanization and decreases in streamflow resulting from water withdrawals in the basin are of concern because of the potential effects on aquatic habitat, water quality, and recreational use of the river. Impaired flow, low dissolved oxygen concentrations, high nutrient concentrations, and the presence of pathogens in the river have led regulators to list the river under Section 303(d) of the Federal Clean Water Act as non-compliant with the Massachusetts Water Quality Standards. This listing requires that Massachusetts develop a management plan to address the impairments.

During the 1989–93 study period, average monthly water withdrawals from all sources exceed monthly mean streamflow above the South Middleton gaging station during July and approaches monthly mean streamflow during September. Average monthly pumping above the Ipswich gaging station approaches the mean monthly streamflow during July during the 1989–93 period. During 1989–93, ground-water withdrawals always exceeded surface-water withdrawals above the South Middleton station, but ground-water withdrawals exceeded surface-water withdrawals only during June through October above the Ipswich station because the state water-use permits restrict surface-water withdrawals between May and October.

The Hydrological Simulation Program-FORTRAN (HSPF) was used to simulate the hydrology and complex water withdrawals in the basin.

Model development involved (1) collecting and assembling data on climate, streamflow, and water-use or estimating this data when necessary, (2) subdividing the land surface into units of similar hydrologic response (HRUs) and the streams into reaches, (3) determining the hydraulic characteristics of each reach, and (4) determining the effects of water withdrawals on streamflows.

Time series of climate, streamflow, and water withdrawals were compiled and entered into the Watershed Data Management system data base. Spatial grids of climate data for the basin were developed by the Marine Biological Laboratory (MBL) from National Weather Service data. Grid cells were averaged to obtain a single set of climatic time series (centroid) for use in the model. The climate data generally are hourly and date back to 1961. Daily streamflow observations on the Ipswich River at South Middleton and at Ipswich gaging stations began in the 1930's. Daily water withdrawal data (often estimated from monthly values) generally began in 1989.

Land-surface and hydraulic data were compiled to discretize the basin and set model parameters. The model includes 15 pervious HRUs (PERLNDs), and 2 impervious HRUs (IMPLNDs), that were developed from unique combinations of land use, surficial geology, and water-use practices to represent the basin. The Ipswich River and its main tributaries were segmented into 67 stream reaches (RCHRES) based on hydrology, water withdrawals, and in a few cases, on habitat considerations. Wetlands cover about 21 percent of the Ipswich River Basin, and because of their effects on the hydrology of the basin, additional RCHRES were defined for most channel segments to represent wetland storage.

Streamflow depletions resulting from ground-water withdrawals were calculated using STRMDEPL, a computer program that analytically computes the delayed effects of ground-water withdrawals on streamflow based on daily pumping rate of wells, aquifer and streambed properties, and the distance of the pumped well from the stream.

The model was calibrated to measured streamflow at the South Middleton and Ipswich stations for the period 1989–93 because water-use information could be obtained or estimated, and because 1991 land-use data were used to define the HRUs. Model-parameter values were calculated from available spatial data to the extent possible, and then an iterative process was used to adjust values to minimize the difference between simulated and observed flows. Parameter values were calibrated using precipitation data from Reading, Mass. and from the MBL centroid data because of uncertainty in which data best represented precipitation over the basin. The model was calibrated to annual, monthly, and daily flows to provide the best model fit, particularly during low-flow periods.

Mean annual discharge at the South Middleton station is undersimulated on average by 2.1 percent for simulations made with centroid precipitation data and oversimulated by 2.2 percent for simulations made with Reading precipitation data. Mean annual discharge at Ipswich is undersimulated on average by 3.1 percent for simulations made with centroid precipitation data and oversimulated on average by about 1.1 percent for simulations made with Reading precipitation data. The coefficient of model-fit efficiency indicates that at a minimum, the model explained 90 percent of the variance in the observed monthly flow and 79 percent of the variance in the observed daily flow for simulations made with either precipitation source. Hydrographs of simulated daily mean discharge for 1989–93 at the South Middleton and Ipswich stations parallel the observed hydrographs over a wide range of flow conditions and seasons. Flow-duration curves computed from simulated and observed daily discharge at the South Middleton and Ipswich stations for 1989–93 indicate a similar magnitude and frequency of flow. In general, the model-fit was slightly better for simulations made with the centroid precipitation data than for simulations made with the Reading data; therefore, the centroid precipitation was used to evaluate various water-withdrawal scenarios.

The GenScn decision-support-system software was used to facilitate examination of six water-use scenarios for this report. Three scenarios each were examined for the 1989–93 period and three for the 1961–95 period. The calibration-period scenarios were compared to the base scenario of calibrated flows resulting from existing water-use practices to evaluate the effects of water withdrawals on streamflow. The calibration-period scenarios included (1) stopping all withdrawals, (2) only ground-water withdrawals, and (3) only surface-water withdrawals. The long-term simulations (1961–95) were used to test the effects of withdrawals on streamflow over a wider range of climatic conditions and to compute 1-, 7-, and 30-day low-flow frequencies using log-Pearson Type III analysis. The long-term simulations included: (1) stopping all withdrawals under 1991 land-use conditions as developed in the calibrated model, (2) stopping all withdrawals and reverting developed HRUs to undeveloped HRUs to predict what the natural streamflow would have been, and (3) simulations of average 1989–93 water withdrawals and 1991 land use.

Flow-duration curves and hydrographs developed from the various withdrawal scenarios for the calibration period indicate that surface-water withdrawals have little or no effect on low flows but the ground-water withdrawals have a large effect on low flows. At both gaging stations, flow-duration curves are about an order of magnitude lower at the 99.8 percent exceedence probability for the 1989–93 water withdrawals and the simulation with only ground-water withdrawals as compared to the simulations with no water withdrawals and with only surface-water withdrawals. The relative difference between curves is somewhat larger at the South Middleton station than at the Ipswich station because the ground-water withdrawals are a larger proportion of the streamflow at South Middleton than at Ipswich. Differences between curves diminish as the probability of exceedence decreases to 50 percent. During periods of low flow (especially during the 1991 and 1993 summers), hydrographs for the simulations with no water withdrawals and only surface-water withdrawals are sustained at higher discharges than the hydrographs for the base simulation and the simulation with only ground-water withdrawals. The surface-water withdrawals have little effect on the flow duration because they are restricted to times of relatively high flow when the withdrawals are only a small portion of the total flow.

Results of long-term simulations were similar to those for the same scenarios for 1989–93 simulations at both sites. Low flows for simulations with average calibration-period water withdrawals were substantially lower than simulations with (1) no water withdrawals with 1991 land use, and (2) simulations with no water withdrawals with undeveloped land use. For example, at the South Middleton station the 7-day, 10-year low-flow (7Q10), a widely used regulatory statistic, was 0.54, 4.1, and 5.9 ft^3/s, for simulations with (1) average 1989–93 water withdrawals and 1991 land use, (2) no withdrawals and 1991 land use, and (3) no withdrawals and undeveloped land use, respectively. At the Ipswich station, the 7Q10 was 2.7 ft^3/s for simulations with average 1989–93 water withdrawals, and about 8.3 ft^3/s for simulations with no withdrawals with either 1991 land use or undeveloped land use.

The Ipswich River Basin precipitation-runoff model was conceptualized and calibrated to evaluate the effects on streamflow of water withdrawals from shallow ground-water wells and from surface sources. As such, the model can be used to evaluate a number of management scenarios or to predict flow under conditions that would be difficult or impossible to obtain otherwise. Although the model is well calibrated to the observed data, consideration should be given to the inherent uncertainty of the model simulations.

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APPENDIX A
Documentation of Computer Program STRMDEPL—A Program to Calculate Streamflow Depletion by Wells Using Analytical Solutions

By Paul M. Barlow

CONTENTS

FIGURES

SUMMARY

The computer program STRMDEPL calculates time-varying streamflow depletion caused by pumping at a well. The program is based on two analytical solutions to the ground-water flow equation for the condition of a pumping well in a semi-infinite, homogeneous, and isotropic aquifer in direct hydraulic connection with a straight and fully penetrating stream. One solution assumes unimpeded connection between the stream and aquifer (Jenkins, 1968); the other solution accounts for resistance to flow at the boundary between the stream and aquifer caused by semi-pervious streambed and streambank materials (Hantush, 1965). Superposition is used to calculate the influence of time-varying daily pumping rates on streamflow depletion. This document summarizes the analytical solutions on which the program is based, describes the program and its input requirements, and presents a sample problem based on a pumped well near the Ipswich River, Massachusetts.

ANALYTICAL SOLUTIONS FOR STREAMFLOW DEPLETION BY WELLS

Several analytical solutions are available for the determination of streamflow depletion by wells. These include steady-state solutions by Newsom and Wilson (1988) and Wilson (1993) and transient solutions by Theis (1941), Conover (1954), Glover and Balmer (1954), Glover (1960), Theis and Conover (1963), Hantush (1964, 1965, and 1967), Jenkins (1968), and Weeks and Appel (1984). The most often applied analytical solution for determining time-varying rates of streamflow depletion by wells is that presented in Jenkins (1968). For application of this solution, several simplifying assumptions concerning the aquifer and adjoining stream must be made. These assumptions, which are described in Theis (1941), Glover and Balmer (1954), and Jenkins (1968), are listed here for reference:

1. The aquifer is isotropic, homogeneous, and semi-infinite in areal extent;
2. The transmissivity of the aquifer does not change with time. Thus, for a water-table aquifer, drawdown is considered to be negligible when compared to the initial saturated thickness of the aquifer;
3. The stream that forms a boundary to the aquifer is straight, fully penetrates the aquifer, and is in direct hydraulic connection with the aquifer;
4. The stage of the stream (as well as the ground-water head at the stream boundary) remains constant with time;
5. Water is released instantaneously from storage;
6. The well is open to the full saturated thickness of the aquifer; and
7. The pumping rate is steady during any period of pumping.

The analytical solution presented in Jenkins (1968) is

$$Q_s = Q_w \operatorname{erfc}(U) \quad , \qquad (1)$$

where

$$U = \sqrt{\frac{d^2 S}{4Tt}}$$

and

Q_s is the rate of streamflow depletion (cubic length per time);
Q_w is the pumping rate of the well (cubic length per time);
d is the perpendicular distance from the well to the stream (length);
S is the storativity (or specific yield) of the aquifer (dimensionless);
T is the transmissivity of the aquifer (square length per time); and
t is time.

Inspection of equation 1 indicates that at small time, the argument of the complementary error function (U) becomes large, and the function itself approaches zero. This indicates that immediately after withdrawal begins, the source of water to the well is aquifer storage, and there is little or no streamflow depletion. As time increases, the proportion of streamflow depletion contributing water to the well will increase, ultimately approaching the rate of withdrawal of the well as steady-state conditions are achieved and contributions from aquifer storage approach zero (that is, $Q_s = Q_w$ as $t \rightarrow \infty$).

Streamflow depletion consists of two components. The first is captured ground-water discharge, which is ground water that would have discharged to the stream and contributed to the total amount of streamflow had the well not been pumping. The second component is induced infiltration, which is streamflow that is drawn out of the stream and into the aquifer. The analytical solutions presented here do not differentiate between these two components of streamflow depletion, they simply provide a total depletion that consists of both captured ground-water discharge and induced infiltration.

Three of the parameters in equation 1 that affect streamflow depletion are often combined into a single parameter that characterizes a particular stream-aquifer-well system. This parameter has been referred to as the streamflow depletion factor (sdf)

$$sdf = \frac{d^2S}{T} .$$

The ratio of transmissivity to storativity is defined as the hydraulic diffusivity of the aquifer (T/S). When a well is located very close to a stream (that is, a small d), or when the diffusivity of the aquifer is very large, streamflow depletion will begin soon after withdrawal begins. Conversely, when a well is located far from a stream, or the diffusivity of the aquifer is very small (such as occurs for water-table aquifers where the storativity, S, is assumed equal to the specific yield of the aquifer), there may be a substantial time lag between when the well begins to pump and the beginning of streamflow depletion.

The amount of streamflow depletion that occurs in response to pumping can be reduced by resistance to flow through streambed and streambank materials at the stream-aquifer boundary. In such cases, the streambed and streambank materials are referred to as being semipervious. Hantush (1965) derived an analytical solution for streamflow depletion by wells that accounts for the presence of semipervious materials at the stream-aquifer boundary for the same aquifer, stream, and well conditions used to derive equation 1. His solution is

$$Q_s = Q_w\{erfc(U) - exp[-U^2 + (U + w)^2]erfc(U + w)\} , \qquad (2)$$

where

$$w = \frac{\sqrt{\frac{Tt}{S}}}{a} ,$$

and a, the streambank leakance term (units of length), is defined by

$$a = \frac{Kb'}{K'} ,$$

where

K is hydraulic conductivity of the aquifer (length per time);

K' is hydraulic conductivity of the streambank (length per time); and

b' is thickness of the streambank (length).

As the value of the streambank leakance term increases (that is, resistance to flow at the stream-aquifer boundary increases), streamflow depletion responds more slowly to pumping and streamflow depletion rates are smaller than those that would occur in the absence of semipervious streambank materials.

The amount of streamflow depletion that occurs in response to pumping also can be reduced by partial penetration of the stream in the aquifer. The effect of partial penetration is accounted for in the analytical solutions by replacing the actual distance from the well to the stream (d) by an effective distance from the pumped well to the streambank (x_0). Guidelines for determining x_0 are provided by Hantush (1965) and Spalding and Khaleel (1991). Spalding and Khaleel show that the effective distance of the well from the stream is a function of the actual distance from the well to the stream and the penetration of the stream into the aquifer.

One of the assumptions that was made in the development of equations 1 and 2 is that the pumping rate of the well is steady during any period of pumping. However, the equations can be used in conjunction with the method of superposition to calculate streamflow depletion that occurs in response to time-varying pumping rates at the well. The use of superposition is appropriate here because the underlying ground-water flow equation on which each solution is based is linear.

In the superposition approach, incremental changes in streamflow depletion that occur in response to time-varying pumping rates are accounted for by summing the depletions that occur in response to each pumping rate. A superposition equation (Stallman, 1962; Moench, 1971; Butt and McElwee, 1985) can be written for total streamflow depletion as

$$Q_s(t_i) = Q_0(t_0)F(t_0) + \sum_{k=1}^{i} \Delta Q_k(t_k)F(t_{i-k+1}) , \qquad (3)$$

where

$Q_s(t_i)$ is the rate of streamflow depletion at time step *i* (cubic length per time);

$Q_0(t_0)$ is the initial pumping rate of the well during t_0 (cubic length per time);

$\Delta Q_k(t_k)$ is the change in pumping rate of the well during interval k (cubic length per time);

$F(t_0)$, $F(t_{i-k+1})$ are the values of either $\mathrm{erfc}(U)$ or $\{\mathrm{erfc}(U) - \exp[-U^2 + (U+w)^2]\mathrm{erfc}(U+w)\}$ (depending on whether equation 1 or equation 2 is selected) at times t_0 and t_{i-k+1}, respectively (dimensionless);

t_i is the length of time from the beginning of pumping to the time of interest;

t_k is the time corresponding to time step k;

t_0 is the length of time of the initial pumping rate prior to the start of the analysis;

i is the number of time steps (dimensionless); and

k is the time step number (dimensionless).

Equation 3 assumes a constant time-step size of one time unit, such as 1 day. Streamflow depletions are calculated for each time of interest (t_i), and each time of interest is equal to the product of the constant time-step size (for example, 1 day) by the number of time steps i.

DESCRIPTION OF COMPUTER PROGRAM STRMDEPL

Computer program STRMDEPL was written in FORTRAN-77 to implement equations 1-3, which calculate streamflow depletion caused by time-varying pumping at a well. STRMDEPL uses a constant time-step size of 1 day; therefore, pumping rates must be specified for each day of analysis. For example, if streamflow depletions are to be calculated for the one-year period January 1, 1999 through December 31, 1999, a total of 365 pumping rates must be specified in the input file, one for each day of the year. Furthermore, the user must specify the value of the initial pumping rate (variable QWINIT) and the length of time for which that initial pumping rate occurred prior to the start of the analysis (variable INTIME). These values are specified so that the program will calculate an initial, constant streamflow depletion that accounts for the effects of pumping that occurred prior to the start of the analysis. Streamflow depletions that are calculated for the period of simulation are added to or subtracted from this initial rate of depletion. The initial pumping rate and length of time during which that pumping rate occurred can be empirically adjusted to obtain the desired initial streamflow depletion. For example, if an initial streamflow depletion equal to the previous 12-month average pumping rate was desired, the user would specify QWINIT to the average pumping rate during the previous 12-months and vary the value of INTIME in a series of simulations until the initial streamflow depletion was equal (or nearly equal) to the 12 month average pumping rate.

The program reads data for a particular simulation from an input file and writes the results of the simulation to result and plot files. Line-by-line instructions for creating the input file follow; example input and program output files are provided in the next section. Variable names that are used in the input file and computer program are shown in upper-case text. The type of each variable (character, integer, or real) is listed after the variable’s definition. All data specified in the input file are read using free format and all real-valued variables are double precision in the program. For example, a real-valued variable of 1.33 x 10-3 could be entered as 1.33D-3 or as 0.00133. The program is designed for specific units for each of the variables; the units for each variable are:

Well distance to stream (variable XWELL): feet

Diffusivity of aquifer (variable DIFFUS): square feet per second

Streambank leakance term (variable SLEAK): feet

Pumping rates at well (variables QWINIT and QWELL): cubic feet per second

Line 1:

TITLE--Title of simulation, which can be up to 70 characters in length. Leave this line blank if no title is specified. (Character variable)

Line 2:

WELLID--An identifier for the well that is being simulated, which can be up to 20 characters in length. (Character variable)

Line 3:

XWELL--Distance of well to stream, in feet. (Real variable)

DIFFUS--Diffusivity of the aquifer, in square feet per second. (Real variable)

IBANK--A code that specifies whether or not semipervious streambank materials are present. (Integer variable)

IBANK = 0: Semipervious streambank materials are absent (equation 1 is used)

IBANK = 1: Semipervious streambank materials are present (equation 2 is used)

SLEAK--The value of the streambank leakance term, in feet, if IBANK = 1. Enter 0.0D0 if IBANK = 0. (Real variable)

Line 4: See discussion on these two parameters at the beginning of this section.

INTIME--Number of pumping days prior to start of analysis. (Integer variable)

QWINIT--Pumping rate prior to start of analysis, in cubic feet per second. (Real variable)

Line 5:

NPD--Number of pumping days in analysis. If NPD is greater than 30,000, parameter IMAXX in program STRMDEPL must be increased to a value greater than or equal to NPD and the program must be recompiled. (Integer variable)

Line 6: Date and pumping rate for each day of analysis. Repeat this line of input data NPD times:

CDATE(I)--Date of day I (8 characters, such as 19990101). (Character variable)

QWELL(I)--Pumping rate for day I, in cubic feet per second. (Real variable)

An example input file for STRMDEPL, which is used in the sample problem described in the next section, is shown in figure 1. Result and plot files created by STRMDEPL using the input file shown in figure 1 are given in figures 2 and 3, respectively.

SAMPLE PROBLEM FOR IPSWICH RIVER BASIN

The streamflow-depletion program was tested for a hypothetical pumped well 486 feet from the river’s bank, using pumping rates for Wenham Well 1 for the period January 1, 1989 through December 31, 1997 (3,287 days). The diffusivity of the aquifer near the well and river was assumed to be 10,000 square feet per day (0.1157 square feet per second) based on hydraulic properties of the aquifer in the Ipswich River Basin given in Baker and others (1964) and Sammel and others (1966). The streambed materials are very coarse in the vicinity of the well and, accordingly, it was assumed that there would be no resistance to flow at the streambank caused by semipervious materials. As a result, equation 1 was used to calculate streamflow depletions (IBANK = 0). Burns and James (1972) also used equation 1 in their analysis of the Ipswich River Basin.

An initial streamflow depletion was desired that was as close as possible to the pumping rate on January 1, 1989, which was 0.1903 ft^3/s (0.123 Mgal/d). As a result, an initial pumping rate of 0.1900 ft^3/s (variable QWINIT) and number of pumping days prior to the analysis of 10,000 (variable INTIME) were simulated. This combination of initial pumping rate and pumping days prior to the start of the analysis (January 1, 1989) resulted in an initial streamflow depletion of 0.1848 ft^3/s, which is 97.3 percent of the initial pumping rate. The initial streamflow depletion does not reach the initial pumping rate of 0.1900 ft^3/s, even after 10,000 days of simulation, because the complementary error function in equation 1 asymptotically approaches unity. As a result, for this combination of well distance from the stream and aquifer diffusivity, it is difficult to obtain an initial streamflow depletion equal to the initial pumping rate.

Specified daily pumping rates at the well and calculated streamflow depletions in the river for the period of analysis are shown in figure 4. As seen in the figure, daily pumping rates are quite variable over the period of analysis, ranging from 0.0 to about 1.0 ft^3/s. The pumping rates also show seasonality—generally increasing during the spring and summer months and decreasing during the fall and winter. Finally, the pumping rates show a general trend upward during the 9-year period. The range and variability of calculated streamflow depletion, however, is much less than the range and variability of the daily pumping rate, which results from the diffusivity of the aquifer and distance of the well from the stream. Variability of the daily pumping rates is effectively damped by the aquifer, which results in a less variable rate of streamflow depletion throughout the year. The calculated streamflow depletions also exhibit a general increasing trend during the 9-year period of analysis.

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```
Depletion for Wenham Well 1
3320000-01G                      Line 2: WELLID
486.00  0.1157  0 0.0            Line 3: XWELL DIFFUS IBANK SLEAK
10000     0.1900                 Line 4: INTIME QWINIT
3287                             Line 5: NPD
19890101  0.1903                 Line 6: CDATE(I) QWELL(I)
19890102  0.1864
19890103  0.0982
19890104  0.1470
19890105  0.3133
19890106  0.1377
19890107  0.2754
19890108  0.1648
19890109  0.0897
19890110  0.2352
19890111  0.1857
19890112  0.1818
19890113  0.1748
19890114  0.2011
19890115  0.1230
19890116  0.2769
19890117  0.1122
19890118  0.3056
19890119  0.1973
19890120  0.0982
19890121  0.3644
19890122  0.0967
19890123  0.1253
19890124  0.2143
19890125  0.1849
19890126  0.1601
19890127  0.2066
19890128  0.2004
19890129  0.1942
19890130  0.1578

3,250 lines of input deleted here

19971225  0.1800
19971226  0.2730
19971227  0.2590
19971228  0.1625
19971229  0.2315
19971230  0.2080
19971231  0.2025
```

Figure 1. Example input file for program STRMDEPL.

```
             ******************************************************
             *                                                    *
             *         ****  U.S. GEOLOGICAL SURVEY  ****         *
             *                                                    *
             *          *** STRMDEPL: PROGRAM OUTPUT ***          *
             *                                                    *
             *    ONE-DIMENSIONAL MODEL OF STREAMFLOW DEPLETION   *
             *                                                    *
             *       BY WELLS, BASED ON ANALYTICAL SOLUTIONS      *
             *                                                    *
             *   DEVELOPED BY JENKINS (1968) AND HANTUSH (1965)   *
             *                                                    *
             *           VERSION CURRENT AS OF 04/12/99           *
             *                                                    *
             ******************************************************


  Depletion for Wenham Well 1


                 SUMMARY OF INPUT DATA
                 ---------------------

WELL IDENTIFIER:                     3320000-01G
WELL DISTANCE TO STREAM (XWELL):     0.486D+03 feet
DIFFUSIVITY (DIFFUS):                0.116D+00 square feet per second
STREAMBANK CODE (IBANK):             0 (semipervious streambank absent)
INITIAL TIME (INTIME):              10000 days
INITIAL PUMPING RATE (QWINIT):       0.190D+00 cubic feet per second
NUMBER OF PUMPING DAYS (NPD):        3287
```

Figure 2. Example result file generated by program STRMDEPL.

```
                         RESULTS
                         -------

STREAMFLOW DEPLETION AT BEGINNING OF ANALYSIS:
           0.1848 cubic feet per second

             PUMPING RATE    STREAMFLOW DEPLETION
   DAY              (cubic feet per second)
   ---       ------------    --------------------
19890101        0.1903             0.1848
19890102        0.1864             0.1848
19890103        0.0982             0.1847
19890104        0.1470             0.1833
19890105        0.3133             0.1812
19890106        0.1377             0.1815
19890107        0.2754             0.1827
19890108        0.1648             0.1840
19890109        0.0897             0.1851
19890110        0.2352             0.1840
19890111        0.1857             0.1828
19890112        0.1818             0.1829
19890113        0.1748             0.1829
19890114        0.2011             0.1827
19890115        0.1230             0.1826
19890116        0.2769             0.1820
19890117        0.1122             0.1821
19890118        0.3056             0.1824
19890119        0.1973             0.1833
19890120        0.0982             0.1852
19890121        0.3644             0.1850
19890122        0.0967             0.1860
19890123        0.1253             0.1871
19890124        0.2143             0.1855
19890125        0.1849             0.1842
19890126        0.1601             0.1838
19890127        0.2066             0.1833
19890128        0.2004             0.1830
19890129        0.1942             0.1833
19890130        0.1578             0.1837

3,250 lines of results deleted here

19971225        0.1800             0.2375
19971226        0.2730             0.2371
19971227        0.2590             0.2373
19971228        0.1625             0.2385
19971229        0.2315             0.2388
19971230        0.2080             0.2382
19971231        0.2025             0.2379
```

Figure 2. Example result file generated by program STRMDEPL—*Continued*.

```
   DATE          QWELL         QS
 19890101       0.1903       0.1848
 19890102       0.1864       0.1848
 19890103       0.0982       0.1847
 19890104       0.1470       0.1833
 19890105       0.3133       0.1812
 19890106       0.1377       0.1815
 19890107       0.2754       0.1827
 19890108       0.1648       0.1840
 19890109       0.0897       0.1851
 19890110       0.2352       0.1840
 19890111       0.1857       0.1828
 19890112       0.1818       0.1829
 19890113       0.1748       0.1829
 19890114       0.2011       0.1827
 19890115       0.1230       0.1826
 19890116       0.2769       0.1820
 19890117       0.1122       0.1821
 19890118       0.3056       0.1824
 19890119       0.1973       0.1833
 19890120       0.0982       0.1852
 19890121       0.3644       0.1850
 19890122       0.0967       0.1860
 19890123       0.1253       0.1871
 19890124       0.2143       0.1855
 19890125       0.1849       0.1842
 19890126       0.1601       0.1838
 19890127       0.2066       0.1833
 19890128       0.2004       0.1830
 19890129       0.1942       0.1833
 19890130       0.1578       0.1837

 3,250 lines of results deleted here

 19971225       0.1800       0.2375
 19971226       0.2730       0.2371
 19971227       0.2590       0.2373
 19971228       0.1625       0.2385
 19971229       0.2315       0.2388
 19971230       0.2080       0.2382
 19971231       0.2025       0.2379
```

Figure 3. Example plot file generated by program STRMDEPL.

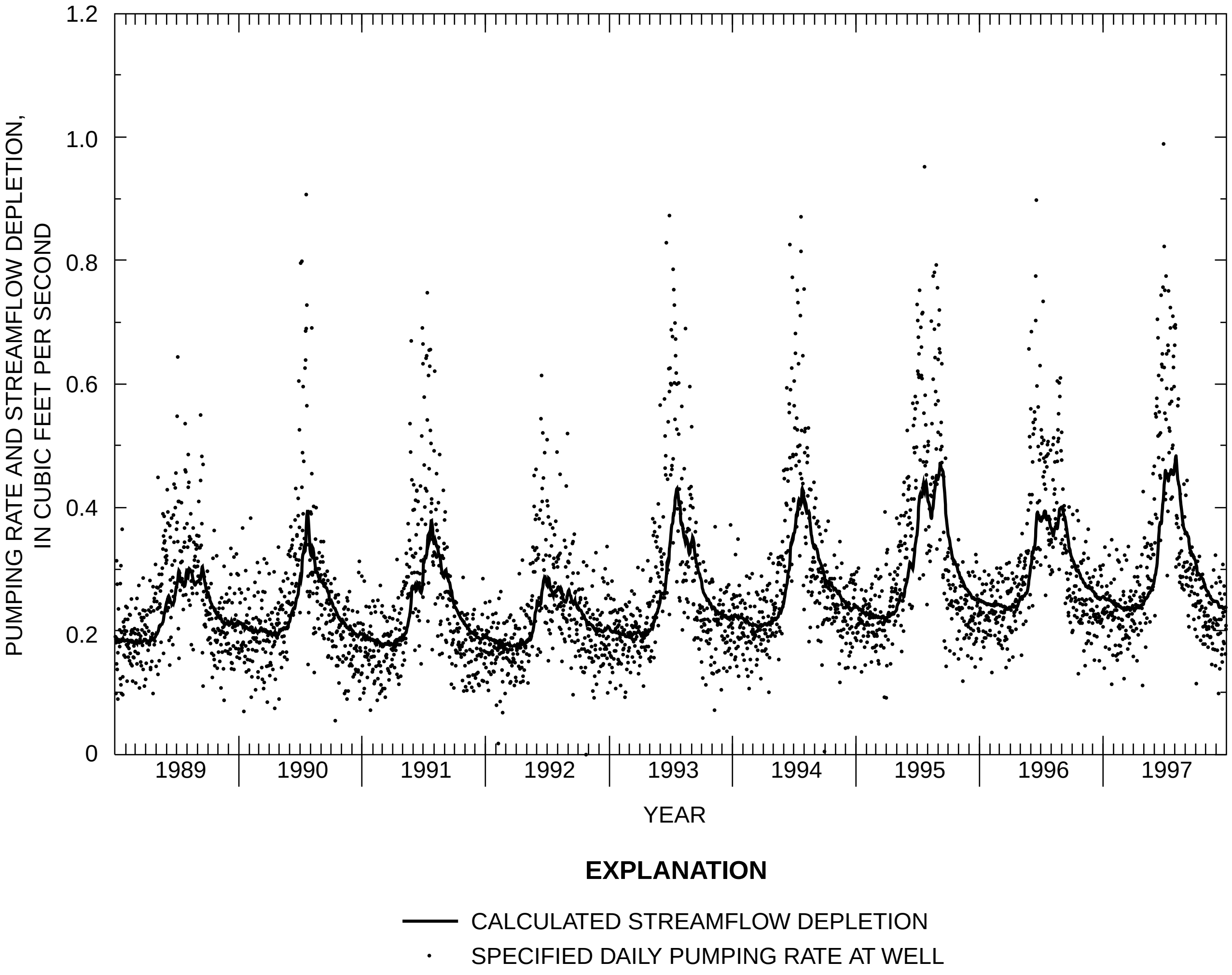

Figure 4. Specified daily pumping rates at well Wenham Well 1, 1989–97, and calculated streamflow depletion.

APPENDIX B
Ipswich River Watershed Model (HSPF) User Control Input File for PERLND and IMPLND Blocks

```
***  HSPF model run for Ipswich River Basin, MA

***  -------------------------------------
***  |  Base simulation                   |
***  -------------------------------------
*** Documentation - HSPF Users manual release 11 (Bicknell and others, 1997)

********************************************************************************
***          PERLND - Pervious land surface  Principles  4.2(1).1  pg 37    ***
***                                          Coding 4.4(1)    pg 300        ***
********************************************************************************
PERLND
  ACTIVITY
    <PLS >          Active Sections (1=Active; 0=Inactive)             ***
    # -  # ATMP SNOW PWAT  SED  PST  PWG PQAL MSTL PEST NITR PHOS TRAC ***
    1   15    0    1    1
  END ACTIVITY

  PRINT-INFO
    <PLS > <-*** Print-flags: 2-PIVL, 3-dy, 4-mn, 5-yr, 6-never  ***-> PIVL  PYR
    # -  # ATMP SNOW PWAT  SED  PST  PWG PQAL MSTL PEST NITR PHOS TRAC       ***
    1   15         5    4                                                 1   12
  END PRINT-INFO

  GEN-INFO
    <PLS ><-------Name------->NBLKS   Unit-systems   Printer ***
  ###--###                          User  t-series Engl Metr ***
                                           in  out           ***
    1      S&G Forest            1    1    1    1   15    0
    2      S&G Open              1    1    1    1   15    0
    3      S&G Opn low-resid     1    1    1    1   15    0
    4      S&G Opn low-res PW    1    1    1    1   15    0
    5      S&G Opn hi-resid      1    1    1    1   15    0
    6      S&G Opn hi-res PW     1    1    1    1   15    0
    7      Open Commercial       1    1    1    1   15    0
    8      Till Forest           1    1    1    1   15    0
    9      Till Open             1    1    1    1   15    0
   10      Till Opn low-resid    1    1    1    1   15    0
   11      Till Opn low-res PW   1    1    1    1   15    0
   12      Till Opn hi-resid     1    1    1    1   15    0
   13      Till Opn hi-res PW    1    1    1    1   15    0
   14      Fine Dep Forest       1    1    1    1   15    0
   15      Fine Dep Open         1    1    1    1   15    0
  END GEN-INFO

*** ------------------------------------------------------------------------- *
***   PERLND -  Section SNOW   Principles  4.2(1).2    pg 40              *
***                            Coding 4.4(1).3    pg 309                      *
*** ------------------------------------------------------------------------- *

  ICE-FLAG
    <PLS >  0= Ice formation not simulated, 1= Simulated ***
  ### -###ICEFG                                          ***
    1   15    1
```

```
  END ICE-FLAG

  SNOW-PARM1
    <PLS >  Snow input info: Part 1                          ***
  ### -###       LAT     MELEV     SHADE    SNOWCF    COVIND ***
    1            42.       60.      0.50      1.60      0.25
    2            42.       60.      0.05      1.60      0.25
    3    7       42.       60.      0.15      1.60      0.25
    8            42.       60.      0.50      1.60      0.25
    9            42.       60.      0.05      1.60      0.25
   10   13       42.       60.      0.15      1.60      0.25
   14            42.       60.      0.50      1.60      0.25
   15            42.       60.      0.10      1.65      0.25
  END SNOW-PARM1

  SNOW-PARM2
    <PLS >  Snow input info: Part 2                                    ***
  ### -###     RDCSN     TSNOW    SNOEVP    CCFACT    MWATER    MGMELT ***
    1           0.15       32.      0.15      0.05      0.90    0.1100
    2           0.15       32.      0.15      0.05      0.90    0.1100
    3    7      0.15       32.      0.20      0.07      1.00    0.1300
    8           0.20       32.      0.15      0.05      0.90    0.1100
    9           0.15       32.      0.15      0.05      0.90    0.1100
   10   13      0.15       32.      0.20      0.07      1.00    0.1200
   14           0.15       32.      0.15      0.05      0.90    0.1100
   15           0.15       32.      0.15      0.05      0.90    0.1100
  END SNOW-PARM2

  SNOW-INIT1 ***
    <PLS >  Initial snow conditions: Part 1                            ***
  ### -###  PACKSNOW   PACKICE PACKWATER    RDENPF      DULL    PAKTMP ***
*** 1   15      2.27       0.0      0.49      0.29      35.6      31.6
  END SNOW-INIT1 ***

  SNOW-INIT2  ***
    <PLS >  Initial snow conditions: Part 2 ***
  ### -###    COVINX    XLNMLT    SKYCLR    ***
*** 1   15      0.10      0.01      0.15
  END SNOW-INIT2  ***
***---------------------------------------------------------------------------*
***  PERLND -  Section PWATER   Princples 4.2(1).3   pg 54                   *
***                             Coding 4.4(1).4   pg 317                     *
***---------------------------------------------------------------------------*

  PWAT-PARM1
***                       1=varies monthly 0=does not
*** <PLS > <PWATER flags><monthly parameter value flags>
***## -### CSNO RTOP UZFG  VCS  VUZ  VNN VIFW VIRC  VLE
    1    6    1    0    0    1    1    1    1    1    1
    7         1    0    0    1    1    1    1    1    1
    8   13    1    0    0    1    1    1    1    1    1
   14   15    1    0    0    1    1    1    1    1    1
  END PWAT-PARM1
```

```
PWAT-PARM2
  <PLS > ***  PWATER input info: Part 2
### -### ***FOREST      LZSN    INFILT      LSUR     SLSUR     KVARY     AGWRC
         ***(none)      (in)   (in/hr)      (ft)    (none)    (l/in)    (l/in)
  1          0.550     14.20     0.286      500.     0.024      0.50     0.996
  2          0.020     14.20     0.287      300.     0.025      0.50     0.996
  3          0.050     11.10     0.242      300.     0.025      0.50     0.992
  4          0.050     11.10     0.242      300.     0.025      0.50     0.992
  5          0.050     10.70     0.212      200.     0.025      0.50     0.990
  6          0.050     10.70     0.212      200.     0.025      0.50     0.990
  7          0.030      8.20     0.080      100.     0.024      0.50     0.980

  8          0.550      9.20     0.038      400.     0.026      0.50     0.988
  9          0.020      9.00     0.038      200.     0.028      0.50     0.988
 10          0.050      8.70     0.028      300.     0.026      0.50     0.984
 11          0.050      8.70     0.028      300.     0.026      0.50     0.984
 12          0.050      8.20     0.022      200.     0.026      0.50     0.982
 13          0.050      8.20     0.022      200.     0.026      0.50     0.982

 14          0.550      8.70     0.095      300.     0.023      0.50     0.985
 15          0.030      8.70     0.092      200.     0.024      0.50     0.985
END PWAT-PARM2


PWAT-PARM3
  <PLS > ***  PWATER input info: Part 3
### -### ***PETMAX    PETMIN    INFEXP    INFILD    DEEPFR    BASETP    AGWETP
  1   15       40.       35.       3.0       1.8      0.00      0.00     0.001
END PWAT-PARM3

PWAT-PARM4
  <PLS >     PWATER input info: Part 4                               ***
  Flag PARM1   VCS       VUZ       VUR       VMN      VIFW       VLE ***
### -###     CEPSC      UZSN      NSUR     INTFW       IRC     LZETP ***
              (in)      (in)    (none)    (none)    (l/da)    (none) ***
  1          0.080      0.28     0.230      1.00      0.75      0.88
  2          0.020      0.22     0.250      1.00      0.75      0.18
  3          0.040      0.16     0.210      1.00      0.75      0.28
  4          0.040      0.16     0.210      1.00      0.75      0.28
  5          0.040      0.16     0.210      1.00      0.75      0.28
  6          0.040      0.16     0.210      1.00      0.75      0.28
  7          0.030      0.12     0.200      1.00      0.75      0.22

  8          0.080      0.22     0.230      1.00      0.75      0.88
  9          0.020      0.19     0.250      1.00      0.75      0.18
 10          0.040      0.14     0.210      1.00      0.75      0.18
 11          0.040      0.14     0.210      1.00      0.75      0.18
 12          0.040      0.14     0.210      1.00      0.75      0.18
 13          0.040      0.14     0.210      1.00      0.75      0.18

 14          0.080      0.26     0.230      1.00      0.75      0.88
 15          0.020      0.22     0.250      1.00      0.75      0.18
END PWAT-PARM4
```

```
MON-INTERCEP
  Monthly interception storage capacity                              ***
  <PLS>   Only required if VCSFG=1 in PWAT-PARM1                    ***
### -###  Interception storage capacity at start of each month       ***
          JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC ***
  1      0.04 0.04 0.04 0.04 0.06 0.12 0.14 0.16 0.17 0.16 0.04 0.04
  2      0.02 0.02 0.02 0.03 0.03 0.04 0.04 0.04 0.04 0.03 0.02 0.02
  3    7 0.02 0.02 0.02 0.03 0.03 0.05 0.05 0.05 0.05 0.03 0.02 0.02

  8      0.04 0.04 0.04 0.04 0.05 0.12 0.14 0.16 0.17 0.16 0.04 0.04
  9      0.02 0.02 0.02 0.03 0.03 0.04 0.04 0.04 0.04 0.03 0.02 0.02
 10   13 0.02 0.02 0.02 0.03 0.03 0.05 0.05 0.05 0.05 0.03 0.02 0.02

 14      0.04 0.04 0.04 0.04 0.05 0.12 0.14 0.16 0.17 0.16 0.04 0.04
 15      0.02 0.02 0.02 0.03 0.03 0.04 0.04 0.04 0.04 0.03 0.02 0.02
END MON-INTERCEP

MON-UZSN
  Upper zone nominal storage                                         ***
  UZSN inversly affects peak flow - as UZSN goes up peaks go down    ***
  <PLS>   Only required if VUZFG=1 in PWAT-PARM1                    ***
### -###  Upper zone storage at start of each month                  ***
          JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC ***
  1      1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
  2    6  .77  .77  .77  .77  .77  .77  .77  .77  .77  .77  .77  .77
  7       .56  .56  .56  .56  .56  .56  .56  .56  .56  .56  .56  .56

  8       .50  .50  .50  .50  .50  .50  .50  .50  .50  .50  .50  .50
  9   13  .62  .62  .62  .62  .62  .62  .62  .62  .62  .62  .62  .62

 14   15  .60  .60  .60  .60  .60  .60  .60  .60  .60  .60  .60  .60
END MON-UZSN

MON-MANNING
  Manning's "n" for overland flow plans                              ***
  <PLS >  Only required if VNNFG=1 in PWAT-PARM1                    ***
### -###  Manning's n for overland flow at start of each month       ***
          JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC ***
  1      0.28 0.28 0.28 0.28 0.29 0.29 0.29 0.29 0.29 0.29 0.28 0.28
  2      0.25 0.25 0.25 0.25 0.27 0.30 0.30 0.30 0.30 0.27 0.25 0.25
  3    7 0.22 0.22 0.22 0.22 0.23 0.26 0.26 0.26 0.26 0.25 0.23 0.22

  8      0.28 0.28 0.28 0.28 0.29 0.29 0.29 0.29 0.29 0.29 0.28 0.28
  9      0.25 0.25 0.25 0.25 0.27 0.30 0.30 0.30 0.30 0.27 0.25 0.25
 10   13 0.22 0.22 0.22 0.22 0.23 0.26 0.26 0.26 0.26 0.25 0.23 0.22

 14      0.25 0.25 0.25 0.25 0.27 0.27 0.27 0.27 0.27 0.25 0.25 0.25
 15      0.25 0.25 0.25 0.25 0.27 0.30 0.30 0.30 0.30 0.27 0.25 0.25
END MON-MANNING
```

```
MON-INTERFLW
  Monthly interflow parameter                                        ***
  <PLS >  Only required if VIFWFG=1 in PWAT-PARM1                    ***
### -###  Monthly interflow  at start of each month                  ***
          JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC ***
  1      8.60 8.60 8.60 8.65 8.65 8.65 8.65 8.65 8.65 8.70 8.70 8.70
  2      8.50 8.50 8.50 8.50 8.55 8.55 8.55 8.55 8.55 8.50 8.50 8.50
  3    7 8.30 8.30 8.30 8.30 8.35 8.35 8.35 8.35 8.35 8.30 8.30 8.30

  8      5.90 5.90 5.90 5.95 5.95 5.95 5.95 5.95 5.95 5.90 5.90 5.90
  9      5.80 5.80 5.80 5.80 5.85 5.85 5.85 5.85 5.85 5.80 5.80 5.80
 10   13 5.70 5.70 5.70 5.70 5.75 5.75 5.75 5.75 5.75 5.70 5.70 5.70

 14      6.50 6.50 6.50 6.55 6.55 6.55 6.55 6.55 6.55 6.50 6.50 6.50
 15      6.40 6.40 6.40 6.40 6.45 6.45 6.45 6.45 6.45 6.40 6.40 6.40
END MON-INTERFLW

MON-IRC
  Monthly interflow recession                                        ***
  <PLS >  Only required if VIRCFG=1 in PWAT-PARM1 (max < 1.0)        ***
### -###  Monthly interflow  at start of each month                  ***
          JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC ***
  1    2 0.90 0.90 0.90 0.90 0.91 0.92 0.92 0.92 0.91 0.90 0.90 0.90
  3    4 0.88 0.88 0.88 0.88 0.89 0.90 0.90 0.90 0.90 0.88 0.88 0.88
  5    6 0.86 0.86 0.86 0.86 0.87 0.88 0.88 0.88 0.87 0.86 0.86 0.86
  7      0.82 0.82 0.82 0.82 0.84 0.86 0.86 0.86 0.84 0.82 0.82 0.82

  8    9 0.90 0.90 0.90 0.90 0.91 0.92 0.92 0.92 0.92 0.90 0.90 0.90
 10   11 0.88 0.88 0.88 0.88 0.89 0.90 0.90 0.90 0.89 0.88 0.88 0.88
 12   13 0.86 0.86 0.86 0.86 0.87 0.88 0.88 0.88 0.87 0.86 0.86 0.86

 14   15 0.90 0.90 0.90 0.90 0.90 0.90 0.90 0.90 0.90 0.90 0.90 0.90
END MON-IRC

MON-LZETPARM
  Lower zone ET                                                      ***
  <PLS >  Only required if VLEFG=1 in PWAT-PARM1  (max < 1.0)        ***
### -###  Lower zone ET parameter at start of each month             ***
          JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC ***
  1       .73  .73  .73  .78  .82  .87  .92  .92  .83  .78  .73  .73
  2       .18  .18  .20  .22  .24  .26  .27  .27  .22  .21  .20  .18
  3    6  .40  .40  .40  .42  .44  .50  .54  .54  .52  .44  .42  .40
  7       .35  .35  .35  .37  .39  .43  .45  .45  .44  .39  .37  .35

  8       .73  .73  .73  .78  .82  .87  .92  .92  .83  .78  .73  .73
  9       .18  .18  .20  .22  .24  .26  .27  .27  .22  .21  .20  .18
 10   13  .40  .40  .40  .42  .44  .50  .54  .54  .52  .44  .42  .40

 14       .73  .73  .73  .78  .83  .87  .92  .92  .83  .78  .73  .73
 15       .22  .22  .25  .27  .28  .32  .33  .33  .32  .28  .25  .22
END MON-LZETPARM
```

```
  PWAT-STATE1
    <PLS > *** Initial conditions at start of simulation
  ### -### ***  CEPS      SURS       UZS      IFWS       LZS      AGWS      GWVS
    1           0.04      0.00      0.39     0.000     15.62      5.93      1.07
    2           0.02      0.00      1.24     0.007     21.08      7.56      1.77
    3    6      0.02      0.00      1.07     0.001     14.35      3.05      1.78
    7           0.02      0.00      0.91     0.007     10.62      0.99      1.27

    8           0.04      0.00      0.76     0.015     10.06      1.41      0.81
    9           0.02      0.00      1.23     0.112     12.38      1.69      1.04
   10   13      0.02      0.00      1.10     0.040     10.00      1.00      1.00

   14           0.04      0.00      0.79     0.002      9.76      1.21      0.91
   15           0.02      0.00      1.03     0.003     11.76      1.48      1.38
  END PWAT-STATE1

END PERLND


**************************************************************************
***   IMPLND  - Impervious land  4.2(2)    Principles  4.2(2)  pg 114  ***
***                                        Coding 4.4(2)  pg 457       ***
**************************************************************************
IMPLND
  ACTIVITY
    <ILS >  Active Sections (1-active, 0-inactive)                     ***
  ### -### ATMP SNOW IWAT  SLD  IWG IQAL                               ***
    1         0    1    1
    2         0    1    1
  END ACTIVITY

  PRINT-INFO
    2-PIVL, 3-dy, 4-mn, 5-yr, 6-never    user  end                     ***
    <ILS > <------ Print-flags --------> PIVL  PYR                     ***
  ### -### ATMP SNOW IWAT  SLD  IWG IQAL ####   ##                     ***
    1              4    4                   1   12
    2              4    4                   1   12
  END PRINT-INFO

  GEN-INFO
    <ILS ><-------Name------->   Unit-systems   Printer                ***
  ### -###                     User  t-series Engl Metr                ***
                                      in  out i/o#                     ***
    1      Residential            1    1    1   15    0
    2      Commercial             1    1    1   15    0
  END GEN-INFO

*** ------------------------------------------------------------------------*
***   IMPLND-  Same as PERLND Section SNOW                                  *
***                           see 4.4(1).3    pg 309                        *
*** ------------------------------------------------------------------------*
```

```
  ICE-FLAG
    <PLS >  0= Ice formation not simulated, 1= Simulated ***
  ### -###ICEFG                                          ***
    1    2    1
  END ICE-FLAG

  SNOW-PARM1
    <PLS >  Snow input info: Part 1                          ***
  ### -###       LAT     MELEV     SHADE    SNOWCF    COVIND ***
    1    2       42.       60.      0.20      1.80      0.15
  END SNOW-PARM1

  SNOW-PARM2
    <PLS >  Snow input info: Part 2                                    ***
  ### -###     RDCSN     TSNOW    SNOEVP    CCFACT    MWATER    MGMELT ***
    1    2      0.20       32.      0.02      0.05      1.00    0.1100
  END SNOW-PARM2

  SNOW-INIT1 ***
    <PLS >  Initial snow conditions: Part 1                            ***
  ### -###  PACKSNOW   PACKICE PACKWATER    RDENPF      DULL    PAKTMP ***
*** 1    2       2.2       0.0      0.61      0.29       35.      31.5
  END SNOW-INIT1 ***

  SNOW-INIT2  ***
    <PLS >  Initial snow conditions: Part 2 ***
  ### -###    COVINX    XLNMLT    SKYCLR    ***
*** 1    2      0.10      0.01      0.15
  END SNOW-INIT2  ***

*** ---------------------------------------------------------------------- *
***   IMPLND - Section IWATER input  Principles  4.2(2).3  pg 114          *
***                                  Coding 4.4(2).4  pg 464               *
*** ---------------------------------------------------------------------- *

  IWAT-PARM1
    <ILS >           Flags          ***
  ### -### CSNO RTOP  VRS  VNN RTLI ***
    1         1    1              0
    2         1    1              0
  END IWAT-PARM1

  IWAT-PARM2
    <ILS >                                         ***
  ### -###      LSUR     SLSUR      NSUR     RETSC ***
    1           400.      .014      .010       .04
    2           200.      .010      .010       .08
  END IWAT-PARM2

  IWAT-PARM3
    <ILS >                     ***
  ### -###    PETMAX    PETMIN ***
    1            40.       35.
    2            40.       35.
  END IWAT-PARM3

END IMPLND
```